J Soils Sediments (2010) 10:787–795
DOI 10.1007/s11368-009-0140-7

SOILS, SEC 3 • REMEDIATION AND MANAGEMENT OF CONTAMINATED OR DEGRADED LANDS • RESEARCH ARTICLE

Forms and profile distribution of soil Fe in the Sanjiang Plain of Northeast China as affected by land uses

Guangyu Chi · Xin Chen · Yi Shi · Taihui Zheng

Received: 20 June 2009 / Accepted: 3 September 2009 / Published online: 25 September 2009
© Springer-Verlag 2009

Abstract
Purpose Since the mid-1950s, the wetlands in Sanjiang Plain of Northeast China have experienced greater changes in land use under which the mobility of soil Fe could be changed giving definite effects on the biomass production of adjacent regions. The aim of this work was to investigate the effects of land use change on the characteristics of soil Fe vertical distribution with a focus on evaluating the effects of cultivation on the soil Fe mobility in Sanjiang Plain.
Materials and methods Twelve sites between two upper reaches of Amur River, i.e., Naoli River and Nongjiang River in the Sanjiang Plain, were selected as sampling sites, covering natural wetland, lowland rice field, and upland soybean field. Samples of different land use type soil were collected at the depths of 0–10, 10–20, 20–40, 40–60, 60–90, and 90–120 cm with their organic C, pH, total Fe (Fe_t), free Fe oxides (Fe_d), amorphous Fe oxides (Fe_o), Fe(II), and water-soluble Fe (Fe_w) determined.
Results and discussion After the conversion of wetland into lowland rice field and upland soybean field, the organic carbon content in 0–10-cm soil layer decreased by 25.7% ($P<0.05$) and 48.0% ($P<0.05$), respectively, and the pH value at the soil depths below 40 cm in lowland rice field and upland soybean field was higher than that in natural wetland. Fe oxides concentration profiles suggested that a significant amount of Fe in wetland soil was moved downward to deeper layers while part of the Fe in farmland soils was deposited in subsurface layer where a good aeration occurred preventing its further leaching loss. Cultivation promoted the production of soil Fe_d and retarded the formation of Fe_o, Fe(II), and Fe_w with the sequence of soil Fe_o/Fe_d ratio, Fe(II), and Fe_w being wetland > lowland rice field > upland soybean field.
Conclusions The results supported the ideas that, in the Sanjiang Plain, the conversion of wetland into farmland, especially into upland, could change the soil Fe vertical distribution giving potential effects on the mobility of soil Fe. A quantitative study on the dissolved iron discharge from different land use type would be made to quantify the flux of dissolved iron from the Sanjiang Plain to the Amur River and the Sea of Okhotsk based on the high-resolution geographical distribution maps of land surfaces in the alluvial plain.

Keywords Land use · Mobility · Profile distribution · Sanjiang Plain of Northeast China · Soil Fe · Wetland

1 Introduction

Fe is an essential micronutrient to all living things (Cullen 1999; Falkowski 2002). The soluble Fe in seawater is a limiting factor to the phytoplankton biomass in high nitrogen low chlorophyll maritime space (Martin and Fitzwater 1988; Martin 1990, 1992) while the land–ocean linkage by Fe transport through rivers is now believed to play a key role in the maintenance of ocean ecosystem (Capone et al. 1997; Karl et al. 1997; Narita et al. 2004;

Responsible editor: Willie Peijnenburg

G. Chi · X. Chen (✉) · Y. Shi · T. Zheng
Agricultural Ecology Engineering, Key Laboratory of Terrestrial Ecological Process, Institute of Applied Ecology,
Chinese Academy of Sciences,
Wenhua Road, P.O. Box 417, Shenyang 110016,
People's Republic of China
e-mail: chenxiniae@126.com

G. Chi · T. Zheng
Graduate University of Chinese Academy of Sciences,
Beijing 100049, People's Republic of China

Shiraiwa 2005; Yoh 2004). Land surface condition affects the mobility of soil Fe, which might affect the transport of dissolved Fe to the river, giving definite effects on the biomass production in the ocean (Narita et al. 2004; Yoh 2004; Shiraiwa 2005).

Sanjiang Plain is an important part of Amur Basin and lies off the southwestern coast of Okhotsk Sea. It has a wide distribution of wetland being considered as a crucial Fe source of the Amur River and Okhotsk Sea (Hao et al. 2003). The wetland area in Sanjiang Plain changed from 19,450 km^2 in 1980 to 9,069 km^2 in 2000 (Chen et al. 2002; Liu and Ma 2000; Fig. 1). The reclamation of wetland always starts with the construction of drainage ditches to reduce excess water, and tillage can increase soil aeration increasing the O_2 flow into and the CO_2 release out of the soil (Reicosky and Lindstrom 1993). Under these conditions, the amount of dissolved soil Fe would be changed giving potential effects on the Fe input of Amur River and further, the phytoplankton growth of the Okhotsk Sea, a famous fishing ground in the world (Narita et al. 2004; Yoh 2004).

In this paper, profile samples of soil in Sanjiang Plain were collected from natural wetland, lowland rice field, and upland soybean field to study the distribution patterns of soil Fe oxides, aimed to elucidate the vertical distribution characteristics of soil Fe under different land use with a focus on evaluating the effects of cultivation on the soil Fe mobility in Sanjiang Plain.

2 Materials and methods

2.1 Sampling sites

The Sanjiang Plain of Northeast China is a low-lying alluvial floodplain of about 66,600 km^2. It has a typical continental monsoon climate, i.e., summer is short, warm, and rainy while winter is long and cold. The water and soil in the wetlands are completely frozen from October to next April, and begin to thaw from late April till July. The minimum, maximum, and mean annual temperatures are −18°C to −21°C, 21°C to 22°C, and 1.6°C to 1.9°C, respectively, and the mean annual precipitation is about 600 mm, in which approximately 60% is concentrated in June– September (Guo et al. 2008). The main soil types are Albic Luvisol, Mollic Planoso1, Mollic Glegsol, and Gleysol (FAO-Unesco 1997).

