# Profile distribution of micronutrients in an aquic brown soil as affected by land use

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**ABSTRACT**

To assess the land use effects on soil micronutrients, this study examined the profile variation and storage of DTPA-extractable iron, manganese, copper and zinc at the depth of 0–150 cm of an aquic brown soil under four land use patterns, i.e. paddy, maize, and fallow fields and woodland, over 14 years in an ecological experimental station of northeastern China. Results showed that land use effect, soil depth, and their interactions on micronutrients were significantly different, and they were decreased with soil depth. Micronutrient storages in woodland and fallow field were significantly greater than in paddy field ($P < 0.05$), and significantly or comparatively greater than in maize field. Micronutrients were positively correlated with soil organic carbon, but negatively with soil pH in profiles. Plant cycling and soil pH may contribute a lot in enhancing soil micronutrient levels in woodland and fallow field, while the lower organic matter content and higher soil pH may inhibit the micronutrient availability in paddy field. The study suggested that the profile distribution of soil micronutrients was mainly controlled by biological cycling, anthropogenic disturbance and leaching and strongly affected by land uses.

**Keywords**: aquic brown soil; micronutrient; land use; profile distribution

Iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn) are essential micronutrients for plant growth. Through their involvement in various enzymes and other physiologically active molecules, these micronutrients are important for gene expression, biosynthesis of proteins, nucleic acids, growth substances, chlorophyll and secondary metabolites, metabolism of carbohydrates and lipids, stress tolerance, etc. (Rengel 2003, Gao et al. 2008). Original geologic substrate and subsequent geochemical and pedogenic regimes determine total levels of micronutrients in soils. Total levels are rarely indicative of plant availability, because availability depends on soil pH, organic matter content, adsorptive surfaces, and other physical, chemical, and biological conditions in the rhizosphere. Micronutrient availability to plants can be measured in direct uptake experiments, or estimated with techniques that correlate quantities of micronutrients extracted chemically from soils (White and Zasoski 1999, Kabata-Pendias 2001). Millions of hectares of arable land in the world have low availability of micronutrients, and many of these deficiencies were brought about by the increased demands of more rapidly growing crops for available forms of micronutrients (Rengel 2007, Alloway 2008). Micronutrient cycling is quite different among various terrestrial ecosystems (Rengel 2007), and land use changes may strongly affect their distributions in agro-forestry ecosystems (Eneji et al. 2003, Venkatesh et al. 2003, Jiang et al. 2005a, Han et al. 2007). For example, a case study conducted in the vertisols of the Mississippi River Delta alluvial plain showed that Mn, Fe and Zn in catfish pond soils were greater in labile fractions and lower in potential labile fractions than in paddy

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and forest soils, while paddy and forest soils had higher Fe, Mn and Zn in potential labile fractions (Han et al. 2007). The aquic brown soil, which is classified as Hapli-Udic Cambosols in Chinese Soil Taxonomy (CRGCST, 2001), is a typical soil for agriculture and forestry at the Liao River Plain in northeastern China, and micronutrient deficiencies frequently occurred in crop production (Jiang et al. 2003). Our hypothesis is that the distribution and bioavailability of cationic micronutrients in this soil are mainly controlled by biological cycling, anthropogenic disturbance and leaching and strongly affected by land uses; the objectives of this study were: (i) to assess and compare the changes of profile distribution and storage of soil available Fe, Mn, Cu, and Zn in response to land use changes, and (ii) to explore the relationships among changes of micronutrients with other soil properties under various land uses.

## MATERIAL AND METHODS

**Site description.** The Shenyang Experimental Station of Ecology, Chinese Academy of Sciences is situated at the lower reaches of the Liao River Plain (41°31'N, 123°22'E), the intersection of two transects driven by hydrologic factors from east to west and by thermic factors from north to south, exhibiting a good regional respective significance. It is located in the continental temperate monsoon zone, with dry-cold winter and warm-wet summer. The mean annual temperature is 7.0–8.0°C, annual precipitation is 650–700 mm, and non-frost period is 147–164 days. The cultivated horizon is loamy, with an apparent plow pan, and the substratum is clayey and tight. Before the establishment of the Station in 1989, all the lands were paddy (*Oryza sativa* L.) field (PF), and after 1989, part of the lands was turned into maize (*Zea mays* L.) field (MF), fallow field (FF), and woodland (*Populus canadensis* Moench, WL). Both paddy and maize were monocultures, and the annul input of urea, $(NH_4)_2HPO_4$ and KCl in PF was 450, 150, and 112.5 kg/ha, and in MF 300, 150 and 75 kg/ha, respectively. The dominant weed species in the fallow field were *Cephalanopis segetum* (Bge.) Kitam, *Trigonogis peduncularis* (Trev.) Benth, *Conyza canadensis* L., *Rubia cordifolia* L., and *Cichorium intybus* L. with the mean height of 60–70 cm, coverage of 70–80%, and biomass production of 600–700 g/m$^2$. The tree canopy coverage was about 80% and the litter layer in forest floor was about 3 cm. The vegetation species under the trees were *Bidens parviflora* Wild, *Rubia cordifolia* L., *Conyza canadensis* L., and *Humulus scandens* (Lour.) Merr.

