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RESEARCH ARTICLE

The effects of pollution by multiple metals derived from long-term smelting activities on soil mite communities in arable soils under different land use types in East China

Manping Liu[1] · Zhu Li[2] · Simin Li[2] · Fang Liang[2] · Chengwang Huang[3] · Hui Pan[3] · Jie Wu[3] · Siyao Liu[2] · Limin Pu[2] · Peter Christie[2] · Jing Song[2] · Paul Henning Krogh[4] · Xin Ke[3] · Yongming Luo[2] · Longhua Wu[2]

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Abstract

Soil pollution represents a threat to soil biodiversity and to soil and human health. However, many ecotoxicological issues, such as the impact of heavy metal pollution on the soil mite community and its spatial distribution in areas with complex environmental factors, are not fully understood. Here, an investigation was conducted in an arable area (about 11 km^2) enclosed by surrounding mountains. The study area was contaminated with potentially toxic metals derived from copper smelting that was functioning for over 10 years. The area comprised four land use types: woodlands, dry fields, paddy fields, and wastelands, and was divided into 141 study sites each with an area of 6.25 ha. The soil metal (Cu, Zn, Pb, and Cd) contents, pH, and organic matter were determined and their distributions were established. Furthermore, soil mite (Acari) community properties (species richness, individual abundance, and Shannon–Wiener diversity index) were determined, and the distributions of total species number and abundance were ascertained. Soil metal pollution strongly reduced soil mite community, but the effects depended on mite groups or species and their sensitivity to different metals as well as land use types. CANOCO analysis revealed that the order Oribatida was more highly correlated with soil metal contents, whereas the other three orders responded to soil metal contents depending on land use types, mite properties, or metals. SADIE method indicated that the coordinate relationship between mite species number and metal concentration was more negative (4–25% of the study sites) than positive (4–12%). The metal pollution levels in the soil were evaluated by single and integrated pollution and ecological risk indices.

Keywords Anthropogenic activity · Community structure property · Cu/Zn/Pb/Cd contamination · Local distribution · Pollution index and assessment · Soil mesofauna · Soil property

Introduction

Excessive input of heavy metal pollutants into arable soils may lead to deterioration of soil organisms and their functions, change the soil physico-chemical properties, and cause other environmental problems. Therefore, there is an increasing concern about soil metal pollution owing to their potential risk and detrimental effects on the soil ecosystem (Papa et al. 2010; Islam et al. 2015a). A full understanding of metal behavior requires information on the metals present, the abiotic and biotic factors involved, and any interactions among these factors (Debecker and Stoks 2019; Rusek and Marshall 2000; van Straalen et al. 2001). To achieve this, a relatively isolated arable area with different types of land uses surrounded by mountains was chosen as a study area in East China. In the study area, preliminary smelting to

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Manping Liu and Zhu Li contributed equally to the study .

✉ Longhua Wu
lhwu@issas.ac.cn

[1] Shanghai Natural History Museum, the branch of the Shanghai Science & Technology Museum, Shanghai 200127, China

[2] CAS Key Laboratory of Soil Environment and Pollution Remediation, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China

[3] Center for Excellence in Molecular Plant Sciences, Chinese Academy of Sciences, Shanghai 200032, China

[4] Department of Ecoscience, Technical Sciences, Aarhus University, Aarhus, Denmark

extract crude metals from ores was conducted over a 10-year period. These activities result in environmental pollution and the contamination of food products for human consumption. Therefore, the area was considered suitable for ecological studies and soil metal pollution measurements due to its comparatively independent environment without external influences. Soils in arable areas may be contaminated with metals from the discharge of contaminated wastewaters or by atmospheric deposition from smelters and the use of agrochemicals (Rusek and Marshall 2000; Seniczak et al. 2002; Naccarato et al. 2020).

The effects of heavy metals pollution on soil are generally complex due to the interaction of these metals with other environmental factors. Soil properties and land use types are correlated with heavy metals in soil, and changes in these factors can influence the effects of heavy metals pollution on soil organisms (Huston 2012; Rivera et al. 2015; Mazurek et al. 2017). The spatial distribution of heavy metals in soils strictly depends on soil characteristics, such as micro-relief and vegetation, and the effects of these characteristics on the distribution and amount of heavy metals are subjected to their geoavailability and pedochemical enrichment (Hernandez et al. 2003; Huston 2012; Pająk et al. 2015; Rivera et al. 2015; Mazurek et al. 2017). Deposition of metals from the atmosphere can alter the soil pH, whereas plant cover type or soil ecosystem can change the soil organic matter (SOM) content, and their values can differ among land use types and are changed by metal pollution (Navarrete and Tsutsuki 2008; Zhou et al. 2016; Mazurek et al. 2017; Wang et al. 2017). Because multiple environmental factors and complex processes control the effects of heavy metal pollution on soil ecosystems, the study considered the main different types of land use, distributions of metals, soil properties, and soil mite species. The local spatial associations between metal concentrations and mite species were analyzed in the study.

Pollution and ecological risk indices are important tools for practical, economical, and scientific evaluation of pollution levels (Håkanson 1980; Mazurek et al. 2017). They can identify the pollution status as well as the distribution and source of metal pollutants in different ecosystems (Carr et al. 2008; Afshin et al. 2009; Acosta et al. 2011; Islam et al. 2015a). Pollution indices are useful for the evaluation of areas with different types of pollution, and can recognize the various toxic effects of pollutants from diverse sources and in different ecosystems, as well as determine the degree of pollution (Håkanson 1980; Sayadi and Sayyed 2011; Ribeiro et al. 2013; Islam et al. 2015a; Mazurek et al. 2017). The extent of soil metal pollution is assessed by comparing background concentrations and/or elemental reference values that are used to distinguish exogenous metals from naturally occurring crustal metals (Islam et al. 2015b; Wu et al. 2015). Manganese, Fe, and Al are generally used as reference elements because they are common in the earth's crust and are seldom derived from non-anthropogenic activities (Chen et al. 2015; Islam et al. 2015a, b; Wu et al. 2015; Kowalska et al. 2016; Mazurek et al. 2017). The background and reference values of elements can be determined simultaneously with the metals of current interest or referenced from data provided by previous investigations (Chen et al. 2015; Xiao et al. 2015). The ecological effects of various types of contaminants must be evaluated by ecologically valid indices for environmental pollution control (Håkanson 1980). Håkanson (1980) indicated that the contents of all metals were correlated with the biomass production levels in different systems. The negative effects of metals tended to increase with decreasing bioproduction, which can be defined as the toxic response factor (Tr^i value), accounting for both the toxic factor (St^i value) and sensitivity (BPI value) of the given metals (Håkanson 1980; Islam et al. 2015a; Mazurek et al. 2017). Although various pollution and ecological risk indices have been used in combination with methods for determining actual metal concentrations, the usefulness of the indices can vary under different conditions.

Soil fauna distributions should be included in investigations of the potential impacts or risks of polluting metals in soil ecosystems (Rusek and Marshall 2000; Pyatt et al. 2002; Holmstrup et al. 2007; Silva and Brandaeo 2010; Howison et al. 2017). Soil fauna comprise a major part of the soil biota and have high species diversity and individual abundances. Soil fauna also have important functions in soil ecosystems and their diversity should be protected (Engelmann 1961; Beare et al. 1992; Wardle et al. 1999, 2001; Hättenschwiler and Gasser 2005; Mikola et al. 2009; Menezes-Oliveira et al. 2013; Howison et al. 2017; Jung et al. 2021). Most soil fauna live their entire lives within a few square meters of soil, making them good representatives of local conditions or soil ecosystems (Wardle et al. 1999, 2001; Pernin et al. 2006; Feketeova et al. 2016; Debecker and Stoks 2019). Soil mites are dominant microarthropods in terms of both species richness and individual abundance. They have important functions in soil ecosystems and can be representative of soil fauna. They can also reflect pollution impacts or risks (Aoki 1983; Austruy et al. 2016; Feketeova et al. 2016). Soil mites may show markedly reduced abundance in habitats subject to negative anthropogenic impacts (Ivan and Vasiliu 2009; Andrievskii and Syso 2012; Feketeova et al. 2016). High concentrations of potentially toxic metals may influence the biological cycles of soil mites (Andrievskii and Syso 2012; Austruy et al. 2016; Manu et al. 2019), and soil mites may accumulate metals from their habitat (van Straalen et al. 2001; Zaitsev and van Straalen 2001; Skubala and Kafel 2004). Soil mites (Acari) are morphologically and biologically dissimilar animals with high species diversity and abundance (Feketeova et al. 2016). They generally have the highest numbers of species and individuals among soil microarthropods in soil ecosystems (Ke et al. 1999, 2004a; Caruso and Migliorini 2006). Therefore, it is useful to study their community structure and species diversity. In particular, species richness, individual abundance, and the Shannon–Wiener diversity index can directly and intuitively reflect changes in soil mite communities and soil ecosystems caused by metal pollution (van Straalen et al. 2001). There are four orders of Acari: Prostigmata, Mesostigmata, Astigmata, and Oribatida. They contain diverse species that differ in sensitivity or tolerance to metal pollutants (Aoki 1983; Ruf 1998; Ruf and Beck 2005; Khalil et al. 2009; Liu et al. 2013). However, most of the sensitive species may not survive in some very highly polluted areas where only the very highly tolerant species will survive (Salminen et al. 2001). Oribatida is the largest of the four orders of Acari. Oribatid mite species are mainly saprophytic and differ widely in their sensitivity or tolerance to pollutants. Mesostigmata is the second largest order and mainly comprises of predatory and parasitic species that are generally more pollution-sensitive. The order Prostigmata contains diverse species of fungivorous, algophagous, phytophagous, predatory, parasitic, and saprophagous mites with a range of sensitivities to pollutants. Astigmata is the smallest order and contains saprophytic, fungivorous, herbivorous, and parasitic species, but the soil species are mainly saprophytic. The Astigmata can form hypopodes (second nymphal stage) in severe environments that can strongly resist adverse environmental conditions (Aoki 1983; Salminen and Sulkava 1997; Ruf 1998; Salminen and Haimi 1998; Koehler 1999; Maraun and Scheu 2000; Ruf and Beck 2005; Gergocs and Hufnagel. 2009, 2017; Liu et al. 2013; Manu et al. 2019). All four orders of mites were included in the present study because the area was polluted with variable concentrations of metals, including very high concentrations in wastelands. The area comprised a large area of paddy rice fields, which is a water system and is therefore unfavorable for mites. The mite species richness and individual abundance may therefore be low in this area.