Twelve sites between two upper reaches of Amur River, i.e., Naoli River and Nongjiang River, were selected as sampling sites covering natural wetland, lowland rice field, and upland soybean field. The wetlands are seasonally waterlogged marshes with *Calamagrostis angustifolia* as the dominant vegetation species, and the farmlands have been cultivated for rice or soybean for 15–17 years (Fig. 2).

2.2 Soil sampling and analysis

2.2.1 Soil samples collection

In August 3rd–9th, soil samples were collected by a piston-corer consisting of a stainless steel cylinder 5 cm in diameter and sharpened at the end with duplicates at each sampling site. The soil cores had a length of 120 cm, which were wrapped with thin-wall plastic films and stored at 0–4°C to prevent oxidation. After being transported to laboratory, the soil cores were cut into segments (0–10, 10–20, 20–40, 40–60, 60–90, and 90–120; Todorova et al. 2005; Xi et al. 2007; Park and Burt 1999).

2.2.2 Analytical methods

Acid ammonium oxalate-extractable Fe-amorphous Fe oxides (Fe_o) and sodium hydrosulfite–sodium citrate–sodium bicarbonate (DCB) extractable Fe-free Fe oxides (Fe_d) are most frequently used to describe pedogenesis (Schwertmann and Murad 1990). Fe_o includes organically

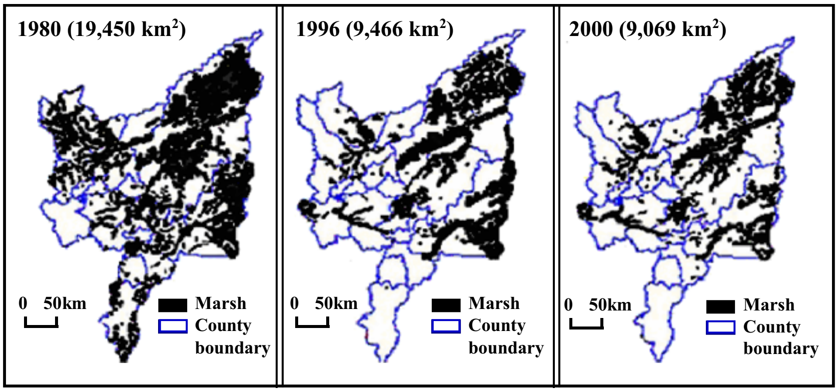


Fig. 1 Changes of wetland area in Sanjiang Plain from 1980 to 2000

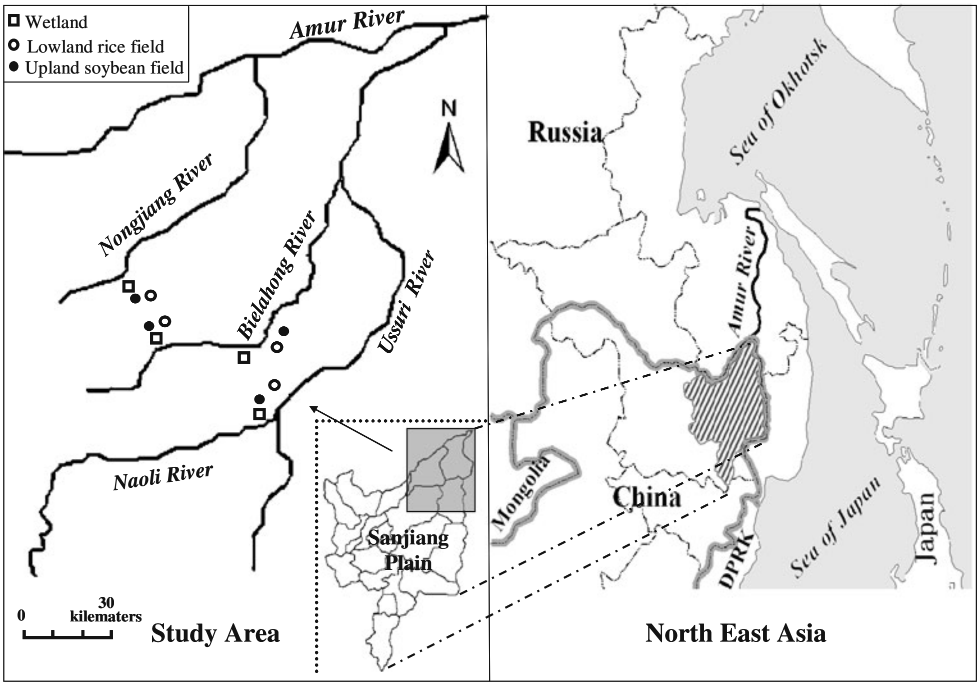


Fig. 2 Sampling sites in the study area

bound Fe and poorly crystallized Fe oxides (Campbell and Schwertmann 1984) accounting for most of the Fe involved in podzolization (Farmer et al. 1983) and partly in gleyization, and Fe_d includes better crystallized forms in addition to Fe_o (Schwertmann and Murad 1990). Fe_d/Fe_t is considered as a useful indicator of soil formation processes and pedogenic environments and of importance in differentiating soil horizon and weathering rate (McKeague and Day 1966; Blume and Schwertmann 1969). Fe_o/Fe_d (often termed the “active ratio”) is used as a measurement of the proportion of amorphous Fe in total Fe oxides and characterizes the Fe oxides crystallinity (Lair et al. 2009; Blume and Schwertmann 1969) and also proposed as a sensitive indicator of soil podzolization and gleyization (Park and Burt 1999). These parameters, together with Fe (II) and water-soluble Fe (Fe_w), the good indicators of Fe mobility, were selected to interpret the effects of land use type on soil Fe in this study.