Before the establishment of the Station in 1989, the mean contents of SOM, total N, $Fe_2O_3$ and $MnO_2$ in the arable layer of the paddy soil were 17.5 g/kg, 0.96 g/kg, 112.1 g/kg, and 1.32 g/kg, respectively, soil pH was about 7.4, and CEC was 17.9 cmol/kg.

**Soil sampling and analyses.** Soil samples were collected from four types of land use patterns, i.e., PF, MF, FF and WL, respectively. Each treatment field was divided into 3 equal parts, which represented 3 replicates. Soil samples were taken randomly in ten depths (0–5, 5–10, 10–20, 20–30, 30–40, 40–60, 60–80, 80–100, 100–120, and 120–150 cm) by using a 2.5-cm-diameter auger in November 2003. Soil cores from four sites were mixed to make one sample. As for soil bulk density determination, four samples in each replicate were collected by using stainless steel ring in 0–40 cm depth, and 3 samples under each land use were collected by using a stainless steel ring inserted into a bucket auger in 40–150 cm depth.

Soil bulk density was oven-dried at 105°C. Available Fe, Mn, Cu, and Zn in soil were extracted with 0.005M diethylenetriaminepentaacetic acid (DTPA), 0.1M $CaCl_2$, and 0.1M triethanolamine (TEA) with pH of 7.3, and determined with flame atomic absorption spectrometry (Perkin-Elmer AAnalyst 100, USA). Soil organic carbon (SOC) was measured using SSM-5000A for TOC-5000 analyzer (Shimadzu, Japan), and total nitrogen was determined by semi-microkjeldahl method. Total P was digested by $H_2SO_4$-$HClO_4$ and determined by Molybdenum-blue complex method, and total S was digested by $Mg(NO_3)_2$-$HNO_3$ and determined by $BaSO_4$ turbidimetry (Page et al. 1982). Soil pH was determined by using a glass electrode (1:2.5, soil/water ratio). Soil exchangeable cations were extracted by 1M $NH_4OAc$ and determined with AAS (Page et al. 1982). The chemicals used were manufactured by the Tianjin Kermel Chemical Reagent Co., Ltd., China.

Blank and duplicate samples were conducted of all the samples. Reference materials were use in QA/QC to ensure accuracy and precision. Standard material for soil agro-chemical analyses (brown soil) was purchased from the Chinese CRM/RM Information Center (ID 21420, Product No. GBW07412 ASA-1). Percent recovery of the analyses was between 93 and 110%.

**Statistical analysis and soil micronutrient pool calculation.** The obtained data were analyzed

Table 1. Profile distribution of DTPA-extractable soil micronutrients (mg/kg) under different land uses