This study aimed to better understand the effects of metal pollution on soil mites from an ecological viewpoint through an integrative study. The study was performed in a relatively isolated area of arable soils that were subject to different land uses and were contaminated with multiple metals derived from long-term smelting activities in east China. A relatively isolated area was chosen so that the study could be performed in an independent environment without the external influences of both abiotic and biotic factors. The study was conducted by integrating mite community properties (species richness, individual abundance, and Shannon–Wiener diversity index) for all four orders of mites, the concentration and distribution of all metals, and soil properties. The study was also conducted by coordinating local distribution associations between mite species richness and metal concentrations, and undertaking correlation analyses between the mite community properties and metal concentrations when other environmental factors, such as different land use types and selected soil properties, are involved. Because pollution was caused by multiple metals, whose concentrations could be very high and spatially varied within the study area and among land use types, a series of single and integrated pollution indices and ecological risk indices were used to evaluate the degree of pollution in the area.

Materials and methods

Study area

The study area was 10.9 km^2 (0.25 × 0.25 km × 175 sites) and was surrounded by mountains (Fig. 1). It was located in Zhejiang Province, east China (29° 55′ 1″–29° 58′ 13″ N, 119° 53′ 56″–119° 56′ 4″ E) and has a subtropical climate. The average annual rainfall is 1441.9 mm, the average annual temperature is 16.1 °C, the average altitude is 664 m, and the prevailing winds in winter and summer are north-westerly and south-easterly, respectively (Yao et al. 2006). The study area is polluted with metals derived from Cu smelting that was conducted for over 10 years from 1989 to 2000, and > 10 groups of smaller smelters and one group of large smelters were largely distributed along the mid-line from north to south. The metals were discharged into the atmosphere in the form of fly ash and then deposited on soils. The main soil types are Typic Agriudic Ferrosols, hydroponic soils, and clayey moist iron-rich soils (Yao et al. 2006; Deng et al. 2016). The area consists of arable fields that are used to grow paddy rice and upland wheat and rape; mountain fields with pine and broadleaf trees and shrubs, and wastelands where the metal pollution is high enough to prevent plant growth. Mountain fields (woodlands), upland crops ("dry" fields), paddy rice (paddy fields), and wastelands were the four different land use types. There are also inhabited villages in and around the area. The plant species in the mountain fields are *Mallotus apeltus*, *Pueraria lobata*, *Wisteria sinensis*, *Boehmeria nivea*, *Paederia scandes*, *Rubus lambertianus*, *Rosa laevigata*, *Sedum alfredii*, *Sedum onychopetalum*, *Pteridium aquilinum*, *Commelina communi*, *Macleaya cordata*, *Onychium japonicums*, and *Rhus chinensis*. The plant species in the dry fields are *Triticum aestivum* and *Brassica napus*. The plant species in paddy fields is *Oryza sativa*. The plant species in the wastelands are *Imperata cylindrical*, *Artemisia lavandulaefolia*, *Ixeris polycephala*, *Capsella bursapastoris*, *Erigeron annuus*, *Polygonum perfoliatum*, and *Inula japonica* (Bi et al. 2006). The sampling was conducted in spring when the temperature was still low. Probably due to the high pollution, the vegetation coverage in the area was generally low. The vegetation in the woodlands was sparse, the tree coverage rate was less than 30%, and few grasses

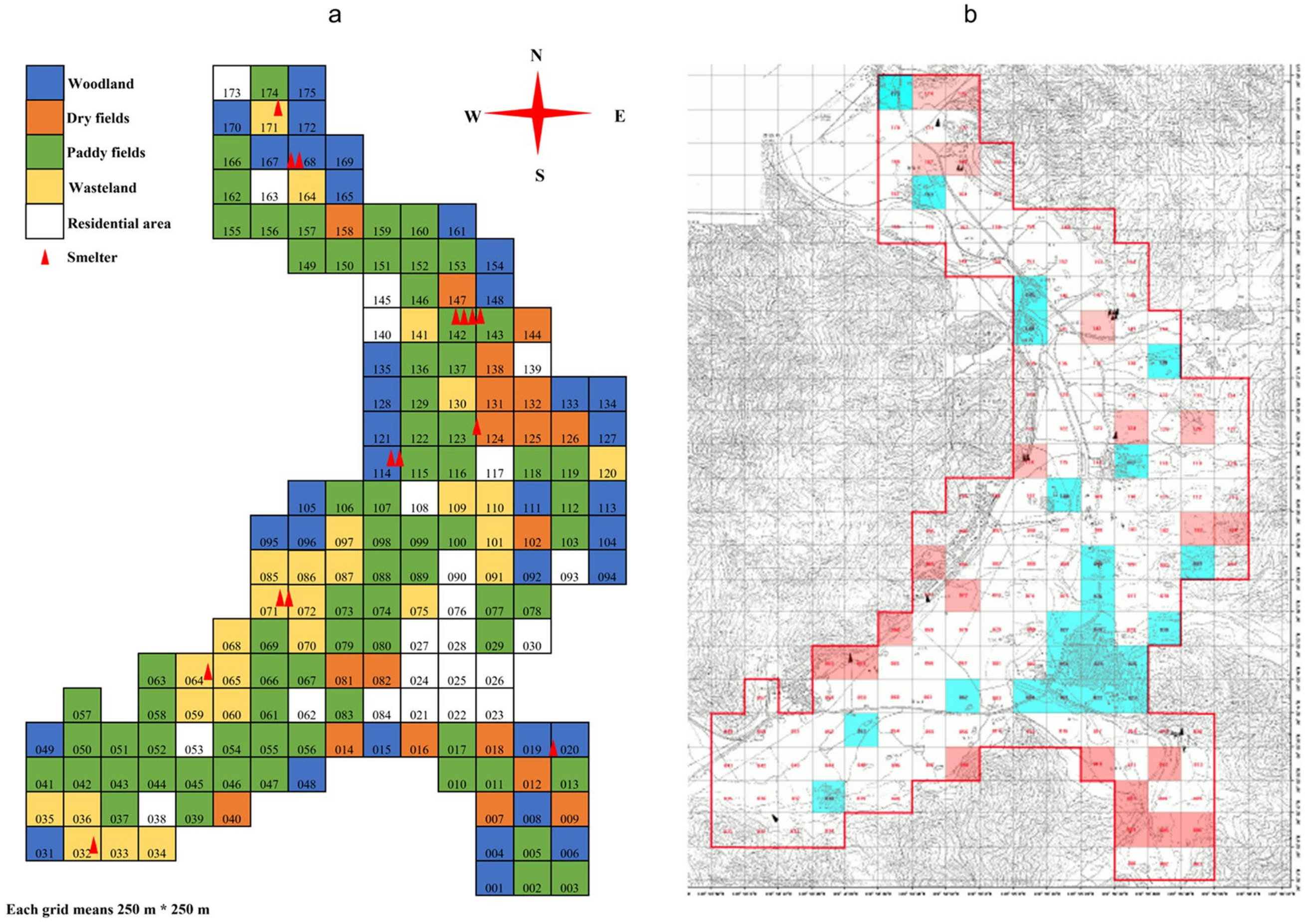


Fig. 1 Plot (**a**) and satellite view of the geographical region (**b**) showing the distribution of the study sites (grids with serial number) across the four land use types (woodlands, dry fields, paddy fields, and wastelands) and the smelter groups in the study area

were growing on the soil surface. In the dry fields, wheat and rape were also sparse and in the seedling stage, with a coverage of less than 50%. In the paddy fields, rice seedlings had not been transplanted and the fields were in the water-free period. In the wastelands, dwarf weeds were the main vegetation type, with a coverage of about 60%.

Sampling

The total area was divided into 175 study sites (each 0.25 × 0.25 km) using a global positioning system, but some sites were in residential parts of villages, which meant that the final number of sites sampled was 141, consisting of 34 in woodlands, 16 in dry fields, 65 in paddy fields, and 26 in wastelands. At each study site, a central 20 × 20 m area was defined for sampling. A total of three soil samples (each 0.5 kg, 0–15 cm depth) were taken from each site and thoroughly mixed to give one composite sample for determination of soil metals and physicochemical properties. A total of 141 composite samples were obtained and analysed for metals and soil properties. Six adjacent soil cores (each 20 cm^2, 0–10 cm depth) were taken for the analysis of soil mites, which represented six replicates from the central area. A total of 846 (141 sites × 6 soil cores) soil samples were obtained for the analysis of mites. The samples were immediately put into a 4 °C refrigerator on a truck so that they could be safely stored during the sampling time outside in the fields. The soil mites were extracted in the laboratory and the extracted mite specimens in the six cores from the same site were mixed to create one composite mite sample. A total of 141 mite composite samples were analysed for mite communities.

Soil chemical analysis

One portion of each air-dried soil sample was ground and passed through a 2-mm sieve for determination of soil pH and organic matter content. The remainder was ground to 0.15 mm and used to determine the Cu, Zn, Pb, and Cd concentrations. Soil pH was measured with a pH meter (Model FE20, Mettler-Toledo, Columbus, OH, USA) at a soil:water ratio of 1:2.5 (w/v). Soil organic matter content (SOM) was determined by the oxidation with potassium dichromate and external heating method (Pansu and Gautheyrou 2006; Liu et al. 2013). Soil subsamples (0.20 g) were digested with 10 mL mixed HNO_3 (65%; ultrapure), HCl (70%; ultrapure), and $HClO_4$ (70%; ultrapure) to determine the total Cu, Zn, Pb, and Cd concentrations (Liu et al. 2018). The digests were analyzed with a flame atomic absorption spectrophotometer (Varian Spectra AA 220, Varian, Palo Alto, CA, USA). Certified reference materials (GBW07401 and GBW07402, national geochemical standard materials, Institute of Geophysical and Geochemical Exploration, Langfang, Hebei Province, China) were used for quality control (Deng et al. 2016).