Fe(II), Fe_w, and soil moisture content were measured with fresh soil. Fe(II) was extracted by 0.5 M HCl which could release any Fe(II) bound to soil particle surfaces. The extract was determined by phenanthroline colorimetry (Analtikjena AG, Germany; Thompson et al. 2006). Fe_w was extracted by deionized water and determined by a flame atomic absorption spectrophotometer (Aanalyst 200, America; Loeppert and Inskeep 1996). The soils from each core were loosely disaggregated, air-dried at room temperature, and passed through 2-mm mesh sieve to determine pH (H_2O) and water soluble Ca^{2+} and through 0.25-mm mesh sieve to determine total Fe (Fe_t), free-Fe oxides (Fe_d), amorphous Fe oxides (Fe_o), and organic C.

The Fe_t content was determined by the flame atomic absorption spectrophotometer (Aanalyst 200, America) after sodium carbonate fusion digestion. Fe_d was extracted by DCB at pH 7.0 and determined by phenanthroline colorimetry (AnaltikjenaAG, Germany; Mehra and Jackson 1960). Fe_o was extracted by acidified ammonium oxalate at pH 4.0 and determined by phenanthroline colorimetry (AnaltikjenaAG, Germany; Schwertmann 1973). Soil moisture content was measured by determining mass loss after heating in 105°C (Hendershot et al. 1993). Soil pH was measured in 1:2.5 soil–water suspension by using Elico Digital EC meter, and organic C was determined by dry combustion using TOC 5000A autoanalyzer (Shimadzu, Japan). Ca^{2+} was extracted by deionized water and determined by AAS.

2.3 Statistic analyses

One-way analysis of variance (ANOVA) was performed to compare the differences of test parameters between different land use types and between different soil layers. The separation of means was made according to Tukey's verified significant difference at $P<0.05$. Pearson correlation analysis was performed to analyze the relationships among test parameters. Both the ANOVA and the Pearson correlation analysis were performed with the software SPSS for Windows, Version 11.0. The figures were drawn with Microsoft Excel 2003 software and Adobe Photoshop 7.1 software.

3 Results

3.1 Vertical distribution of soil organic C and pH

The soil organic C content in wetland and reclaimed lands had a marked decrease from 0–10 to 40–60 cm, and a lesser change downward. In 0–10 cm layer, there was a significant difference in the soil organic C content under different land use ($P<0.05$) with the sequence of wetland > lowland rice field > upland soybean field. Compared with that in wetland, the soil organic C content in 0–10 cm layer in lowland rice field and upland soybean field was decreased by 75.3% ($P<0.05$) and 82.6% ($P<0.05$), respectively (Table 1).

Soil pH increased with depth in reclaimed lands and was higher below 40 cm in reclaimed lands than in wetland (see Table 1).

3.2 Vertical distribution of soil Fe_t

Soil Fe_t content in wetland increased with depth and was 76.2% higher ($P<0.05$) in 90–120 than in 0–10 cm. The Fe_t content in the soil profiles was decreased in the sequence of upland soybean field > lowland rice field > wetland. In 20–40 cm, the Fe_t content increased by 65.3% ($P<0.05$) in lowland rice field and by 71.4% ($P<0.05$) in upland soybean field compared with that in wetland (Fig. 3).

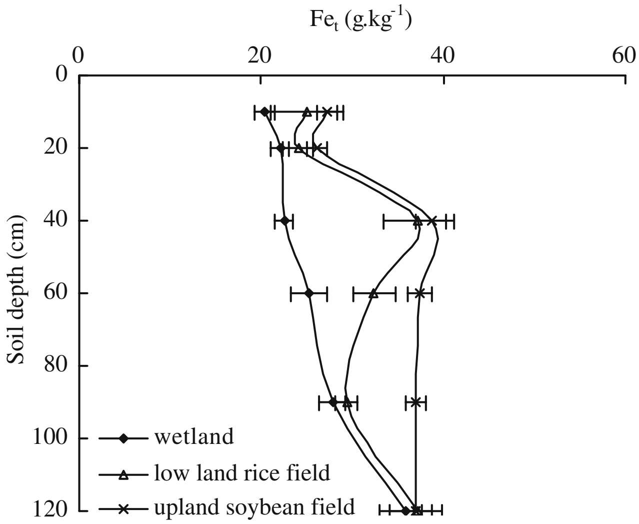


Fig. 3 Vertical distribution of Fe_t. Data shown were the means of 16 replicates and error bars

3.3 Vertical distribution of soil Fe_d and Fe_d/Fe_t

The Fe_d in soil profiles was decreased in the sequence of upland soybean field > lowland rice field > wetland. In wetland, the Fe_d concentration in 90–120 cm soil layer was 306.9% higher ($P<0.05$) than that in 0–10 cm. At the depth of 20–40 cm, Fe_d concentration increased by 311.6% ($P<0.05$) in lowland rice field and 498.1% ($P<0.05$) in upland soybean field compared with that in wetland (Fig. 4).

Table 1 Some soil physical and chemical properties at sample sites

Land use type	Reclamation history	Soil depth (cm)	Organic C (g.kg^{-1})	pH (H_2O)	Moisture content (%)
Wetland	Uncultured	0–10	48.1±2.9	4.9±0.1	34.5±2.7
		10–20	27.3±1.4	5.3±0.1	24.3±1.2
		20–40	12.6±2.0	5.2±0.1	26.3±1.2
		40–60	7.9±0.9	5.1±0.1	21.5±0.8
		60–90	5.5±0.8	5.0±0.1	20.5±1.2
		90–120	4.4±1.0	5.1±0.1	23.4±1.3
Paddy field (rice)	15–17 years	0–10	35.7±3.0	5.2±0.1	31.9±1.3
		10–20	25.6±1.0	5.2±0.1	26.1±1.7
		20–40	5.3±0.6	5.7±0.1	25.4±1.0
		40–60	4.8±0.8	5.8±0.1	25.1±1.9
		60–90	3.5±0.8	6.0±0.1	21.5±1.5
		90–120	2.0±0.9	6.1±0.2	20.4±1.8
Upland field (soybean)	15–17 years	0–10	25.1±0.9	5.5±0.1	21.2±1.0
		10–20	18.4±1.0	5.6±0.1	22.4±0.8
		20–40	6.3±0.8	5.9±0.1	21.4±0.8
		40–60	5.7±0.6	5.9±0.2	22.9±1.1
		60–90	3.6±0.7	6.0±0.1	22.6±1.1
		90–120	2.7±0.7	6.1±0.1	21.4±0.8