| Depth (cm) | Paddy field | Maize field | Fallow field | Woodland |
|---|---|---|---|---|
| DTPA-Fe | | | | |
| 0–5 | 47.54 ± 24.88$^{a}$ | 37.78 ± 10.10$^{a}$ | 41.70 ± 14.01$^{a}$ | 23.93 ± 6.34$^{a}$ |
| 5–10 | 43.49 ± 17.34$^{a}$ | 35.97 ± 11.78$^{a}$ | 38.03 ± 12.56$^{a}$ | 39.33 ± 10.46$^{a}$ |
| 10–20 | 20.98 ± 13.00$^{b}$ | 30.70 ± 10.36$^{ab}$ | 41.65 ± 10.09$^{a}$ | 45.17 ± 3.18$^{a}$ |
| 20–30 | 9.30 ± 3.00$^{b}$ | 16.75 ± 3.26$^{b}$ | 24.42 ± 5.64$^{a}$ | 28.13 ± 1.47$^{a}$ |
| 30–40 | 8.09 ± 2.08$^{b}$ | 10.42 ± 1.08$^{ab}$ | 19.15 ± 7.74$^{a}$ | 19.26 ± 6.44$^{a}$ |
| 40–60 | 8.60 ± 1.31$^{b}$ | 10.02 ± 1.33$^{b}$ | 11.20 ± 4.27$^{b}$ | 18.59 ± 3.83$^{a}$ |
| 60–80 | 9.11 ± 1.40$^{b}$ | 8.09 ± 0.63$^{b}$ | 10.74 ± 0.63$^{b}$ | 20.21 ± 2.42$^{a}$ |
| 80–100 | 8.74 ± 0.94$^{b}$ | 9.01 ± 1.35$^{b}$ | 12.84 ± 2.30$^{b}$ | 20.45 ± 3.36$^{a}$ |
| 100–120 | 8.67 ± 1.25$^{c}$ | 7.28 ± 1.09$^{c}$ | 12.34 ± 2.41$^{b}$ | 16.72 ± 1.39$^{a}$ |
| 120–150 | 8.75 ± 1.86$^{a}$ | 7.91 ± 2.53$^{a}$ | 12.66 ± 3.11$^{a}$ | 13.87 ± 4.83$^{a}$ |
| DTPA-Mn | | | | |
| 0–5 | 35.51 ± 15.38$^{b}$ | 56.33 ± 4.36$^{a}$ | 37.25 ± 8.95$^{b}$ | 29.13 ± 6.91$^{b}$ |
| 5–10 | 29.42 ± 15.85$^{b}$ | 50.36 ± 6.03$^{a}$ | 40.02 ± 8.17$^{ab}$ | 30.58 ± 8.59$^{ab}$ |
| 10–20 | 20.12 ± 6.00$^{b}$ | 45.79 ± 3.11$^{a}$ | 46.46 ± 6.79$^{a}$ | 38.87 ± 4.44$^{a}$ |
| 20–30 | 10.85 ± 5.04$^{c}$ | 25.61 ± 2.27$^{b}$ | 31.82 ± 1.53$^{a}$ | 30.41 ± 1.41$^{ab}$ |
| 30–40 | 7.73 ± 3.15$^{b}$ | 16.09 ± 4.35$^{a}$ | 22.09 ± 6.26$^{a}$ | 23.16 ± 2.08$^{a}$ |
| 40–60 | 6.12 ± 2.63$^{b}$ | 14.05 ± 4.41$^{a}$ | 12.38 ± 2.01$^{ab}$ | 19.56 ± 5.70$^{a}$ |
| 60–80 | 6.01 ± 2.86$^{b}$ | 8.10 ± 1.56$^{b}$ | 9.13 ± 4.93$^{b}$ | 17.34 ± 3.52$^{a}$ |
| 80–100 | 3.99 ± 1.72$^{a}$ | 7.40 ± 1.23$^{a}$ | 7.90 ± 2.31$^{a}$ | 7.84 ± 3.63$^{a}$ |
| 100–120 | 3.39 ± 1.76$^{b}$ | 4.21 ± 0.70$^{b}$ | 8.31 ± 3.35$^{a}$ | 6.00 ± 1.39$^{ab}$ |
| 120–150 | 3.19 ± 0.68$^{b}$ | 3.88 ± 1.18$^{ab}$ | 6.23 ± 2.33$^{a}$ | 5.04 ± 1.32$^{ab}$ |
| DTPA-Cu | | | | |
| 0–5 | 2.40 ± 0.54$^{a}$ | 2.33 ± 0.66$^{a}$ | 3.26 ± 0.74$^{a}$ | 2.34 ± 0.54$^{a}$ |
| 5–10 | 2.40 ± 0.30$^{ab}$ | 2.26 ± 0.74$^{b}$ | 3.33 ± 0.49$^{a}$ | 2.45 ± 0.24$^{ab}$ |
| 10–20 | 2.22 ± 0.86$^{b}$ | 2.04 ± 0.54$^{b}$ | 3.54 ± 0.24$^{a}$ | 2.35 ± 0.32$^{b}$ |
| 20–30 | 1.24 ± 0.47$^{c}$ | 2.04 ± 0.38$^{bc}$ | 3.57 ± 0.60$^{a}$ | 2.59 ± 0.12$^{b}$ |
| 30–40 | 0.81 ± 0.30$^{b}$ | 1.28 ± 0.15$^{ab}$ | 2.32 ± 0.94$^{a}$ | 1.84 ± 0.44$^{ab}$ |
| 40–60 | 0.69 ± 0.07$^{b}$ | 1.17 ± 0.22$^{ab}$ | 0.97 ± 0.42$^{b}$ | 1.59 ± 0.26$^{a}$ |
| 60–80 | 0.67 ± 0.13$^{b}$ | 0.81 ± 0.13$^{b}$ | 0.65 ± 0.11$^{b}$ | 1.65 ± 0.26$^{a}$ |
| 80–100 | 0.56 ± 0.11$^{b}$ | 0.85 ± 0.09$^{b}$ | 0.74 ± 0.20$^{b}$ | 1.44 ± 0.25$^{a}$ |
| 100–120 | 0.50 ± 0.22$^{b}$ | 0.58 ± 0.03$^{b}$ | 0.64 ± 0.10$^{b}$ | 1.12 ± 0.14$^{a}$ |
| 120–150 | 0.50 ± 0.11$^{b}$ | 0.65 ± 0.19$^{ab}$ | 0.74 ± 0.13$^{ab}$ | 0.95 ± 0.23$^{a}$ |
| DTPA-Zn | | | | |
| 0–5 | 0.66 ± 0.15$^{b}$ | 1.06 ± 0.36$^{b}$ | 2.90 ± 0.77$^{a}$ | 4.04 ± 1.13$^{a}$ |
| 5–10 | 0.58 ± 0.20$^{b}$ | 0.95 ± 0.34$^{ab}$ | 1.16 ± 0.33$^{a}$ | 0.78 ± 0.14$^{ab}$ |
| 10–20 | 0.41 ± 0.17$^{a}$ | 0.69 ± 0.18$^{a}$ | 1.20 ± 0.74$^{a}$ | 0.68 ± 0.29$^{a}$ |
| 20–30 | 0.35 ± 0.02$^{b}$ | 0.53 ± 0.02$^{b}$ | 0.87 ± 0.18$^{a}$ | 0.55 ± 0.11$^{b}$ |
| 30–40 | 0.20 ± 0.06$^{b}$ | 0.36 ± 0.11$^{ab}$ | 0.67 ± 0.29$^{a}$ | 0.44 ± 0.14$^{ab}$ |
| 40–60 | 0.17 ± 0.04$^{c}$ | 0.28 ± 0.04$^{b}$ | 0.37 ± 0.08$^{ab}$ | 0.43 ± 0.04$^{a}$ |
| 60–80 | 0.18 ± 0.03$^{b}$ | 0.30 ± 0.13$^{ab}$ | 0.32 ± 0.08$^{ab}$ | 0.39 ± 0.03$^{a}$ |
| 80–100 | 0.20 ± 0.06$^{a}$ | 0.39 ± 0.30$^{a}$ | 0.35 ± 0.06$^{a}$ | 0.40 ± 0.13$^{a}$ |
| 100–120 | 0.20 ± 0.06$^{b}$ | 0.21 ± 0.06$^{b}$ | 0.43 ± 0.09$^{a}$ | 0.35 ± 0.02$^{a}$ |
| 120–150 | 0.23 ± 0.01$^{a}$ | 0.36 ± 0.20$^{a}$ | 0.43 ± 0.04$^{a}$ | 0.44 ± 0.15$^{a}$ |