Analysis of soil animals

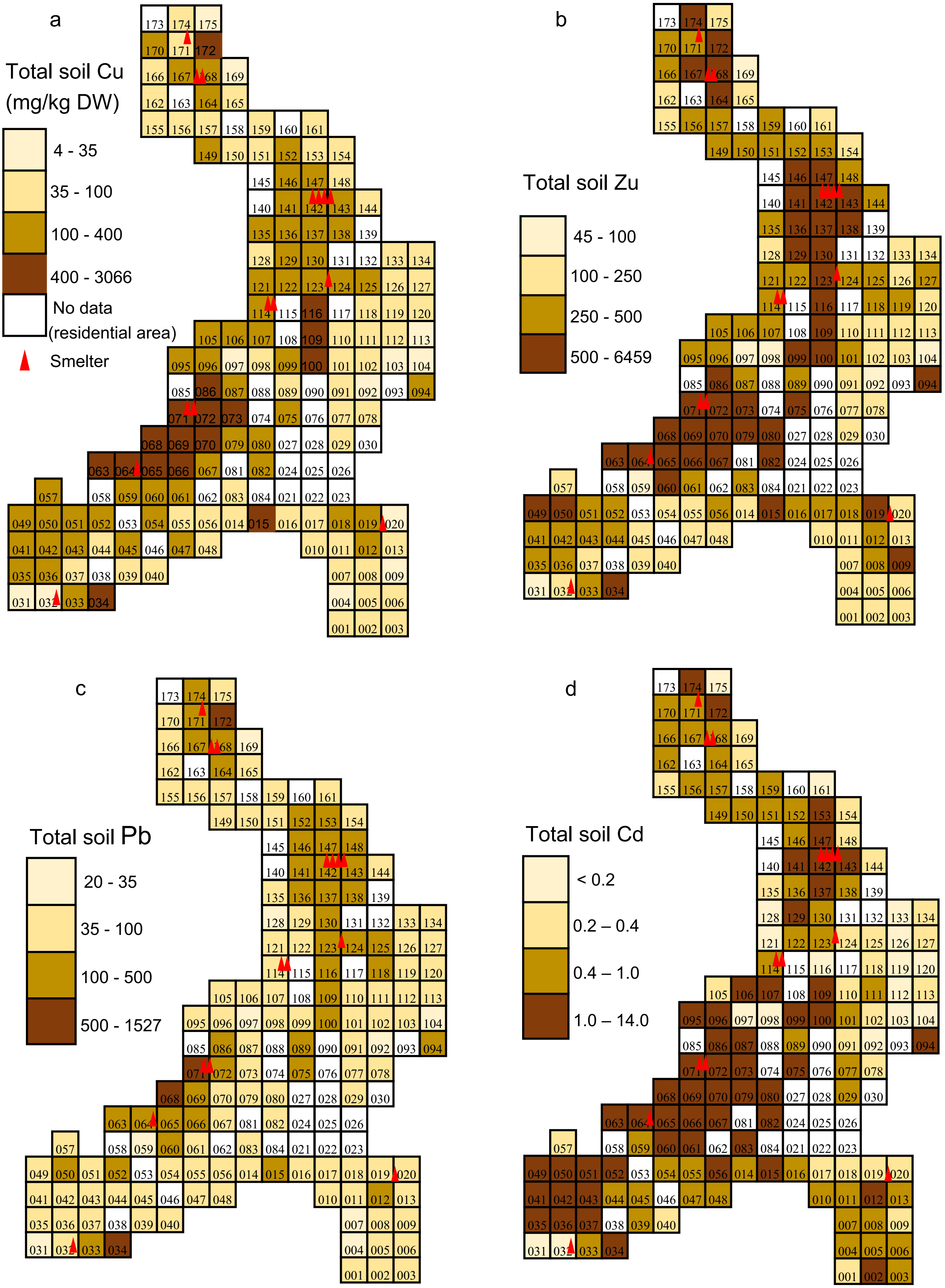
Soil mites were extracted from the soil samples using modified Tullgren extractors with a temperature increase from 20 to 50 °C at a rate of 5 °C per day for 6 days (Liu et al. 2013). The mites were preserved in 75% alcohol before species identification. A drop of Hoyer's medium (distilled water 50 mL, chloral hydrate 200 g, glycerin 20 g, and Arabic gum 30 g) was added to a glass slide. A mite specimen was placed in the medium and then a cover glass was placed over it to make a slide specimen (Xin 1984; Kuang 1986; Yin 1992). They were then identified and counted. All soil mites were identified to species level within the four orders (Oribatida, Mesostigmata, Prostigmata, and Astigmata) using taxonomic keys and other references (Baker et al. 1958; Balogh 1972; Ghilarov and Krivolutski 1975; Xin 1984; Kuang 1986; Ma et al.1987; Deng et al. 1989; Xin 1989; Dindal 1990; Yin 1992; Liu and Kuang 1997; Zhang and Liang 1997; Liu and Kuang 1998a, b; Yin 1998; OSU 2006; Walter 2006; Krantz and Walter 2009). We calculated the soil mite species richness (species number per site), individual abundance (individual number per site), and the Shannon–Wiener diversity index $H' = -\sum_{i=1}^{S} p_i \ln p_i$, where p_i is the proportion of species i in the total mite abundance of S number of species for each study site.

Assessment of metal pollution

A series of pollution indices were used to assess the status or degree of metal pollution. The enrichment factor ($EF = (C_m/C_{Mn})_{sample}/(C_m/C_{Mn})_{background}$), pollution index ($PI = (C_m)_{sample}/(C_m)_{background}$), and geoaccumulation index ($Igeo = \log_2[(C_m)_{sample}/1.5(C_m)_{background}]$) were used to evaluate the pollution status due to individual metals and are referred to as single pollution indices. Degree of contamination ($C_d = \sum_{i=1}^{n} PI_i$), the pollution load index ($PLI = (PI_1 \times PI_2 \times PI_3 \times \cdots PI_n)^{1/n}$), and the Nemerow pollution index $\left(PI_{Nemerow}\sqrt{\frac{\left(\frac{1}{n}\sum_{i=1}^{n} PI_i\right)^2 + PI_{imax}^2}{n}}\right)$ were used to evaluate the pollution status or degree of complexity arising from several metals occurring together and these are termed integrated pollution indices. The ecological risk factor ($E_r^i = T_r^i \times PI_i$), which was used to evaluate the ecological risks of pollution by a certain single metal, and the potential ecological risk index ($RI = \sum_{i=1}^{n} E_r^i$), which expresses the potential ecological risks of pollution by several metals, are referred to as the ecological risk indices. It must be noted that C_m refers to the metal concentration, C_{Mn} is manganese (Mn) concentration, *sample* refers to the metal content of the soil samples, *background* means the background values, PI_i is the PI of ith individual metal, n is the total number of metals, T_r^i is the biological toxic factor of an individual metal, and the toxic-response factors for Cu, Zn, Pb, and Cd were 5, 1, 5, and 30, respectively (Håkanson 1980; Chen et al. 2015; Islam et al. 2015a, b; Kowalska et al. 2016). Soil Mn content was obtained from previous investigations in Zhejiang Province and was used as a reference element when calculating the EF (Rong et al. 1992; Islam et al. 2015a, b). Local soil heavy metal background concentrations were obtained from previous studies (Rong et al. 1992; Chen et al. 2015; Xiao et al. 2015).

Data analysis

Metal concentration, soil properties (pH and SOM), pollution index data, and soil mite community properties are expressed as the mean ± standard error (SE). To match the Chinese Soil Quality Standard, the study sites were classified into four concentration groups according to the four pollution grades for Cu pollution concentrations in the Chinese Soil Quality Standard (GB15618-1995 and GB15618-2018) (SEPAC 1995; MEEC 2018). Group C1 consisted of the study sites with soil Cu concentrations of 4–35 mg kg^{-1}, C2 sites contained 35–100 mg kg^{-1}, C3 sites contained 100–400 mg kg^{-1}, and C4 sites contained 400–3066 mg Cu kg^{-1}. The data were analyzed using two-way analysis of variance (ANOVA) with the concentration group (C1, C2, C3, and C4) and the land use (woodlands, dry fields, paddy fields, and wastelands) as the two factors affecting the concentrations of the four soil metals, soil pH and SOM, the pollution indices, the ecological risk values, and the mite community properties for Acari (all mites) and each of the four orders. Statistically significant differences between the study sites, land uses, concentration groups, and the interactions between land use and concentration group were determined using Tukey's test. Correlations between the Cu concentrations and the other metals (Zn, Pb, and Cd) and those between the concentrations of the four metals and the soil pH and SOM at all study sites and for each land use were


a
Total soil Cu (mg/kg DW)
4 - 35
35 - 100
100 - 400
400 - 3066
No data (residential area)
Smelter
b
Total soil Zu
45 - 100
100 - 250
250 - 500
500 - 6459
c
Total soil Pb
20 - 35
35 - 100
100 - 500
500 - 1527
d
Total soil Cd
< 0.2
0.2 – 0.4
0.4 – 1.0
1.0 – 14.0

◂**Fig. 2** Distributions of Cu (**a**), Zn (**b**), Pb (**c**), and Cd (**d**) concentrations in the soils (mg kg^{-1} DW) from the study sites in the study area. The concentration ranges (mg kg^{-1} DW) of the metals were classified according to the Chinese Soil Quality Standard

analyzed using Pearson's correlation analysis. Local spatial distribution associations between mite species number and Cu concentration at each study site were analyzed using the Spatial Analysis by Distance Indices (SADIE) method/software (SADIESshell 1.22) (Perry et al. 1996, 1999; Holland et al. 2000; Campos-Herrera et al. 2013; Park et al. 2014; Wu et al. 2019; Gireesh et al. 2021). SADIE was used to determine the spatial patterns of the mites and metals and is a useful way to assess the spatial aggregation of a population. It can be used to formally test whether there are spatial associations between different factors (Perry et al. 1999; Blackshaw et al. 2007; Park et al. 2014; Wu et al. 2019; Gireesh et al. 2021). Because all the metals (Cu, Zn, Pb, and Cd) and the selected soil properties (pH, and SOM) existed synchronously in the same natural environment in the study sites, the correlations of the metals as one unit, each of the individual metals with the mite communities as one unit, and each of the mite community properties were analyzed. The relative importance or contribution to the correlations were compared among all the environmental factors, including each of the metals and the soil properties. The analysis and a comparison were conducted through a redundancy analysis (RDA) of the correlations and a Monte Carlo replacement test was conducted using the Canoco 4.5 program. The statistical analyses were conducted using the Statistica 7.1 software package (StatSoft, Inc., Tulsa, OK, USA) (Stat Soft Inc 2005).

Results

Soil metal concentrations, soil pH, and SOM

The Cu (Fig. 2a), Zn (Fig. 2b), Pb (Fig. 2c), and Cd (Fig. 2d) distributions at the study sites were generally higher along the midline of the study area where the smelter groups were located. The concentrations of metals ranged widely at 4.1–3065, 45.7–6459, 19.7–1527, and 0.02–13.9 mg kg^{-1} for Cu, Zn, Pb, and Cd, respectively. There were also large variations within each land use type (Table 1). The Cu concentrations were significantly positively correlated with those of the other three metals (Table 2), and therefore, the concentrations of all four metals were determined by the extent of the Cu smelting activity. The 141 sampling sites in the study area were classified into four concentration groups for each land use type (see above). The mean values with standard errors and the maximum and minimum ranges for the concentrations of the four metals in each concentration group under the four land use types are shown in Table 1.

The Cu and Pb concentrations in the wastelands were significantly 2–5 times greater than those for the other three land use types. Zinc and Cd concentrations also tended to be higher in the wastelands where they were 2–5 times higher than those in the other three land use types (Tables 1 and 3). The concentrations of the four metals in the four soil groups (C1, C2, C3, and C4) generally followed the sequence C1 < C2 < C3 < C4, but the differences between the four concentration groups differed with land use type. Generally, across the four metals, ~ 76.5, 87.5, 98.5, and 92.3% of the study sites exceeded grade 1 at the lowest pollution points and 5.9, 0.0, 9.2, and 34.6% exceeded grade 3 at the highest pollution point in the woodlands, dry fields, paddy fields, and the wastelands, respectively. The background values used for the four metals were those for the local province (Table 1). The metal concentrations in the woodlands were ~ 1.4–46.0, 2.4–67.1, 1.8–32.0, and 6.8–178.6 times the background values for Cu, Zn, Pb, and Cd, respectively, according to the mean values across the four concentration groups (C1, C2, C3, and C4). The corresponding values were 2.7–6.1, 5.4–14.9, 2.1–5.8, and 14.6–35.7 times the background values in the dry fields; 1.0–25.4, 2.0–14.7, 1.4–6.4, and 1.1–38.0 in the paddy fields; and 1.3–101, 2.0–59.7, 1.6–21.8, and 4.3–275 in the wastelands.