Mean ±SE, $n=16$)

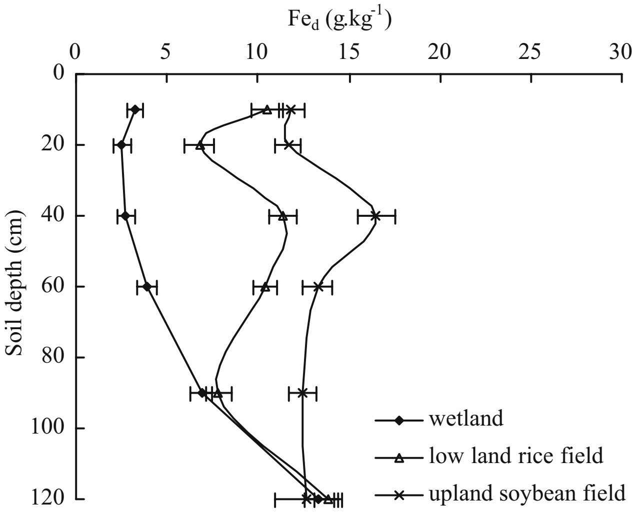


Fig. 4 Vertical distribution of Fe_d. Data shown were the means of 16 replicates and error bars

Soil Fe_d/Fe_t ratio had the similar variation trend with Fe_d. In 20–40 cm layer, it was increased by 150.0% ($P<0.05$) in lowland rice field and by 249.7% ($P<0.05$) in upland soybean field compared with that in wetland (Fig. 5).

3.4 Vertical distribution of soil Fe_o/Fe_d, Fe(II), and Fe_w

Land use change led to a significant decrease of Fe_o/Fe_d along soil profiles ($P<0.05$). In 0–20 cm soil layer, the Fe_o/Fe_d was higher in lowland rice field than in upland soybean field, but no significant differences were found below 40 cm (Fig. 6).

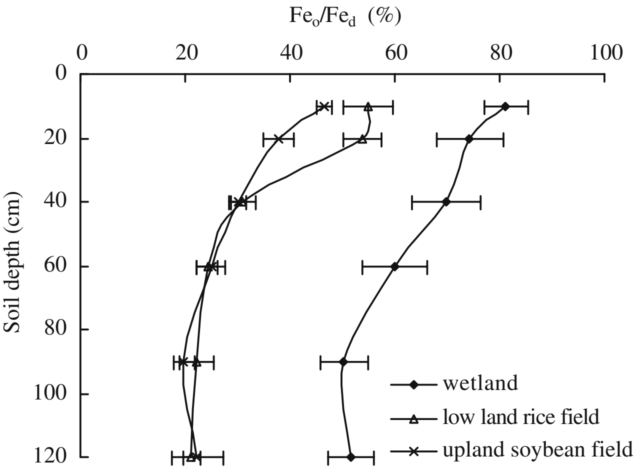


Fig. 6 Vertical distribution of Fe_o/Fe_d. Data shown were the means of 16 replicates and error bars

The Fe(II) content in the soil profiles was decreased in the sequence of wetland > lowland rice field > upland soybean field. Comparing with that in wetland, the Fe(II) content in 0–10 cm soil layer in lowland rice field and upland soybean field was decreased by 39.6% ($P<0.05$) and 94.7% ($P<0.05$), respectively (Fig. 7). The Fe_w had the similar variation trend with Fe(II). At the soil depth of 0–10 cm, Fe_w concentration decreased by 39.0% ($P<0.05$) in lowland rice field and 99.5% ($P<0.05$) in upland soybean field compared with that in wetland (Fig. 8).

The correlations among soil Fe forms and soil physical and chemical properties showed that there was a positive relationship between Fe_o/Fe_d and Fe(II; Fig. 9), and both Fe_o/Fe_d and Fe(II) were positively correlated with soil organic C and moisture content but negatively correlated with soil pH (Fig. 10).

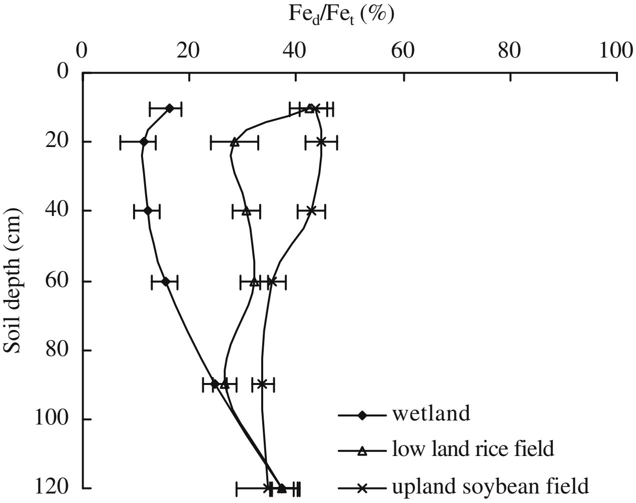


Fig. 5 Vertical distribution of Fe_d/Fe_t. Data shown were the means of 16 replicates and error bars