Data presented are mean values ± standard deviation of three replications, and different letters in the same line indicate significantly different values at $P < 0.05$ with one-way ANOVA and Duncan's pairwise comparison

with SPSS 11.5 statistical software, using one-way ANOVA and Duncan's pairwise comparison for means separation, and using two-way ANOVA to test land use and soil depth effects. A significance level of $P < 0.05$ was chosen for detecting significant differences.

DTPA- extractable soil micronutrient pools were calculated by the formula: (1)

$$MN_s = \sum_{i=1}^{n} (MN_i \times \rho_i \times T_i)/10$$

where: $MN_s$ is DTPA-extractable Fe, Mn, Cu, or Zn pool (kg/ha) at a given depths, $MN_i$ is the concentration of test micronutrient (g/kg) of layer i, $\rho_i$ is soil bulk density (g/cm$^3$) of layer i, $T_i$ is the thickness (cm) of layer i, and $n$ is the number of layers.

## RESULTS

**Profile distributions of DTPA-extractable soil micronutrients.** In soil profile under different land uses, there was a tendency of DTPA-extractable soil micronutrient concentrations to decrease with soil depths (Table 1). Statistical analysis showed that land use effect, soil depth, and the cross-effects of land use and soil depth were significantly different for all the test DTPA-extractable micronutrient concentrations (Table 2), indicating that both land use and soil depth were key factors that affect DTPA-extracting soil micronutrient distributions in profiles.

DTPA-Fe concentrations were significantly greater in woodland (WL) than in paddy field (PF) in 10–120 cm layers, than in maize field (MF) in 20–120 cm layers, and than in fallow field (FF) in 40–120 cm layers, while there was no significant difference between MF and PF. DTPA-Mn concentration was significantly greater in MF than in the other three land uses in 0–5 cm depth, and the concentrations were significantly greater in WL of 10–80 cm, in FF of 10–40 cm and 100–150 cm, and in MF of 5–60 cm than in PF of the corresponding layers, while there was no significant difference between FF and WL in the whole profile (Table 1).

DTPA-Cu concentrations were comparatively greater in FF than in the other three land uses in 0–40 cm depth, and greater in WL than in FF, MF, and PF in 40–150 cm depth, while there was no significant difference between MF and PF in the whole profile. DTPA- Zn concentrations were significantly greater in WL and FF than in MF and PF in 0–5 cm depth, and comparatively greater in FF than in the other three land uses (Table 1).

**DTPA- extractable soil micronutrient pools under different land uses.** The differences of DTPA-extractable soil micronutrient pools under different land uses were shown in Figure 1. In 0–20 cm depth, DTPA-extractable Fe pool was not significantly different among the four land uses. In 0–100 cm depth, it was greater in WL than in MF and PF ($P < 0.01$), and greater in FF than in PF ($P < 0.05$), and in 0–150 cm depth, it was greater in WL and FF than in MF ($P < 0.01$ and 0.05) and PF ($P < 0.01$ and 0.05, respectively).

DTPA-extractable Fe pool in 0–20 cm depth was in the sequence of MF > FF > WL > PF, and it was greater in MF and FF than in WL ($P < 0.01$ and 0.05, respectively) and PF ($P < 0.01$). In 0–100 cm depth, it was significantly greater in WL, FF, and MF than in PF ($P < 0.01$), but no significant difference was observed among WL, FF, and MF. DTPAFe pool among the four land uses was similar in 0–150 cm depth to that in 0–100 cm depth.