The soil pH (Fig. 3a) and SOM (Fig. 3b) levels were also generally higher along the midline of the study area where groups of smelters were located. The pH values in the study area ranged from 4.1 to 8.3 with a variation of ~ 3 pH units within each land use type (Table 1). The pH values were related to land use type with higher values in the wastelands and paddy fields and the lowest in the woodlands, which had slightly acid soils (Table 3). Soil organic matter content ranged from 0.6 to 10.1% with a 2.5 to 4.5% variation in SOM in the woodlands, dry fields, and wastelands. However, the variation was ~ 8.5% in the paddy fields (Table 1). The SOM content was also higher in the paddy fields and wastelands and highest values were recorded for the paddy fields, which were 1.7 times higher than in the woodlands.

Assessment of metal pollution

Because the indices for pollution assessment differ in their applicability for different types of pollution or contamination scenarios, such as different types of metals, different concentration ranges of pollutants, and complex or multiple pollution sources, a series of indices consisting of different single and integrated pollution indices and ecological risk indices were used.

Table 1 Soil metal (Cu, Zn, Pb, and Cd) concentrations (mg kg^{-1}), pH and soil organic matter content (SOM, %), and the total number of mite species and individuals in soils from the different sample sites classified according to concentration groups (C1, C2, C3, and C4, based on Cu concentration[1]) and land use type (woodlands, dry fields, paddy fields, and wastelands). Also shown are the metal background values and the guideline values of the Chinese Soil Quality Standard

Site		Metal				pH	SOM	Mite	
		Cu	Zn	Pb	Cd			Species	Individual
Woodlands	Mean ± SE	132 ± 27	465 ± 162	104 ± 28	1.1 ± 0.4	5.3 ± 0.1	2.3 ± 0.2	94	938
	Range	4.1–764	72.0–5637	19.7–942	0.02–8.7	4.1–7.4	0.6–4.5		
C1 (*n* = 8)[2]	Mean ± SE	17.9 ± 3.6	112 ± 14	38.0 ± 6.0	0.19 ± 0.06	4.8 ± 0.1	2.3 ± 0.3	33	185
	Range	4.2–35.0	72.0–191	19.7–69.5	0.02–0.47	4.5–5.3	1.5–3.9		
C2 (*n* = 12)	Mean ± SE	51.4 ± 3.0	210 ± 24	61.6 ± 6.5	0.30 ± 0.04	5.2 ± 0.2	2.0 ± 0.3	61	331
	Range	37.0–67.7	115–438	29.3–104	0.11–0.54	4.7–6.8	0.6–3.6		
C3 (*n* = 12)	Mean ± SE	187 ± 25	506 ± 76	94.3 ± 16.3	1.9 ± 0.7	5.5 ± 0.3	2.7 ± 0.3	35	259
	Range	115–369	267–1233	45.4–263	0.19–7.8	4.1–7.4	1.1–4.5		
C4 (*n* = 2)	Mean ± SE	593 ± 171	3172 ± 2464	681 ± 261	5.0 ± 3.8	5.9 ± 0.1	3.1 ± 0.1	33	163
	Range	423–764	708–5637	420—942	1.2–8.7	5.7–6.0	2.9–3.2		
Dry fields	Mean ± SE	120 ± 27	476 ± 124	86.3 ± 15.7	0.7 ± 0.1	6.0 ± 0.2	2.4 ± 0.2	73	617
	Range	32.2–393	149–2236	33.1–200	0.2–2.2	5.0–8.3	1.0–3.7		
C1 (*n* = 2)	Mean ± SE	35.0 ± 2.8	444 ± 243	45.5 ± 1.1	0.41 ± 0.20	5.9 ± 0.9	2.8 ± 0.6	17	91
	Range	32.2–37.8	201–686	44.5–46.6	0.21–0.62	5.0–6.8	2.1–3.4		
C2 (*n* = 7)	Mean ± SE	56.9 ± 7.1	255 ± 32	60.9 ± 7.1	0.48 ± 0.10	6.1 ± 0.3	2.3 ± 0.3	58	318
	Range	41.8–90.0	149–350	33.1–86.4	0.18–0.87	5.0–7.4	1.6–3.7		
C3 (*n* = 7)	Mean ± SE	208 ± 43	707 ± 259	123 ± 31	1.0 ± 0.3	6.0 ± 0.4	2.3 ± 0.2	37	208
	Range	112–345	264–2236	59.1–300	0.2–2.2	5.1–8.3	1.0–3.0		
Paddy fields	Mean ± SE	161 ± 18	478 ± 43	94.5 ± 7.0	1.6 ± 0.2	6.6 ± 0.1	3.9 ± 0.1	31	79
	Range	19.9–610	45.7–1724	35.9–370	0.1–11.4	4.7–8.1	1.6–10.1		
C1 (*n* = 1)		19.9	159	43.2	0.15	5.6	3.0	10	19
C2 (*n* = 31)	Mean ± SE	67.9 ± 3.3	284 ± 20.7	72.1 ± 6.2	0.70 ± 0.08	6.1 ± 0.2	3.7 ± 0.3	20	39
	Range	35.9–95.8	45.7–647	35.9–206	0.12–2.10	4.7–7.9	1.6–10.1		
C3 (*n* = 27)	Mean ± SE	191 ± 15	554 ± 55	101 ± 8	1.7 ± 0.2	7.2 ± 0.2	3.9 ± 0.2	9	15
	Range	102–337	198–1160	57.6–192	0.4–4.8	5.4–8.1	1.7–5.2		
C4 (*n* = 6)	Mean ± SE	531 ± 31	1186 ± 143	191 ± 41	5.4 ± 1.6	7.2 ± 0.4	4.7 ± 0.2	5	6
	Range	424–610	1049–1724	98.4–370	0.2–11.4	5.5–7.9	3.8–5.2		
Wastelands	Mean ± SE	530 ± 156	1224 ± 339	216 ± 61	3.3 ± 0.8	6.9 ± 0.2	3.7 ± 0.2	39	182
	Range	13.1–3065	77.4–6459	29.2–1527	0.1–13.9	5.0–8.2	1.2–5.6		
C1 (*n* = 2)	Mean ± SE	16.3 ± 3.1	94.3 ± 17.0	34.7 ± 5.5	0.12 ± 0.01	6.4 ± 1.4	3.4 ± 2.2	13	20
	Range	13.1–19.4	77.4–111	29.2–40.2	0.11–0.13	5.0–7.8	1.2–5.6		
C2 (*n* = 5)	Mean ± SE	59.3 ± 6.5	269 ± 44	75.3 ± 10.4	0.42 ± 0.13	6.3 ± 0.6	3.0 ± 0.5	15	93
	Range	40.9–74.0	192–436	49.8–111	0.13–0.76	5.3–8.1	1.9–4.5		
C3 (*n* = 10)	Mean ± SE	175 ± 23	488 ± 75	97.9 ± 13.2	1.5 ± 0.4	7.1 ± 0.3	3.8 ± 0.3	15	39
	Range	103.5–333.2	78.9–842	31.0–168	0.5–4.0	5.1–7.9	2.4–5.1		
C4 (*n* = 9)	Mean ± SE	1298 ± 323	2824 ± 730	465 ± 148	7.7 ± 1.4	7.0 ± 0.3	4.0 ± 0.4	11	30
	Range	410–3065	842–6459	88.4–1527	1.5–13.9	5.3–8.2	2.6–5.5		
Background values of the metals in soils of Zhejiang province, China [1]									
	Paddy fields	20.9	80.9	29.8	0.142				
	Others	12.9	47.3	21.3	0.028				
Chinese soil quality standard[2,3]									
	Grade I	35	100	35	0.2				
	Grade II	100	250	100	0.4				
	Grade III	400	500	500	1				

(1) The study sites were classified by Cu concentration into four concentration groups according to the Chinese Soil Quality Standard: C1 (sites with a soil Cu concentration of 4–35 mg kg^{-1}), C2 (35–100 mg kg^{-1}), C3 (100–400 mg kg^{-1}), and C4 (400–3,066 mg kg^{-1})

"n" is the number of sites

[1] Rong et al. (1992)

[2] SEPAC (1995)

[3] MEEC (2018)

Table 2 R-values for the Cu, soil pH values, and soil organic matter content (SOM) correlations with Zn, Pb, and Cd concentrations for all study sites combined and for each of the land use types

	Cu	Zn	Pb	Cd
All sites (*n* = 141)				
Cu	1	0.79*	0.81*	0.76*
pH	0.16	0.14	0.10	0.26*
SOM	0.15	0.09	0.07	0.30*
Woodlands (*n* = 34)				
Cu	1.00	0.83*	0.86*	0.86*
pH	0.16	0.21	0.21	− 0.04
SOM	0.28	0.17	0.18	0.30
Dry fields (*n* = 16)				
Cu	1.00	0.58*	0.75*	0.42
pH	− 0.08	0.10	0.18	0.35
SOM	− 0.36	− 0.01	− 0.07	0.35
Paddy fields (*n* = 65)				
Cu	1.00	0.82*	0.64*	0.75*
pH	0.40*	0.27*	0.15	0.36*
SOM	0.31*	0.06	− 0.06	0.29*
Wastelands (*n* = 26)				
Cu	1.00	0.81*	0.85*	0.81*
pH	− 0.09	− 0.07	− 0.05	0.13
SOM	0.01	0.02	0.04	0.23

*Correlations are significant at $P < 0.05$

“n” = number of sites

Assessment of the single and integrated pollution indices

The single pollution EF, PI, and Igeo values are provided in Online Resource 3. The statistical results for the EF and PI values were similar (Table 4). The Cd Igeo values were generally higher than those for the other three metals. The Cu and Zn Igeo values were generally similar to each other and higher than Pb for all four land use types. The Igeo values of all four metals in the wastelands were higher than those for the other three land use types, and were generally lowest in the paddy fields. Most of the Igeo values for the four metals exceeded the unpolluted category value (the lowest grade), although there were some values at the unpolluted grade (Online Resource 5). Generally, the Igeo indices showed that the Cd levels were higher than those for Cu or Zn, and the Pb levels were the lowest, with levels in the paddy fields lower than those in the other three land use types. The Cu and Zn Igeo values were generally at the highly to extremely highly polluted (sixth) or extremely highly polluted (the seventh, i.e., the highest) grade in C4. The Pb values reached the fifth or sixth grade in C4.