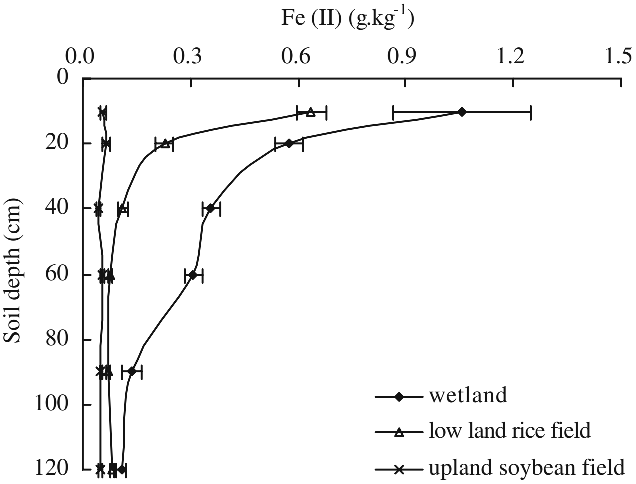


Fig. 7 Vertical distribution of Fe(II). Data shown were the means of 16 replicates and error bars

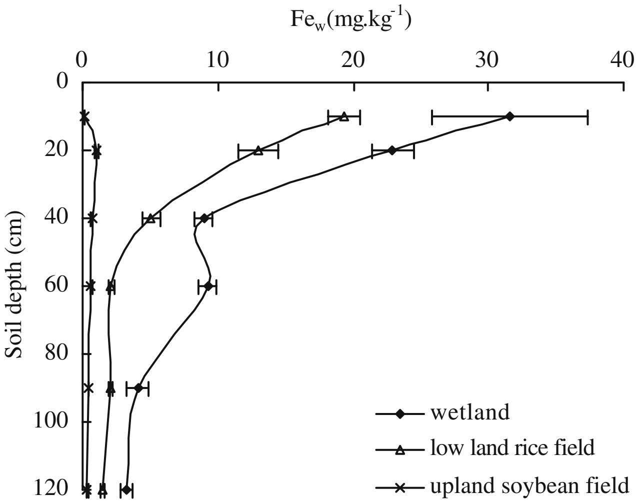


Fig. 8 Vertical distribution of Fe_w. Data shown were the means of 16 replicates and error bars

4 Discussions

4.1 Effects of land use change on the profile distribution of soil organic C and pH

The higher storage of organic C in surface soil layer was closely related to the accumulation of plant materials while the differences in the dynamics of organic C in this soil layer should have close relations with the amount and quality of plant residues as well as the environmental and soil conditions (Dick 1983; Wander et al. 1998; Needelman et al. 1999). The greater amount of soil organic C in wetland than in cultivated land was often accompanied by its concentration gradient from surface to subsurface layers (Dick 1983). Under cultivation, the organic C in upper soil layers reduced due to the oxidation resulted from a relatively well-mixing of soil body during farming practices (Thomas et al. 2007).

The higher soil weathering rate as a result of farming practices promoted the higher concentrations of base cations and higher bicarbonate alkalinity and hence maintained the pH near neutral. Near-neutral pH was an indicator of high soil Ca^{2+} concentration, which was desirable for crop growth, as opposite to low pH values. In all test sites, soil Ca^{2+} concentration was highly correlated with soil pH (r>0.6, P<0.01, data not shown) indicating that Ca^{2+} was a strong competitor with H^+ and Al^{3+} for exchange sites on the soil particle surface (Sartori et al. 2007; Richter and Markewitz 1995; Reich et al. 2005).

4.2 Effects of land use change on profile distribution of Fe_t

The Fe_t concentration in wetland increased with depth and was greatly higher at the depth of 90–120 cm than in surface soil. Such a vertical distribution could be explained by podzolization which often occurred in flooded soil and implied that a significant amount of Fe was leached out from topsoil (Schwertmann and Murad 1990). The vertical distribution pattern of soil Fe_t in test sites corresponded with the results of Fiedler and Sommer (2004), who found the low level of Fe_t in the topsoil where permanent water saturation occurs.

The weathering and activation in surface soil was most likely enhanced by the presence of organic acids that would form complexes with Fe. Fe formed soluble organic complexes with organic acid anions and other organic functional groups, which might contribute significantly to the total soluble Fe in soil solution (Lindsay 1991). Some of the Fe-organic matter complexes in top soils were leached out via lateral and vertical migration resulting in the presence of “albic” horizon, and some were accumulated in the bottom (Giesler et al. 2000).

Under the conversion of wetland to farmland, a redox soil layer at lower positions occurred due to the artificial disturbances, and the horizons with high accumulation of Fe were characterized by highly variable redox conditions. Significant amounts of leached Fe from topsoil, which moved vertically within the soil profile, were deposited in subsurface soil (20–40 cm) where a good aeration occurred preventing the further loss of Fe as a solute.

Due to the scarcity of accurate mineralogical and geochemical data, we were not able to reveal all the processes involved in the mobilization and precipitation of soil Fe at the study sites, but the vertical distribution patterns of soil Fe_t in test sites gave clear evidence of the mobilization and precipitation of soil Fe.

4.3 Effects of land use change on profile distribution of Fe_d and Fe_d/Fe_t

The similar variation trend of soil Fe_d and Fe_t and their significant positive relationship (0.817, P<0.01) suggested