DTPA-extractable Cu pool in 0–20 cm depth was greater in FF than in PF ($P < 0.05$), MF ($P < 0.05$), and WL ($P < 0.01$), while there was no significant difference among PF, MF, and WL. In 0–100 cm depth, it was greater in WL and FF than in MF ($P <$

Table 2. Univariate analysis of variance between land use and depth effects for DTPA- extractable soil micronutrients

| Index | Land use | | Soil depth | | Land use × soil depth | |
|---|---|---|---|---|---|---|
| | *F* | *P* | *F* | *P* | *F* | *P* |
| DTPA-Fe | 6.890 | < 0.001 | 29.028 | < 0.001 | 1.766 | 0.027 |
| DTPA-Mn | 23.310 | < 0.001 | 81.026 | < 0.001 | 4.031 | < 0.001 |
| DTPA-Cu | 24.722 | < 0.001 | 51.943 | < 0.001 | 3.367 | < 0.001 |
| DTPA-Zn | 25.513 | < 0.001 | 46.462 | < 0.001 | 8.219 | < 0.001 |

Land use and soil depth effects are tested using two-way ANOVA

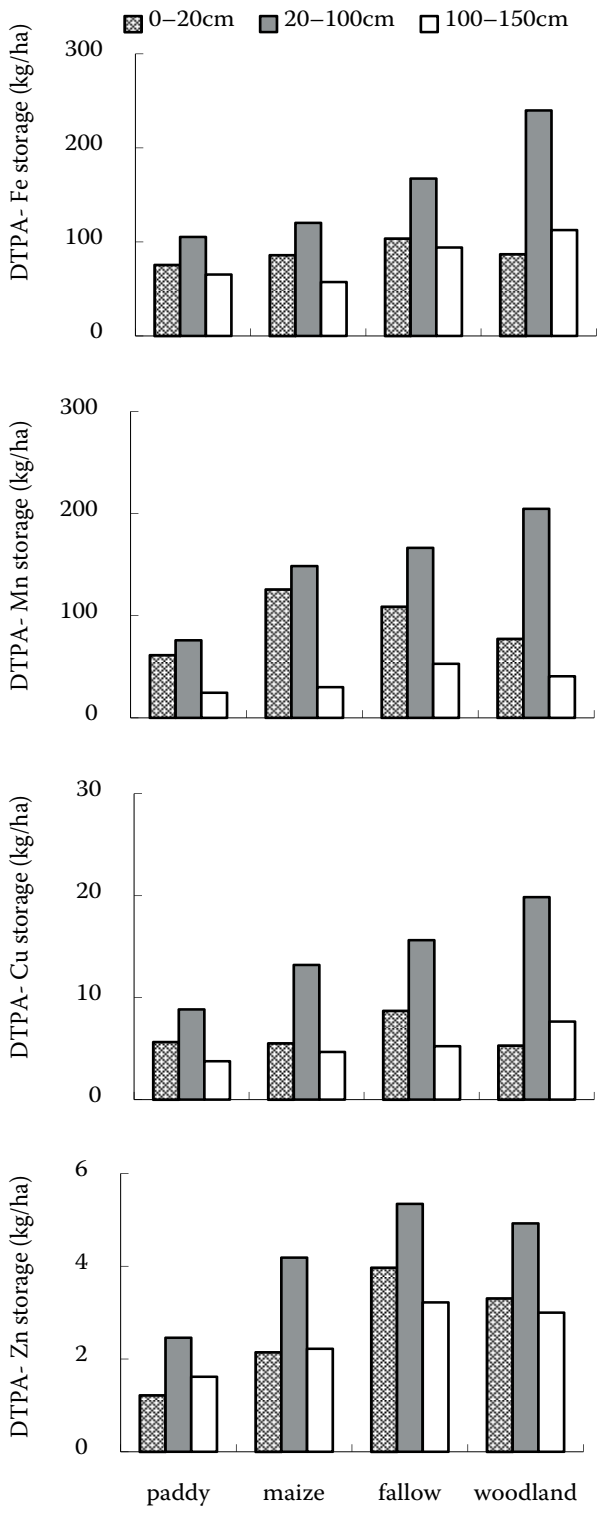


Figure 1. DTPA-extractable soil micronutrient pools under different land uses

0.05) and PF ($P < 0.01$). In 0–150 cm depth, the DTPA-Cu pool was in the sequence of WL > FF > MF > PF, and it was significantly greater in WL and FF than in MF ($P < 0.05$) and PF ($P < 0.01$).

The sequence of DTPA- extractable Zn pool in all the depths of 0–20, 0–100, and 0–150 cm was FF > WL > MF > PF, and it was significantly greater in FF and WL than in PF ($P < 0.01$ and 0.05, respectively) in 0–20 cm depth, and it was greater in FF than in MF and PF ($P < 0.05$ and 0.01, respectively) and greater in WL than in PF ($P < 0.01$) in both 0–100 cm and 0–150 cm depths (Figure 1).

**Relationships of soil micronutrients with other chemical properties.** In the soil profiles of PF, MF and FF, DTPA-extractable micronutrients were significantly and positively correlated with each other ($P < 0.001$), while in that of WL, DTPA-extractable Fe, Mn and Cu were significantly and positively correlated with each other ($P < 0.001$), but Zn was not significantly correlated with Fe and Mn (Table 3).

Under the four land uses, DTPA-extractable micronutrients were positively and significantly correlated with soil organic carbon (SOC), total nitrogen (N) and sulfur (S), except for Fe in WL. Soil total P was negatively and significantly correlated with DTPA-extractable micronutrients in PF and WL except for Zn in WL; however, neither in MF nor in FF this relationship was so (Table 3).

Soil pH was negatively and significantly correlated with DTPA-extractable micronutrients in PF, MF and FF, but this relationship was not observed in WL. The sum of exchangeable cations was negatively correlated with DTPA-extractable micronutrients in MF, FF and WL, except for Zn in WL. However, there was no significant correlation between exchangeable cations and micronutrients in PF (Table 3).