The integrated pollution indices C_d, PLI, and PI_{Nemerow} were used to indicate the integrated effects of the four metals (Online Resource 3). The C_d values had similar tends across the land use types and concentration groups. The C_d values for paddy fields were lower than those for the other land use types (Table 4). The C_d index values for the C4 concentration group under all land use types were at the high contamination (the fourth, i.e., the highest) grade (Online Resource 5).

Assessment of the ecological risk indices

The single ecological risk factor E_r^i was used to evaluate the ecological risk of each metal and the integrated ecological risk index RI was used to evaluate the potential ecological risk of the four metals combined. The E_r^i values for Cd were much higher than those for the other three metals for all four land use types (Online Resource 4 and Table 4). The E_r^i values for the wastelands were much higher than for the other land use types, whereas they were lowest in the paddy fields. The comparative results for Cu, Zn, Pb, and Cd among the four land use types were similar to the Igeo index. The ecological risk levels of the metals assessed by E_r^i showed that Cd levels were higher than the Cu levels, and the Zn and Pb levels were the lowest. In addition, the metal levels in the paddy fields were lower than those in the woodland, dry fields, or wastelands, The ecological risk levels for Cu pollution according to the E_r^i assessment were at the high risk (fourth grade) in concentration group C4, and the Zn and Pb risk levels in C4 were generally at the second or the considerable risk (third) grades, but were dependent on land use type (Online Resource 5). The Cd risk levels for C4 were at the highest grade.

The integrated ecological risk index (RI) values for combined pollution with the four metals were also lower in the paddy fields (Online Resource 4 and Table 4). In the RI assessment, the potential ecological risk levels were generally high (Online Resource 5). The RI risk levels in the woodlands, dry fields, and wastelands were generally similar and higher than

Table 3 *F*-values for the two-way ANOVA of the effects of land use (woodlands, dry fields, paddy fields, and wastelands) and metal concentration group (C1, C2, C3, and C4) on the concentrations of the four metals, soil pH, and organic matter contents (SOM)

Factor	Cu	Zn	Pb	Cd	pH	SOM
Land	2.9*	1.9	3.5*	0.5	11.1***	7.4***
Metal	3.3*	2.4	1.4	4.6*	4.3*	1.6
Land*Metal	3.7***	2.8**	3.4**	1.1	0.8	0.4

$^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$

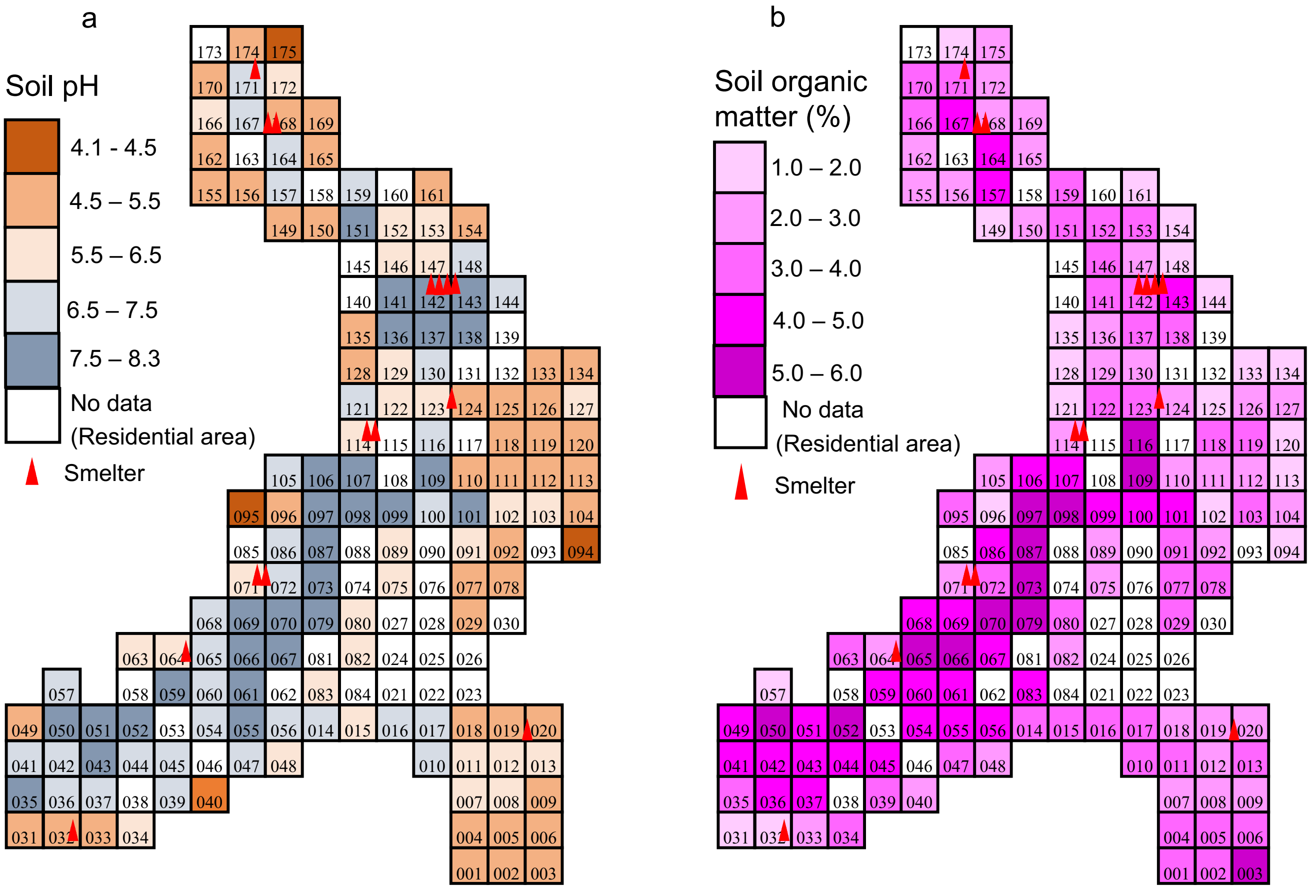


Fig. 3 Distributions of the soil pH values (**a**) and soil organic matter contents (%) (**b**) across the study sites in the study area

Table 4 *F*-values of the two-way ANOVA for the effects of land use type (woodlands, dry fields, paddy fields, and wastelands) and metal concentration groups (C1, C2, C3, and C4) on the values of the three single and three integrated pollution indices, the single ecological risk factor, and the integrated potential ecological risk index

	$EF_{Mn}/PI/E_r^i$				$Igeo$				C_d	PLI	$PI_{nemerow}$	RI
	Cu	Zn	Pb	Cd	Cu	Zn	Pb	Cd				
Land	4.5*	4.6*	5.7**	8.0***	6.9**	4.5*	6.0**	14.3***	9.4***	6.7**	9.0***	8.3***
Metal	2.8	2.0	1.2	4.3*	134.7***	25.2***	15.0***	22.5***	5.3**	3.5*	5.2**	4.5*
Land*Metal	5.2***	4.1***	4.1***	6.7***	2.3*	1.9	2.1*	1.1	8.6***	6.0***	8.0***	7.1***

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

those in the paddy fields, but there were small differences among the former three land use types.

Soil mite communities

General community composition of soil mites in the study area

A total of 132 species were found, of which 44 were identified to the species level. There were 1816 individuals from the four orders: Mesostigmata, Prostigmata, Astigmata, and Oribatida (Online Resource 1). Species number (86) was highest for the Oribatid mites, which accounted for > 65% of the total, followed by Mesostigmata (23), Prostigmata (19), and Astigmata (4). The Oribatida also had the highest number of individuals (1424) accounting for > 78% of the total individuals, followed by Mesostigmata (180), Prostigmata (112), and Astigmata (100, of which 77 were hypopodes). The highest numbers of individuals (938) and total species (94) were obtained from the woodlands with 617 and 73, 182 and 39, and 79 and 31 in the dry fields, wastelands, and paddy fields, respectively. The highest numbers of total species (101) and total individuals (781) were recorded for the C2 group, followed by C3 (66 and 521, respectively), C1 (51 and 315, respectively), and C4 (42 and 199, respectively).

Mite community properties under different land use types

The Acari species richness in the woodlands and dry fields was ~ 9.5 and ~ 12.5 times that in the paddy fields and ~ 2.5 and ~ 3.4 times that in the wastelands, respectively (Table 5, Fig. 4a). The corresponding values for individual abundance were ~ 22.7 and ~ 31.7, and ~ 4.6 and ~ 6.4 times greater than in the paddy fields and wastelands, respectively (Fig. 4b). The diversity index values in woodlands, dry fields, and wastelands were ~ 5.7, ~ 7.7, and ~ 4.0 times that in the paddy fields, and the value for the dry fields was ~ 1.9 times that in the wastelands (Fig. 4c). The results for the Oribatida were similar to those for the Acari with only small differences in species richness and individual abundance. The diversity index values for the Oribatida were statistically different among the four land use types, but the sequence was the same as that for Acari, namely dry fields > woodlands > wastelands > paddy fields. The Prostigmata species richness values for the dry fields were 10.4 and 5.9 times those for paddy fields and wastelands, respectively, and species richness in woodlands was 6.3 times that in the paddy fields. The individual abundance in the dry fields was 24.4 and 7.8 times those in the paddy fields and wastelands, respectively, and the individual abundance in the woodlands was 10.3 times that in the paddy fields. The diversity index for the dry fields was 12.6 times that for the paddy fields. For the Mesostigmata and Astigmata, no statistical differences were found in species richness, individual abundance, and the Shannon–Wiener diversity index among the land use types.

Mite community properties in the different metal concentration groups

The community properties (species richness, individual abundance, and the Shannon–Wiener diversity index) for Acari in general and the four orders mainly decreased with increasing concentration group (C1 to C4) (Table 5, Fig. 4d, e, and f). The community properties of the Acari and the Oribatida were similar and decreased with increasing concentration group, but there were no statistically significant differences in the individual abundances among the concentration groups. The species richness for the Acari in the lowest concentration group (C1) were 1.5, 2.4, and 2.0 times greater than those in C2, C3, and C4, respectively, and the diversity indices were 1.8, 2.3, and 2.1 times greater than those in C2, C3, and C4, respectively (Table 6). For the Astigmata, in general, the C1 species richness was 8.8 times greater than that for C3; the C1 individual abundances were 6.7, 29.1, and 35.3 times greater than those for C2, C3, and C4, respectively. However, the Astigmata results were dependent on land use type. Statistical differences in species richness among concentration groups were only found in woodlands and significant diversity index differences only occurred in the dry fields. For the Mesostigmata and Prostigmata, the species richness, individual abundance, and Shannon–Wiener diversity indices generally showed no statistical differences among the concentration groups, but the Prostigmata were dependent on land use type because species richness, individual abundance, and diversity index were only statistically different in the woodlands. The values for all three properties in woodlands were much higher in C1 than in the other three concentration groups.