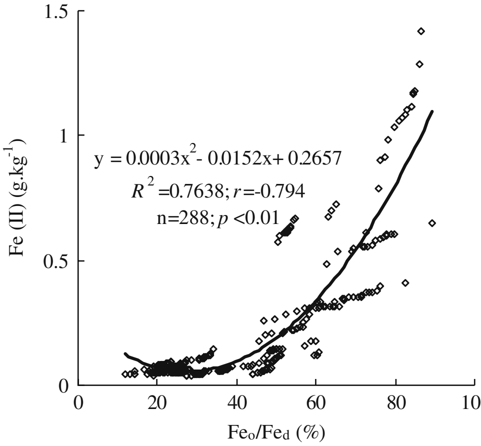
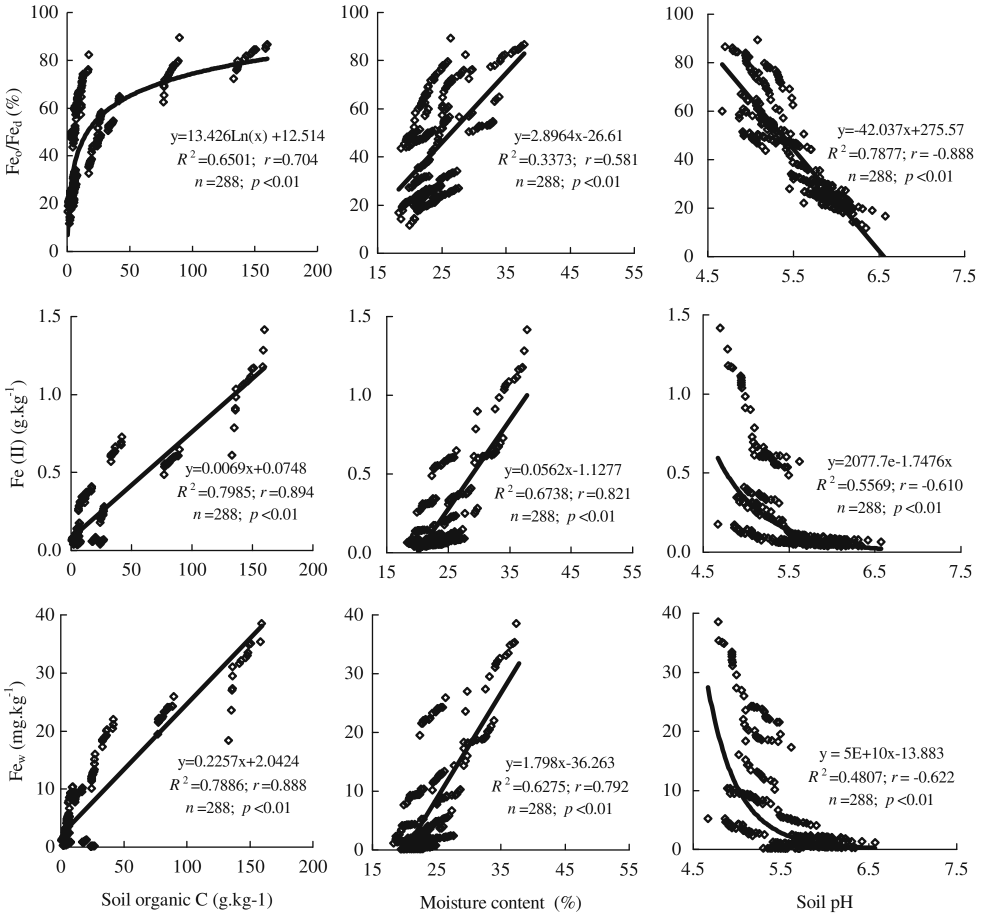


Fig. 9 Relations between the Fe(II) and Fe_o/Fe_d of soil at 12 sample sites

Fig. 10 Relations between the Fe forms and physical and chemical properties of soil at 12 sample sites



that different soil Fe$_t$ content undoubtedly contributed to the observed differences in the mean concentration of soil Fe$_d$ between wetland and reclaimed lands. Similar results were also found in other studies (Blume and Schwertmann 1969).

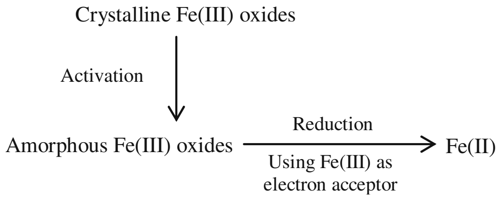
In our study, the higher Fe$_d$/Fe$_t$ ratio in reclaimed lands revealed that reclamation increased the Fe$_d$ concentration via increasing weathering rate (Collins and Jenkins 1996). Weathering was known to be related to soil temperature and moisture content and was likely to be increased by farming practices.

4.4 Effects of land use change on profile distribution of Fe$_o$/Fe$_d$, Fe(II), and Fe$_w$

Comparing with that of soil Fe$_d$ and Fe$_d$/Fe$_t$, the vertical distribution pattern of soil Fe$_o$/Fe$_d$ could reflect more dynamic aspects of the removal processes of Fe oxides associated with podzolization and gleyization (Park and Burt 1999). Fe$_o$ including oxidized Fe(III) and reduced Fe (II) was the most reactive and soluble Fe form in soils (Chen and Barak 1982). Amorphous Fe(III) oxides were relatively immobile while Fe(II) was readily soluble in water and thus, quite mobile.

In this study, the decreased Fe$_o$/Fe$_d$, Fe(II), and Fe$_w$ in the whole soil profile in reclaimed lands than in wetland indicated the decreased Fe mobility after reclamation while the higher values of these three indicators in upper soil layers in lowland rice field than in upland soybean field suggested the stronger effects of upland farming practices than lowland farming practices on the soil Fe mobility.

There was a positive relationship among Fe$_w$, Fe(II), and Fe$_o$/Fe$_d$, which could be explained by the following scheme (Wahid and Kamalam 1993).



Reclamation would change the soil physical and chemical properties such as soil organic C, moisture content, and pH, which might decrease the production of Fe(II) and Fe$_w$ by restraining the activation of crystalline Fe(III) oxides and the reduction of amorphous Fe(III) oxides to Fe(II; see Fig. 10).

Soil organic C might have inhibitory effects on the crystallization of Fe_o and play important roles in the solubility and availability of Fe (Coates et al. 1998; Jansen et al. 2003; Ammari and Mengel 2006; Hyun et al. 2007). One reason was that the strong adsorption of Fe_o by organic anions could disturb and even prevent the rapid crystallization of Fe_o (Schwertmann 1966) and another reason was that most soils had the microsites where organic C was actively metabolized. If oxygen existed, it could be utilized as electron acceptor, and thus, soil organic C and microorganisms were responsible for the reduction and increased solubilization of Fe. It was generally considered that Fe(III) reducers must come into direct contact with Fe(III) oxides to reduce them. The need for this contact could be overcome in subsurface environment with soil organic C because the organic C might solubilize the Fe(III) prior to the reduction or function as a soluble electron-shuttling compound shuttling the electrons from the surface of Fe(III) reducers to Fe(III) oxide surface (Lovley 1997).