The distribution of DTPA-extractable micronutrients under various land uses in this study was consistently decreased from surface to the subsurface horizons (Table 1). Plant cycling was considered as the leading factor, and anthropogenic disturbance and leaching were the secondary factors that affecting the vertical distributions and topsoil accumulation of nutrients under different land uses (Jobbáge and Jackson 2001, Jiang et al. 2005b, 2006).

In the surface soil horizon, micronutrient distribution was controlled by soil pH, Eh and cation exchange capacity, and so on (Jiang et al. 2006). The natural and human disturbance was greater in the surface horizon than in the deeper layers, and hence the variation of micronutrient concentration in the surface soil horizon, e.g. 0–20 cm layers in the paddy field, was comparatively greater. Moreover, soil sampling might contribute to part of the variations.

In this paper, we hypothesize that plant cycling exerts the dominant control on the vertical distribu-

Table 3. Pearson's correlation coefficients of DTPA- extractable microelements with some soil chemical properties

| | DTPA-Fe | DTPA-Mn | DTPA-Cu | DTPA-Zn |
|---|---|---|---|---|
| Paddy field（$n$ = 30） | | | | |
| DTPA-Mn | 0.921*** | | | |
| DTPA-Cu | 0.776*** | 0.792*** | | |
| DTPA-Zn | 0.758*** | 0.784*** | 0.911*** | |
| Soil organic C | 0.785*** | 0.861*** | 0.879*** | 0.799*** |
| Total N | 0.780*** | 0.870*** | 0.861*** | 0.758*** |
| Total P | 0.744*** | 0.804*** | 0.532** | 0.626*** |
| Total S | 0.873*** | 0.866*** | 0.920*** | 0.842*** |
| Soil pH | –0.798*** | –0.864*** | –0.407* | –0.471** |
| Sum of exchangeable cations | –0.134 | –0.269 | 0.244 | 0.127 |
| Maize field （$n$ = 30） | | | | |
| DTPA-Mn | 0.946*** | | | |
| DTPA-Cu | 0.894*** | 0.893*** | | |
| DTPA-Zn | 0.927*** | 0.849*** | 0.847*** | |
| Soil organic C | 0.767*** | 0.865*** | 0.843*** | 0.713*** |
| Total N | 0.795*** | 0.890*** | 0.833*** | 0.733*** |
| Total P | 0.234 | 0.132 | –0.073 | 0.267 |
| Total S | 0.799*** | 0.875*** | 0.814*** | 0.748*** |
| Soil pH | –0.883*** | –0.953*** | –0.819*** | –0.808*** |
| Sum of exchangeable cations | –0.683*** | –0.769*** | –0.752*** | –0.536** |
| Fallow field （$n$ = 30） | | | | |
| DTPA-Mn | 0.897*** | | | |
| DTPA-Cu | 0.878*** | 0.938*** | | |
| DTPA-Zn | 0.818*** | 0.665*** | 0.671*** | |
| Soil organic C | 0.754*** | 0.728*** | 0.739*** | 0.877*** |
| Total N | 0.751*** | 0.708*** | 0.711*** | 0.879*** |
| Total P | 0.248 | 0.118 | 0.118 | 0.429* |
| Total S | 0.750*** | 0.723*** | 0.744*** | 0.878*** |
| Soil pH | –0.687*** | –0.785*** | –0.861*** | –0.360 |
| Sum of exchangeable cations | –0.402* | –0.464** | –0.528** | –0.230 |
| Woodland （$n$ = 30） | | | | |
| DTPA-Mn | 0.821*** | | | |
| DTPA-Cu | 0.782*** | 0.905*** | | |
| DTPA-Zn | 0.106 | 0.335 | 0.408* | |
| Soil organic C | 0.179 | 0.417* | 0.496* | 0.973*** |
| Total N | 0.205 | 0.448* | 0.524** | 0.976*** |
| Total P | –0.383* | –0.652*** | –0.506** | 0.101 |
| Total S | 0.146 | 0.348* | 0.432* | 0.957*** |
| Soil pH | –0.156 | 0.161 | 0.154 | 0.760*** |
| Sum of exchangeable cations | –0.584*** | –0.646*** | –0.542** | 0.235 |

*$P$ < 0.05; **$P$ < 0.01; *** $P$ < 0.001

tion of DTPA-extractable micronutrients. Generally, biological cycling generally moves nutrients upwards because some proportion of the nutrients absorbed by plants are transported aboveground and then recycled to the soil surface by litterfall and throughfall (Stark 1994). Litterfall and throughfall in WL, weeds growing in FF, and crop residues in MF and PF could return micronutrients to the surface soil that plant took up from the subsurface soil. Hence, plant cycling should therefore produce nutrient distributions that are shallower or decrease with depth (Jobbáge and Jackson 2001).