Distribution association between soil mites and metal concentrations

The numbers of soil mite species (Fig. 5a) and individuals (Fig. 5b) were generally lower along the midline of the study area where the smelter groups were located, which was opposite to the distributions of the four soil metal concentrations (Fig. 2a, b, c, and d). Based on the soil samples, 94 out of the 141 sites in the study area contained mites (67%), but this differed among the land use types. In the woodlands and dry fields, 31 woodlands sites and 15 dry fields sites contained mites (91% and 94%, respectively), whereas 30 paddy fields sites and 18 wastelands sites contained mites

Table 5 *F*-values of the two-way ANOVA for the effects of land use types (woodlands, dry fields, paddy fields, and wastelands) and metal concentration groups (C1, C2, C3, and C4) on mite species richness (Spec), individual abundance (Indi), and the Shannon–Wiener diversity index (Dive) for all mites (Acari) and the four orders (Mesostigmata, Prostigmata, Astigmata, and Oribatida)

	Acari			Mesostigmata			Prostigmata			Astigmata			Oribatida		
	Spec	Indi	Dive	Spec	Indi	Spec	Spec	Indi	Dive	Spec	Indi	Dive	Spec	Indi	Dive
Land	8.0***	12.0***	3.1*	2.2	2.9	10.8***	10.8***	9.2***	8.5***	1.3	0.8	0.6	8.1***	11.7***	3.1*
Metal	3.2*	1.5	6.5**	1.4	0.8	0.1	0.1	1.7	0.3	6.8**	11.8***	4.4*	3.5*	1.7	5.8**
Land*Metal	1.5	1.7	1.8	1.4	1.6	3.4**	3.4**	3.9***	2.8**	2.2*	7.4***	0.6′	1.5′	1.8	2.0

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

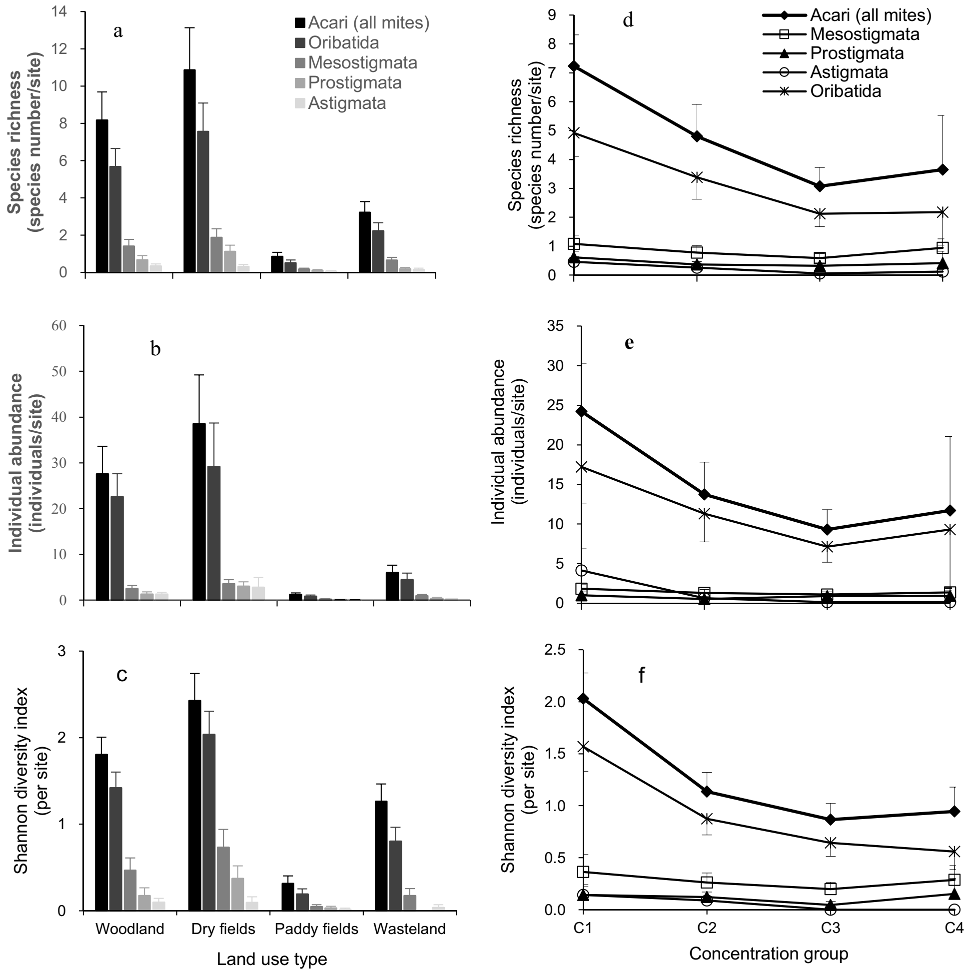


Fig. 4 Species richness (**a**), individual abundance (**b**), and the Shannon–Wiener diversity index (**c**) values for the study sites across the four land use types (woodlands, dry fields, paddy fields and wastelands). Species richness (**d**), individual abundance (**e**), and the Shannon–Wiener diversity index (**f**) for each study site in the four concentration groups (C1, C2, C3, and C4). Data are mean ± SE, *n* (study sites) = 34, 16, 65, and 26 for the woodlands, dry fields, paddy fields, and wastelands, respectively, and 13, 55, 56, and 17 for C1, C2, C3, and C4, respectively

(46% and 69%, respectively). The local association analysis using the SADIE method showed that both soil mite species number ($I_a = 2.4$, $P < 0.05$) and Cu concentration ($I_a = 1.8$, $P < 0.05$) had aggregated distributions, and the local association between the mite species number and Cu concentration was generally negative ($X = -0.1$), although the results was not statistically significant (Fig. 6). A total of 17 sites in the study area showed a negatively significant association between the mite species number and Cu concentration and accounted for 12% of all the sites or 18% of the sites with mites. In contrast, 11 sites showed a positively significant association and accounted for 8% of all the sites or 12% of the sites with mites. However, the results differed among the land use types. In the woodlands and dry fields, six woodlands sites showed negatively significant associations, accounting for 18% of all the woodland sites or 19% of the woodland sites with mites, and four dry field sites showed negatively significant associations, accounting for 25% of all the dry field sites or 27% of the dry field sites with mites. Four woodland sites and one dry field site showed positively significant associations, accounting for 12% of the woodland sites or 13% of the woodland sites with mites, and 6% of the dry field sites or 7% of the dry field sites with mites. However, six paddy fields sites and one wastelands site showed negatively significant associations, accounting for 9% of the paddy field sites or 20% of the paddy field sites with mites, and 4% of the wasteland sites or 6% of the wasteland sites with mites, respectively. Five paddy field sites and one wastelands site showed positively significant associations, accounting for 8% of the paddy field sites or 17% of the paddy field sites with mites, and 4% of the wasteland sites or 6% of the wasteland sites with mites, respectively. In summary, both negative and positive significant associations between mite species number and Cu concentration were found in the study sites. The negative associations were greater than the positive associations in all land use types. The negative associations in the woodlands and dry fields were greater than those in paddy fields and wastelands. The differences between the negative associations and the positive associations in woodlands and dry fields were larger than those in paddy fields and wastelands; i.e., the percentage of the study sites with negative associations was much higher than the percentage with positive associations in the woodlands and dry fields, while the percentage with

Table 6 Species richness (Spec, species number/6 samples per site), individual abundance (Indi, individual number/6 samples per site), and the Shannon–Wiener diversity index (Dive, one per site) results for Acari (all mites) and the four mite orders (Mesostigmata, Prostigmata, Astigmata, and Oribatida) in the concentration groups (C1, C2, C3, and C4) and the four land use types