Fe_o/Fe_d and Fe(II) were positively correlated with soil moisture content, which was supported by related studies. Wahid and Kamalam (1993) suggested that, in flooded soil, crystalline Fe oxides were rapidly converted into Fe_o. This transformation appeared to be a prerequisite for the microbial reduction of Fe_o. Moreover, most soils contain microsites where organic matter was actively metabolized. When these sites became water-saturated, oxygen entry was restricted, and the sites became partially anaerobic. Parts of Fe oxides dissolved releasing Fe(III) and Fe(II) that combined into multivalence and less stable Fe hydroxides (Lindsay 1991).

Soil Fe_o/Fe_d and Fe(II) increased with decreasing pH in present study. It followed from reaction (1) that the activity of Fe increased with decreasing pH because the positive charges on Fe oxide surface increased with decreasing soil pH.

$$FeOOH + e^- + 3H^+ \rightarrow Fe^{2+} + 2H_2O \qquad (1)$$

Furthermore, chloride or sulfate ions might form a surface complex together with H^+ at the Fe oxide surface, speed up the dissolution process of Fe by further weakening Fe–O bond. However, with the subsequent decrease in pH, the dissolution would ultimately slow down because the ligands were increasingly protonated and discharged resulting in lesser adsorption. Therefore, the maximum dissolution rate of Fe with organic ligands was often found at a certain pH (Schwertmann 1991).

5 Conclusions

The distribution of various Fe forms in soils under different land use type was examined in the Sanjiang Plain of Northeast China where a relatively uniform parent material allowed the direct comparison of the effects of land use type on the vertical distribution of soil Fe.

Our findings showed that in wetland, significant amount of leached Fe from topsoil was moved vertically without any enrichment in subsurface leading to the low levels of Fe_t and Fe_d in upper layers while in farmland, eluviated Fe moved vertically along soil profile and deposited in subsurface layers where a good aeration occurred preventing the further loss of Fe as a solute. Wetland reclamation promoted the production of soil Fe_d and retarded the formation of Fe_o, Fe(II), and Fe_w. The soil Fe mobility decreased in the sequence of wetland > lowland rice field > upland soybean field suggesting the stronger effects of upland farming on the soil Fe mobility than lowland farming.

The results supported the ideas that, in the Sanjiang Plain, the conversion of wetland into farmland, especially into upland, could change the soil Fe vertical distribution giving potential effects on the mobility of soil Fe.

6 Recommendations and perspectives

Further researches would be made to better understand the functions of different land use in discharging soil-dissolved iron and to quantify the flux of dissolved iron from the Sanjiang Plain to the Amur River and the Sea of Okhotsk based on the high-resolution geographical distribution maps of land surfaces in the alluvial plain.

Acknowledgements This work is supported by the multilateral international cooperation project (Amur–Okhotsk Project). The helpful comments from anonymous reviewers are acknowledged. Especially, we thank Dr. Muneoki Yoh for their helpful suggestions on the mensuration.

References

Ammari T, Mengal K (2006) Total soluble Fe in soil solutions of chemically different soils. Geoderma 136:876–885

Blume HP, Schwertmann U (1969) Genetic evaluation of profile distribution of aluminium, Fe, and manganese oxides. Soil Sci Soc Am Proc 33:438–444

Campbell AS, Schwertmann U (1984) Iron oxide mineralogy of placic horizons. J Soil Sci 35:569–582

Capone DG, Zehr JP, Paerl HW, Bergman B, Carpenter EJ (1997) Trichodesmium, a globally significant marine cyanobacterium. Science 276:1221–1229

Chen Y, Barak P (1982) Iron nutrition of plants in calcareous soils. Advanced Agronomy 35:217–240

Chen PQ, Deng W, Yan MH (2002) Climate change in the Sanjiang Plain disturbed by large-scale reclamation. J Geograph Sci 12:405–412

Coates JD, Councell T, Ellis DJ, Lovley DR (1998) Carbohydrate oxidation coupled to Fe(III) reduction, a novel form of anaerobic metabolism. Anaerobe 4:277–282

Collins R, Jenkins A (1996) The impact of agricultural land use on stream chemistry in the Middle Hills of the Himalayas, Nepal. J Hydrol 185:71–86

Cullen JJ (1999) Oceanography: iron, nitrogen and phosphorus in the ocean. Nature 402:372

Dick WA (1983) Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci Soc Am J 47:102–107

Falkowski PG (2002) The ocean's invisible forest. Scientific American 8:38–45

FAO-Unesco (1997) Soil map of the world—revised legend, Technical Paper 20. International Soil Reference and Information Centre, Wageningen

Fiedler S, Sommer M (2004) Water and redox conditions in wetland soils—their influence on pedogenic oxides and morphology. Soil Sci Soc Am J 68:326–335

Giesler R, Ilvesniemi H, Nyberg L, Hees PV, Starr M, Bishop K, Kareinen T, Lundstroöm US (2000) Distribution and mobilization of Al, Fe and Si in three podzolic soil profiles in relation to the humus layer. Geoderma 94:249–263

Guo XL, Lu XG, Tong SZ, Dai GH (2008) Influence of environment and substrate quality on the decomposition of wetland plant root in the Sanjiang Plain, Northeast China. J Environ Sci 20:1445–1452

Hao QJ, Wang QC, Wang YS, Wang CK (2003) The impact of reclamation activities on soil sulfur contents in the Sanjiang Plain. Acta Scientiae Circumstantiae 5:614–618

Hendershot WH, Lalande H, Duquette M (1993) Soil Sampling and methods of analysis. In: Carter MR (ed) Canadian Society of Soil Science. Lewis Publishers, London

Hyun JH, Smith AC, Kostka JE (2007) Relative contributions of sulfate- and iron (III) reduction to organic matter mineralization and process controls in contrasting habitats of the Georgia salt marsh. Appl Geochem 22:2637–2651