Root distributions and maximum rooting depth may play an important role in shaping micronutrient profiles (Jobbáge and Jackson 2001). Nutrients taken up by deep roots are transported into the above-ground parts and re-deposited on the soil surface through litterfall, stemflow and throughfall. Theoretically, such a mechanism may be especially significant in soils where deep layers contain substantial micronutrient reserves, and for plants that have deep roots (Rengel 2007). In contrast to trees, which are generally deep-rooted, both rice and maize have relatively shallow rooting depths (Liedgens et al. 2000, Lafitte et al. 2001), and the weeds in the fallow field also have relatively shallow rooting depth (Jiang et al. 2006). Hence, trees in WL might take up more micronutrients from deeper layer and then redistribute them in soil profile. In this study, both Fe and Cu in the deep layers were significantly greater in WL than in the other three land uses, Mn and Zn were greater than in PF (Table 1), indicating the deep root effect in shaping the vertical distribution of soil micronutrients in WL.

Plant cycling differed a lot among the four land uses and thus shaped various micronutrient profiles. It is to be supposed that micronutrients input from atmospheric deposition are the same and irrigation input is negligible under the four land uses. Paddy and maize may take up micronutrients from soil and fertilizer, however, fertilizers used for crop production were mainly urea, diammonium phosphate, and potassium chloride that contain lower amount of micronutrients in the study site, thus soil was regarded as the main source of micronutrient input. Micronutrients in soil profiles might be decreased as they were exported by crop harvests from PF and MF. In contrast, fallow field underwent less human disturbance and the aboveground biomass was naturally returned to the surface soil, while WL could return micronutrients from litterfall and throughfall. The biomass return could accumulate micronutrients in the topsoil horizon and leaching could transport them in different soil layers in profiles (Jobbáge and Jackson 2001, Jiang et al. 2006), thus the concentrations in some layers and the micronutrient pools were comparatively greater in WL and FF than in MF and PF (Table 1 and Figure 1).

Iron, Mn, Cu, and Zn are the most soluble under acid conditions. As soil pH is increased, the ionic forms of these micronutrient cations are changed first to the hydroxyl ions and finally to the insoluble hydroxides or oxides of the elements (Brady and Weil 2002). For every unit increase in pH, solubility of cationic micronutrients may decrease from 100-fold for divalent Mn, Cu and Zn to 1000-fold for trivalent Fe (Rengel 2001). Although the differences in this study were not so much significant, the tendency was similar as described by Rengel (2001). A previous study showed that soil pH in 0–20 cm layer of PF, MF, FF, and WL averaged 7.0, 5.9, 6.5, and 6.4, respectively, and in 30–150 cm depth the values were 7.4–7.5, 6.9–7.0, 6.6–6.9, 6.4–6.6, respectively; in 30–40 cm depth pH was 7.5 for PF and 6.4 for MF, FF, and WL (Zhang et al. 2004a). Soil micronutrients were negatively and significantly correlated with soil pH in profiles of PF, MF and FF, except for WL (Table 3), in which only slight changes of soil pH occurred in deeper layers. Owing to the higher soil pH in profiles of PF, the micronutrients concentrations and pools were much lower in PF than in the other three land uses (Table 1 and Figure 1).

Organic matter, organic residues, and manure applications affect the immediate and potential availability of micronutrient cations (Rengel 2007). The cationic micronutrients react with certain organic molecules to form organometallic complexes as chelates, and the soluble chelates can increase the availability of the micronutrient and protect it from precipitation reactions. These chelates may be synthesized by plant roots and released to the surrounding soil, may be present in the soil humus, or may be synthetic compounds added to the soil to enhance micronutrient availability (Brady and Weil 2002). Previous studies showed that both SOC and total N were significantly greater in WL and FF than in MF and PF, owing to plant cycling and water regimes under various land uses (Zhang et al. 2004b, Jiang et al. 2005c). The higher amount of organic matter may contribute a lot to increasing micronutrient availability in soils of WL and FF. In this study, soil organic matter related to chemical indexes, including SOC, total N and S, were positively and significantly correlated with DTPA-extractable micronutrients under the four land uses (Table 3), indicating the role of soil organic matter in enhancing available micronutrients. However, SOM does not only

mobilize micro- elements but immobilizes them as well. For an example, EDTA-extractable Cu was significantly greater at higher SOM content than at lower organic content. This was attributed to the formation of highly stable copper-humate complexes and to their increasing dissolution that occurred in the soils with higher organic matter level (Di Palma et al. 2007).

As a whole, the interactions between abiotic and biotic processes that shaped the micronutrient profiles after land use change.

The profile distribution and storage of soil available Fe, Mn, Cu, and Zn differed among the four land uses examined within an ecological research station in Liaoning province of China. In soil profile under different land uses, there was a tendency of DTPA-extractable soil micronutrient concentrations to decrease with soil depths. Statistical analysis showed that land use effect, soil depth, and the cross-effects of land use and soil depth were significantly different for all the tested DTPA-extractable micronutrient concentrations, indicating that both land use and soil depth were key factors affecting DTPA-extracting soil micronutrient distributions in profiles. The storages of available micronutrients were comparatively greater in natural ecosystems (woodland and fallow field) than in farmland ecosystems (maize and paddy field). Micronutrients were positively correlated with soil organic carbon, but negatively with soil pH in profiles. The variation can be explained by the interactions between abiotic and biotic processes after land use change. Plant cycling, the turnover of organic matter and the suitable soil pH may strongly contribute to enhancing soil available micronutrient levels in woodland and fallow field, while the lower organic matter content and higher soil pH may inhibit the micronutrient availability in paddy field.