Sites1)		Acari			Mesostigmata			Prostigmata			Astigmata			Oribatida		
		Spec	Indi	Dive	Spec	Indi	Dive	Spec	Indi	Dive	Spec	Indi	Dive	Spec	Indi	Dive
Woodlands																
C1 (*n* = 8)	Mean ± SE	6.4 ± 1.6	23.1 ± 7.1	1.6 ± 0.3	0.6 ± 0.4	0.8 ± 0.4	0.2 ± 0.2	0.5 ± 0.3	0.5 ± 0.3	0.1 ± 0.1	0.5 ± 0.3	2.3 ± 1.4	0.2 ± 0.1	4.6 ± 1.2	19 ± 6.7	1.3 ± 0.3
	Range	0–13	0–54	0–2.6	0–3	0–3	0–1.6	0–2	0–2	0–1	0–2	0–10	0–0.9	0–10	0–54	0–2.3
C2 (*n* = 12)	Mean ± SE	9.7 ± 3.2	27.6 ± 9.7	2.0 ± 0.4	2.0 ± 0.8	3.4 ± 1.8	0.7 ± 0.3	0.7 ± 0.3	0.8 ± 0.5	0.2 ± 0.1	0.6 ± 0.2	0.8 ± 0.2	0.2 ± 0.1	6.5 ± 2.1	21.2 ± 7.6	1.5 ± 0.4
	Range	0–31	0–107	0–4.7	0–10	0–21	0–3.1	0–3	0–5	0–1.6	0–2	0–7	0–1	0–20	0–83	0–4.0
C3 (*n* = 12)	Mean ± SE	6.3 ± 1.6	21.6 ± 7.2	1.7 ± 0.3	1.2 ± 0.4	2.0 ± 1.7	0.4 ± 0.2	0.4 ± 0.1	1.1 ± 0.5	0.0 ± 0.0	0 ± 0	0 ± 0	0 ± 0	4.7 ± 1.2	18.5 ± 6.4	1.3 ± 0.3
	Range	0–15	0–78	0–3.2	0–5	0–8	0–2.2	0–1	0–6	0	0	0	0	0–11	0–69	0–2.9
C4 (*n* = 2)	Mean ± SE	17.5 ± 15.5	81.5 ± 79.5	2.1 ± 1.1	2.5 ± 5.5	5.5 ± 5.5	0.9 ± 0.9	3.5 ± 3.5	8.0 ± 8.0	1.3 ± 1.3	0.5 ± 0.5	0.5 ± 0.5	0 ± 0	11 ± 9	67.5 ± 65.5	1.7 ± 0.7
	Range	2–33	2–161	1–3.2	0–5	0–11	0–1.9	0–7	0–16	0–2.6	0–1	0–1	0	2–20	2–133	1–2.4
Dry fields																
C1 (*n* = 2)	Mean ± SE	9.5 ± 2.5	45.5 ± 27.5	2.6 ± 0.0	1.5 ± 0.5	3.5 ± 1.5	0.4 ± 0.4	1.5 ± 0.5	4.0 ± 3.0	0.4 ± 0.4	0.5 ± 0.5	17.5 ± 17.5	0.3 ± 0.3	5.5 ± 2.5	20.5 ± 14.5	1.8 ± 0.3
	Range	7–12	18–73	2.5–2.6	1–2	2–5	0–0.7	1–2	1–7	0–0.9	0–1	0–35	0–0.5	3–8	6–35	1.5–2.1
C2 (*n* = 7)	Mean ± SE	13.0 ± 4.5	45.4 ± 22.6	2.6 ± 0.6	2.1 ± 0.9	3.4 ± 1.3	0.9 ± 0.4	0.9 ± 0.5	1.6 ± 1.0	0.3 ± 0.2	0.3 ± 0.2	0.4 ± 0.3	0.1 ± 0.1	9.6 ± 3.2	40.0 ± 21.2	2.3 ± 0.5
	Range	0–37	0–175	0–4	0–6	0–8	0–2.6	0–3	0–7	0–1.6	0–1	0–2	0–1	0–26	0–164	0–3.7
C3 (*n* = 7)	Mean ± SE	9.1 ± 2.7	29.7 ± 11.0	2.3 ± 0.5	1.7 ± 0.6	3.7 ± 1.6	0.6 ± 0.3	1.3 ± 0.7	4.1 ± 2.0	0.3 ± 0.2	0.3 ± 0.2	1.0 ± 0.7	0.0 ± 0.0	6.1 ± 1.5	20.9 ± 7.4	1.9 ± 0.4
	Range	1–19	2–73	0–3.9	0–5	0–11	0–2.0	0–5	0–14	0–1.8	0–1	0–4	0	1–12	2–46	0–3.5
Paddy fields																
C1 (*n* = 1)	Mean	10.0	19.0	3.3	2.0	3.0	0.9	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.0	1.0	0.0	7.0	15.0	2.7
C2 (*n* = 31)	Mean ± SE	1.0 ± 0.3	1.3 ± 0.4	0.4 ± 0.1	0.03 ± 0.03	0.03 ± 0.03	0.0 ± 0.0	0.2 ± 0.1	0.2 ± 0.1	0.06 ± 0.04	0.06 ± 0.06	0.06 ± 0.06	0.03 ± 0.03	0.7 ± 0.2	0.9 ± 0.3	0.3 ± 0.1
	Range	0–6	0–9	0–2.5	0–1	0–1	0	0–2	0–3	0–0.9	0–2	0–2	0–1	0–4	0–6	0–1.9
C3 (*n* = 27)	Mean ± SE	0.4 ± 0.2	0.6 ± 0.3	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.2	0.1 ± 0.1	0.04 ± 0.04	0.04 ± 0.04	0.0 ± 0.0	0.04 ± 0.04	0.04 ± 0.04	0.0 ± 0.0	0.2 ± 0.1	0.2 ± 0.1	0.03 ± 0.03
	Range	0–4	0–7	0–2.0	0–2	0–4	0–1	0–1	0–1	0	0–1	0–1	0	0–2	0–3	0–0.9
C4 (*n* = 6)	Mean ± SE	0.8 ± 0.5	1.0 ± 0.6	0.3 ± 0.3	0.5 ± 0.2	0.5 ± 0.2	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.3	0.5 ± 0.5	0.2 ± 0.2
	Range	0–3	0–4	0–1.5	0–1	0–1	0	0	0	0	0	0	0	0–2	0–3	0–0.9
Wastelands																
C1 (*n* = 2)	Mean ± SE	7.0 ± 2.0	10.0 ± 2.0	2.5 ± 0.5	2.0 ± 1.0	4.0 ± 0.0	0.8 ± 0.8	0.5 ± 0.5	0.5 ± 0.5	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	4.5 ± 1.5	5.5 ± 2.5	2.0 ± 0.4
	Range	5–9	8–12	2–3.0	1–3	4.00	0–1.5	0–1	0–1	0	0	0	0	3–6	3–8	1.6–2.4
C2 (*n* = 5)	Mean ± SE	5.4 ± 1.6	13.6 ± 7.0	1.9 ± 0.5	0.6 ± 0.2	0.6 ± 0.2	0.0 ± 0.0	0.2 ± 0.2	0.2 ± 0.2	0.0 ± 0.0	0.6 ± 0.2	1.0 ± 0.6	0.2 ± 0.2	4.0 ± 1.4	11.8 ± 6.4	1.2 ± 0.3
	Range	1–10	1–40	0–3.1	0–1	0–1	0	0–1	0–1	0	0–1	0–3	0–0.9	0–8	0–36	0–1.9
C3 (*n* = 10)	Mean ± SE	2.1 ± 0.8	3.9 ± 1.7	0.8 ± 0.3	0.2 ± 0.1	0.5 ± 0.4	0.0 ± 0.0	0.3 ± 0.2	0.8 ± 0.5	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.6 ± 0.6	2.6 ± 1.1	0.6 ± 0.3
	Range	0–7	0–13	0–2.7	0.00	0.00	0	0–1	0–4	0	0	0	0	0–6	0–10	0–2.4
C4 (*n* = 9)	Mean ± SE	2.4 ± 0.6	3.3 ± 0.8	1.1 ± 0.3	0.9 ± 0.3	1.0 ± 0.3	0.3 ± 0.2	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	1.4 ± 0.3	2.2 ± 0.5	0.6 ± 0.2
	Range	0–5	0–8	0–1.9	0–2	0–2	0–1	0	0	0	0–1	0–1	0	0–3	0–5	0–1.6

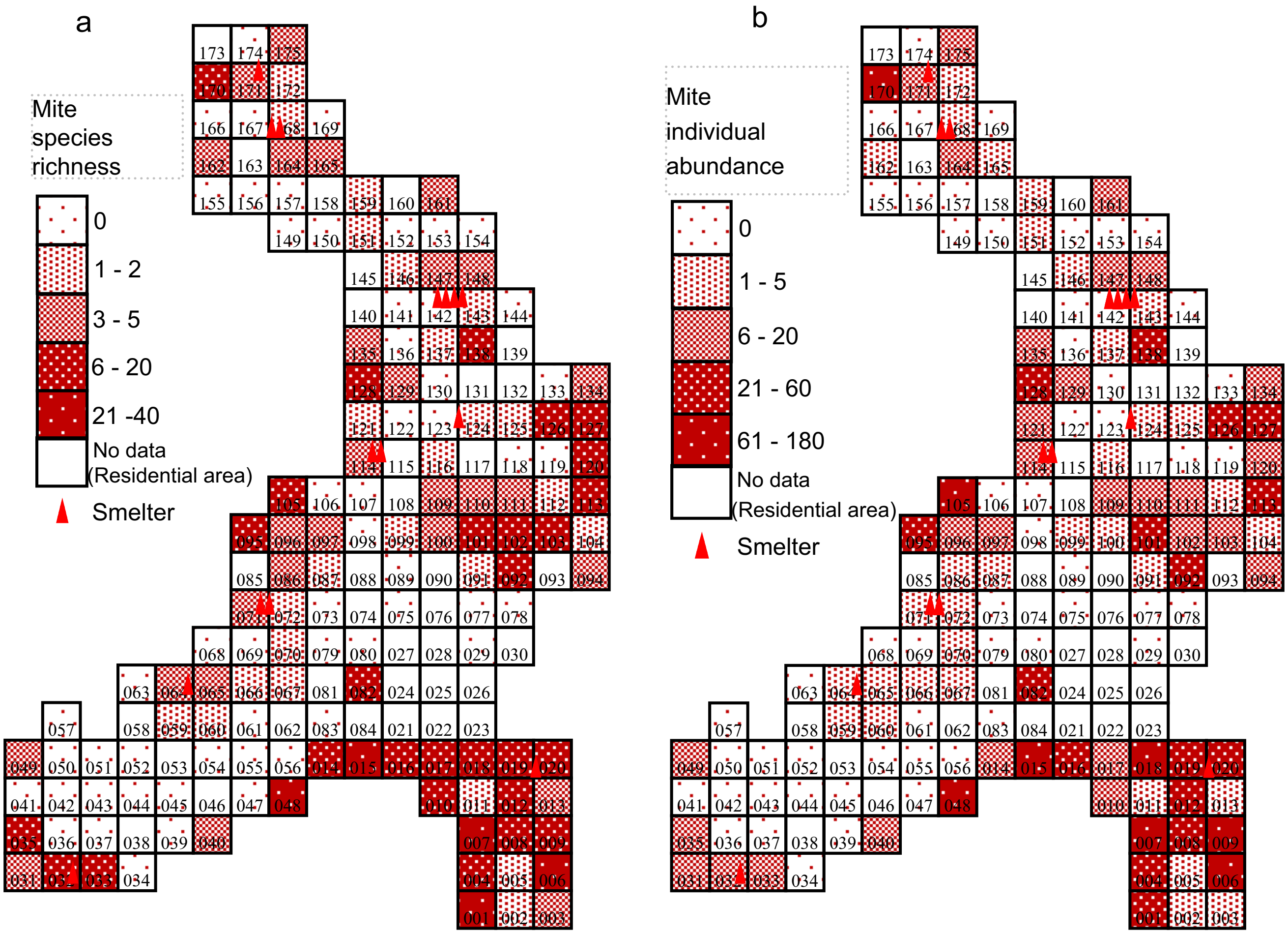


Fig. 5 Distributions of species richness (species number/6 samples per site) (**a**) and individual abundance (individual number/6 samples per site) (**b**) of soil mites across the study sites in the study area

negative associations was small higher than or similar to the percentage with positive associations in the paddy fields and wastelands.

Correlations between soil mite properties and environmental factors

Correlations between all the mite community properties and all environmental factors

Overall, the mite community properties were generally negatively correlated with the soil metal concentrations, soil pH, and SOM, although there were some differences among land use types and different mite community properties. Across all study sites, the environmental explanatory variables' effect on mite properties accounted for 8.2% of the total variation in the original matrix, of which the first two canonical axes accounted for 8.1% and 0.06%, respectively (Table 7, Fig. 7). In the woodlands, the explanatory variables accounted for 48.9% of the total variation and 48.4% of the first axis, and these percentages were significant according to the permutation test (Table 7, Fig. 8a). The explanatory variables had the next largest effect in dry fields (Fig. 8b), followed by wastelands (Fig. 8d) and paddy fields (Fig. 8c).