Jansen B, Nierop KG, Verstraren JM (2003) Mobility of Fe(II), Fe(III) and Al in acidic forest soils mediated by dissolved organic matter: influence of solution pH and metal/organic carbon ratios. Geoderma 113:323–340

Karl D, Letelier R, Tupas L, Dore J, Christain J, Hebel D (1997) The role of nitrogen fixation in biogeochemical cycling in the subtropical North Pacific Ocean. Nature 388:533–538

Lair GJ, Zehetner F, Hrachowitz M, Franz N, Maringer FJ, Gerzabek MH (2009) Dating of soil layers in a young floodplain using iron oxide crystallinity. Quaternary Geochronology 4:260–266

Lindsay WL (1991) Iron oxide solubilization by organic matter and its effect on iron availability. Plant Soil 130:27–34

Liu XT, Ma XH (2000) Effect of large-scale reclamation on natural environment and regional environmental protection in the Sanjiang Plain. Scienta Geographic Sinica 20:14–19

Loeppert RL, Inskeep WP (1996) Iron. In: Sparks D (ed) Methods of soil analysis, part 3, chemical methods. Soil Science Society of America, Inc., Madison, pp 652–653

Lovley DR (1997) Microbial Fe(III) reduction in subsurface environments. FEMS Microbiol Rev 20(3):305–313

Martin JH (1990) Glacial-interglacial CO_2 change: the iron hypothesis. Paleoceanography 5(1):1–13

Martin JH (1992) Iron as a limiting factor in oceanic productivity. In: Falkowski PG, Woodhead AD (eds) Primary productivity and biogeochemical cycles in the sea. Plenum, New York, pp 123–137

Martin JH, Fitzwater SE (1988) Iron deficiency limits phytoplankton growth in the north-east Pacific Subarctic. Nature 331:341–343

McKeague JA, Day JH (1966) Dithionite and oxalate extractable Fe and A1 as aids in differentiating various classes of soils. Can J Soil Sci 46:13–22

Mehra OP, Jackson ML (1960) Iron oxide removal from soils and clays by a dithionite-citrate buffered with sodium bicarbonates. Clays Clay Miner 7:317–327

Narita H, Shiraiwa T, Nakatsuka T (2004) Human activities in northeastern Asia and their impact to the biological productivity in North Pacific Ocean. In: Narita H, Shiraiwa T (eds) Report on Amur-Okhotsk Project (No.2). Amur-Okhotsk Project, Kyoto, pp 1–24

Needelman BA, Wander MM, Bollero FGA, Boast CW, Sims GK, Bullock DG (1999) Interaction of tillage and soil texture: biologically active soil organic matter in Illinois. Soil Sci Soc Am J 63:1326–1334

Park SJ, Burt TP (1999) Identification of throughflow using the distribution of secondary iron oxides in soils. Geoderma 93:61–84

Reich PB, Oleksyn J, Modrzynski J, Mrozinski P, Hobbie SE, Eissenstat DM, Chorover J, Chadwick OA, Hale CM, Tjoelker MG (2005) Linking litter calcium, earthworms and soil properties: a common garden test with 14 tree species. Ecol Lett 8:811–818

Reicosky DC, Lindstrom MJ (1993) Fall tillage method: effect on short-term carbon dioxide flux from soil. Agron J 85:1237–1243

Richter DD, Markewitz D (1995) How deep is the soil? BioScience 45:600–609

Sartori F, Lal R, Ebinger MH, Eaton JA (2007) Changes in soil carbon and nutrient pools along a chronosequence of poplar plantations in the Columbia Plateau, Oregon, USA. Agri Ecosys Environ 122:325–339

Schwertmann U (1966) Inhibitory effect of soil organic matter on the crystallization of amorphous ferric hydroxide. Nature 5:645–646

Schwertmann U (1973) Use of oxalate for Fe extraction from soils. Can J Soil Sci 53:244–246

Schwertmann U (1991) Solubility and dissolution of iron oxides. Plant Soil 130:1–25

Schwertmann U, Murad E (1990) Forms and translocation of iron in podzolized soils. In: Kimble JM, Yeck RD (eds) Proceedings of the Fifth International Soil Correlation Meeting: Characterization, Classification, and Utilization of Spodosols. USDA Soil Conservation Service, Lincoln, NE, pp 319–342

Shiraiwa T (2005) The Amur Okhotsk project. In: Shiraiwa T (ed) Report on Amur–Okhotsk Project (No.3). Amur–Okhotsk Project, Kyoto, pp 1–2

Thomas GA, Dalal RC, Standley J (2007) No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a luvisol in the semi-arid subtropics. Soil Tillage Res 94:295–304

Thompson A, Chadwick OA, Rancourt DG, Chorover J (2006) Iron-oxide crystallinity increases during soil redox oscillations. Geochim Cosmochim Ac 70:1710–1727

Todorova SG, Siegel DI, Costello AM (2005) Microbial Fe(III) reduction in a minerotrophic wetland - geochemical controls and involvement in organic matter decomposition. Appl Geochem 20:1120–1130

Wahid PA, Kamalam NV (1993) Reductive dissolution of crystalline and amorphous Fe (III) oxides by microorganisms in submerged soil. Biol Fert Soils 15:144–148

Wander MM, Bidart MG, Aref S (1998) Tillage impacts on depth distribution of total and particulate organic matter in three Illinois soils. Soil Sci Soc Am J 62:1704–1711

Xi M, Lu XG, Li Y, Kong FL (2007) Distribution characteristics of dissolved organic carbon in annular wetland soil–water solutions through soil profiles in the Sanjiang Plain, Northeast China. J Environ Sci 19:1074–1078

Yoh M (2004) Possible fundamental sources of dissolved iron in terrestrial environments: their mechanisms, presumed anthropogenic impact, and research needs. In: Narita H, Shiraiwa T (eds) Report on Amur–Okhotsk Project (No.2). Amur-Okhotsk Project, Kyoto, pp 81–86