## REFERENCES


Alloway B.J. (2008): Micronutrient Deficiencies in Global Crop Production. Springer, Netherlands.

Brady A.C., Weil R.R. (2002): The Nature and Properties of Soils. 13th Edition. Prentice Hall, New Jersey.

CRGCST (Cooperative Research Group on Chinese Soil Taxonomy) (2001): Chinese Soil Taxonomy. Science Press, Beijing and New York, 166–167.

Di Palma L., Ferrantelli P., Merli C., Petrucci E., Pitzolu I. (2007): Influence of soil organic matter on copper extraction from contaminated soil. Soil and Sediment Contamination, *16*: 323–335.

Eneji A.E., Agboola A., Aiyelari E.A., Honna T., Yamamoto S., Irshad M., Endo T. (2003): Soil physical and micronutrient changes following clearing of a tropical rainforest. Journal of Forest Research, *8*: 215–219.

Gao S., Yan R., Cao M., Yang W., Wang S., Chen F. (2008): Effects of copper on growth, antioxidant enzymes and phenylalanine ammonia-lyase activities in *Jatropha curcas* L. seedling. Plant, Soil and Environment, *54*: 117–122.

Han F.X., Kingery W.L., Hargreavesc J.E., Walkerd T.W. (2007): Effects of land uses on solid-phase distribution of micronutrients in selected vertisols of the Mississippi River Delta. Geoderma, *142*: 96–103.

Jiang Y., Hao W., Zhang Y.G., Liang W.J. (2006): Changes in soil nutrients with profile depth in aquic brown soil under different land uses. Journal of Soil and Water Conservation, *20*: 93–96.

Jiang Y., Liang W.J., Wen D.Z. (2003): Middle- and Micro-elements in Cultivated Soils of Shenyang Suburbs. Chinese Agricultural Science and Technology Press, Beijing. (In Chinese)

Jiang Y., Liang W.J., Wen D.Z., Zhang Y.G., Chen W.B. (2005a): Spatial heterogeneity of DTPA-extractable zinc in cultivated soils induced by city pollution and land use. Science in China Series C, *48*: 82–91.

Jiang Y., Zhang Y.G., Liang W.J., Li Q. (2005b): Pedogenic and anthropogenic influence on calcium and magnesium behaviors in Stagnic Anthrosols. Pedosphere, *15*: 341–346.

Jiang Y., Zhang Y.G., Liang W.J., Wen D.Z. (2005c): Profile distribution and storage of soil organic carbon in an aquic brown soil as affected by land use. Agricultural Sciences in China, *4*: 199–206.

Jobbáge E.G., Jackson R.B. (2001): The distribution of soil nutrients with depth: global patterns and the imprint of plants. Biogeochemistry, *53*: 51–77.

Kabata-Pendias A. (2001): Trace Elements in Soils and Plants. 3rd Edition. CRC Press, Boca Raton, Florida.

Lafitte H.R., Champouxa M.C., McLaren G., O'Toole J.C. (2001): Rice root morphological traits are related to isozyme group and adaptation. Field Crops Research, *71*: 57–70.

Liedgens M., Soldati A., Stamp P., Richner W. (2000): Root development of maize (*Zea mays* L.) as observed with minirhizotrons in lysimeters. Crop Science, *40*: 1665–1672.

Page A.L., Miller R.H., Keeney D.R. (1982): Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties. 2nd Edition. ASA and SSSA, Madison, Wisconsin.

Rengel Z. (2001): Genotypic differences in micronutrient use efficiency in crops. Communications in Soil Science and Plant Analysis, *32*: 1163–1186.

Rengel Z. (2003): Heavy metals as essential nutrients. In: Prasad M.N.V., Hagemeyer J. (eds): Heavy Metal

Stress in Plants: Molecules to Ecosystems. Springer-Verlag, Berlin, Heidelberg, 271–294.

Rengel Z. (2007): Cycling of micronutrients in terrestrial ecosystems. In: Marschner P., Rengel Z. (ed): Nutrient Cycling in Terrestrial Ecosystems. Springer-Verlag, Berlin, Heidelberg, 93–121.

Stark J.M. (1994): Causes of soil nutrient heterogeneity at different scales. In: Caldwell M.M., Pearcy R.W. (eds): Exploitation of Environmental Heterogeneity by Plants. Academic Press, San Diego.

Venkatesh M.S., Majumdar B., Kailash K., Patiram (2003): Status of micronutrient cations under various land use systems of Meghalaya. Journal of the Indian Society of Soil Science, *51*: 60–64.

White J.G., Zasoski R.J. (1999): Mapping soil micronutrients. Field Crops Research, *60*: 11–26.

Zhang Y.G., Jiang Y., Liang W.J., Meng F.X. (2004a): Vertical variation of soil pH and Olsen-P in an aquic brown soil as affected by land use. Journal of Soil and Water Conservation, *18*: 89–92.

Zhang Y.G., Jiang Y., Liang W.J., Wen D.Z., Zhang Y.L. (2004b): Vertical variation and storage of nitrogen in an aquic brown soil under different land uses. Journal of Forestry Research, *15*: 192–196.

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