Correlations between mite community properties and each of the environmental factors

In the woodlands, the mite properties were generally negatively correlated with the four metals, and were significantly correlated with Cu and Zn according to the permutation test. The explanatory variables and relative contributions of the metals to the mite properties on the first axis followed the descending order: Cu, Zn, Cd, and Pb (Table 8, Fig. 8a). Similarly, in the dry fields, the mite properties were also generally negatively correlated with the metals, except for Zn where there was a significant correlation. The contribution made by Cu was very small, and the explanatory variables and relative contribution of the metals to the mite properties on the first axis followed the descending order: Zn, Pb, Cd, and Cu

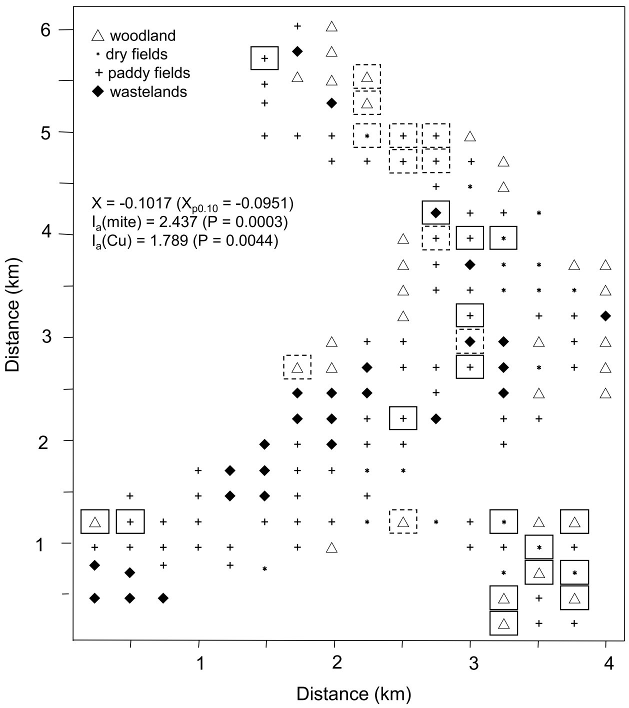


Fig. 6 Local association map of the distributions between mite species number and Cu concentration at the study sites. Solid line frame: negatively significant association (desired 90% critical interval). Dash line frame: positively significant association (desired 90% critical interval)

(Fig. 8b). In the paddy fields and wastelands, the mite properties were still generally negatively correlated with the four metals, but the correlations were not significant. The contributions made by Cd in the paddy fields and Pb in the wastelands were very small, and the explanatory variables and relative contributions of the metals to the mite properties on the first axis followed the descending order: Zn, Cu, Pb, and Cd in the paddy fields, and Zn, Cu, Cd, and Pb in the wastelands (Fig. 8c, d).

Correlations between each of mite community properties and all the environmental factors combined

The eigenvalues for axis 1 in the RDA analysis were statistically significant for species richness (ProSpec), individual abundance (ProIndi), and diversity index (ProDive) for the order Prostigmata, were significant for species richness (AcarSpec) and individual abundance (AcarIndi) for the Acari, and were significant for species richness (OribSpec) and individual abundance (OribIndi) for the Oribatida in the woodlands. Species richness (ASpec), individual abundance (AIndi), and diversity index (ADive) were significant for the Astigmata in the paddy fields (Table 9).

Table 7 Eigenvalues of explanatory variables (Expl var) and axis1 and axis2 of the RDA relationship analysis. *F*-values of the Monte Carlo Replacement test (number of permutations = 499) on axis 1 and all axes for correlations between the mite properties (AcarSpec, AcarIndi, AcarDive, MesoSpec, MesoIndi, MesoDive, ProSpec, ProIndi, ProDive, ASpec, AIndi, ADive, OribSpec, OribIndi, and OribDive$^{1)}$) and environmental factors (Cu, Zn, Pb, and Cd, and soil pH and SOM) for all the study sites on all land use types combined and for each of the land use types

Study sites	Eigenvalues (%)			*F*	
	Expl. var	Axis 1	Axis 2	Axis 1	All axis
All land uses	8.2	8.1	0.06	11.8	2.0
Woodlands	48.9	48.4	0.07	25.4*	4.3*
Dry fields	28.9	26.9	1.4	3.3	0.6
Paddy fields	6.9	5.6	0.7	3.4	0.7
Wastelands	12.8	11.0	1.4	2.4	0.5

*$P < 0.05$

$^{1)}$*AcarSpec* Acari species richness, *AcarIndi* Acari individual abundance, *AcarDive* Acari diversity index, *MesoSpec* Mesostigmata species richness, *MesoIndi* Mesostigmata individual abundance, *MesoDive* Mesostigmata diversity index, *ProSpec* Prostigmata species richness, *ProIndi* Prostigmata individual abundance, *ProDive* Prostigmata diversity index, *ASpec* Astigmata species richness, *AIndi* Astigmata individual abundance, *ADive* Astigmata diversity index, *OribSpec* Oribatida species richness, *OribIndi* Oribatida individual abundance, *OribDive* Oribatida diversity index

Correlations between each mite community property and each environmental factor

In the woodlands, Zn, Pb, and Cd were the main contributory environmental factors to ProSpec, and these contributions were significant according to the permutation test; i.e., the mite properties' ProSpec results were statistically related to Zn, Pb, and Cd (Online Resource 2, Fig. 8a). Similarly, ProIndi was related to all four metals, but ProDive was only related to Zn. The Acari results were very similar to those for the Oribatida, with AcarSpec significantly related to Cu and OribSpec related to Cu and Zn. Both AcarIndi and OribIndi were related to Cu and Zn, and ASpec and AIndi were statistically related to Cd and Cu, respectively. In the paddy fields, the mite properties AcarSpec and AcarIndi were statistically related to Cu and ADive was related to Cd. Mesostigmata species richness (MesoSpec) and individual abundance (MesoIndi) were related to Zn, and ProSpec was related to Pb (Fig. 8c). In the dry fields and wastelands, the eigenvalues for axis 1 in the RDA analysis were not statistically significant in respect to any mite properties, but some mite properties, such as the AcarIndi and diversity index for the Mesostigmata (MesoDive) were related to Pb and Cd in the dry fields (Fig. 8b). AcarSpec, ProSpec, and OribSpec were

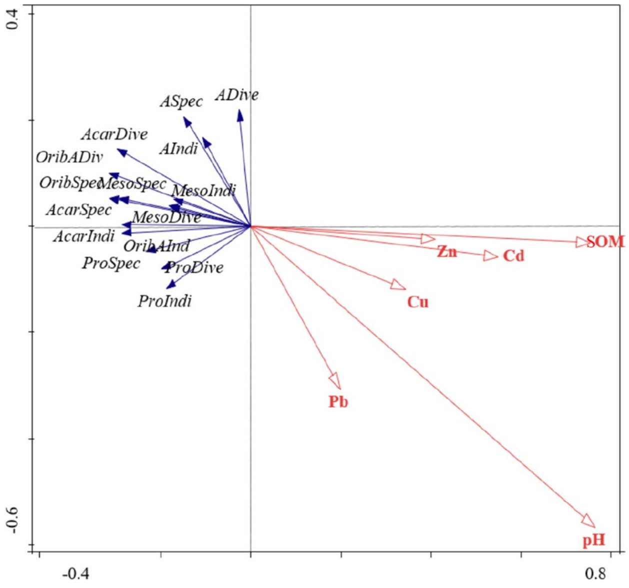


Fig. 7 Canonical correspondence analysis bi-plot for correlations between mite properties (AcarSpec, AcarIndi, AcarDive, MesoSpec, MesoIndi, MesoDive, ProSpec, ProIndi, ProDive, ASpec, AIndi, ADive, OribSpec, OribIndi, OribDive[1]) and environmental factors (Cu, Zn, Pb, and Cd in soils, soil pH and SOM) for all study sites (all land use types combined). [1]AcarSpec, Acari species richness; AcarIndi, Acari individual abundance; AcarDive, Acari diversity index; MesoSpec, Mesostigmata species richness; MesoIndi, Mesostigmata individual abundance; MesoDive, Mesostigmata diversity index; ProSpec, Prostigmata species richness; ProIndi, Prostigmata individual abundance; ProDive, Prostigmata diversity index; ASpec, Astigmata species richness; AIndi, Astigmata individual abundance; ADive, Astigmata diversity index; OribSpec, Oribatida species richness; OribIndi, Oribatida individual abundance; OribDive, Oribatida diversity index

related to Zn, Cd, and Zn, respectively, in the wastelands (Fig. 8d).

Correlations between mite community properties, pH, and SOM

Soil pH values were generally negatively correlated with the mite community properties, but the SOM values were not always correlated. Only the pH contribution was statistically significant irrespective of land use type (Table 8; Fig. 7). The soil pH contribution to the relationships was large in the paddy fields, intermediate in the wastelands and dry fields, and very small in the woodlands, while the SOM contribution to the relationships was large in the woodlands, small in the wastelands, and very small in the dry and paddy fields. The SOM values were positively correlated with mite properties in the woodlands (Fig. 8a), but negatively correlated with them in the wastelands (Fig. 8d). Due to the very small contribution of SOM in the dry and paddy fields, the correlation between the SOM and the mite community properties in the two land use types was very small (Fig. 8b, c). Only ASpec, AIndi, ADive, the diversity index for Acari (AcarDive), and OribSpec mite properties were related to pH in the paddy fields. SOM were also statistically related to mite properties. These were AcarSpec, AcarDive, ProSpec, ASpec, ADive, and OribSpec in the woodlands, MesoSpec, MesoIndi, MesoDive, AcarDive, and OribDive in the dry fields, ASpec, AIndi, ADive, and OribDive in the paddy fields, and AcarSpec in the wastelands (Online Resource 2).

Discussion

Soil metal pollution

Large-scale copper smelting activities in the study area were conducted for about 11 years and they involved many irregularly distributed groups of smelters. This led to pollution with multiple potentially toxic metals. The soil concentrations of metals determined at 141 study sites were highly variable and irregularly distributed. This is probably mainly because the smelters were irregularly distributed and there are different land use types, as well as other environmental factors such as wind direction, vegetation coverage, and soil properties (Migliorini et al. 2005; Manu et al. 2019). The smelters were generally distributed along the midline from north to south and the concentrations of the metals in the soils appeared to coincide with the distribution of the smelters, that is, generally higher along the midline and gradually decreasing from the line to the edges of the area. The soil heavy metal concentration results for the four concentration groups and for the four land use types greatly exceeded the background values and the reference values taken from the Chinese Soil Quality Standard. The concentrations of the four metals (Cu, Zn, Pb, and Cd) were up to 46 times the background values for Cu, 67 times for Zn, 32 times for Pb, and 178 times for Cd. In addition, the concentrations across 76–98% of the study area exceeded the reference values in the Chinese Soil Quality Standard. These results were comparable for Zn and Pb, and higher for Cu than those obtained in a mining area in the Metalifer Mountains, which is part of the Southern Apuseni Mountains in the Western Carpathians of Romania, where soil pollution is due to heavy metal deposits from residual material after processing the ore (Manu et al. 2019). These results were much higher than those obtained in grasslands, situated in the Zlatna Depression within the Trascău Mountains, Transylvania, Romania, where soil pollution is due to the atmospheric heavy metal deposits from industrial activity in an old mining area (Manu et al. 2017, 2019). The background values for the metals across the entire local province (including the study area) have been documented by Rong et al. (1992)

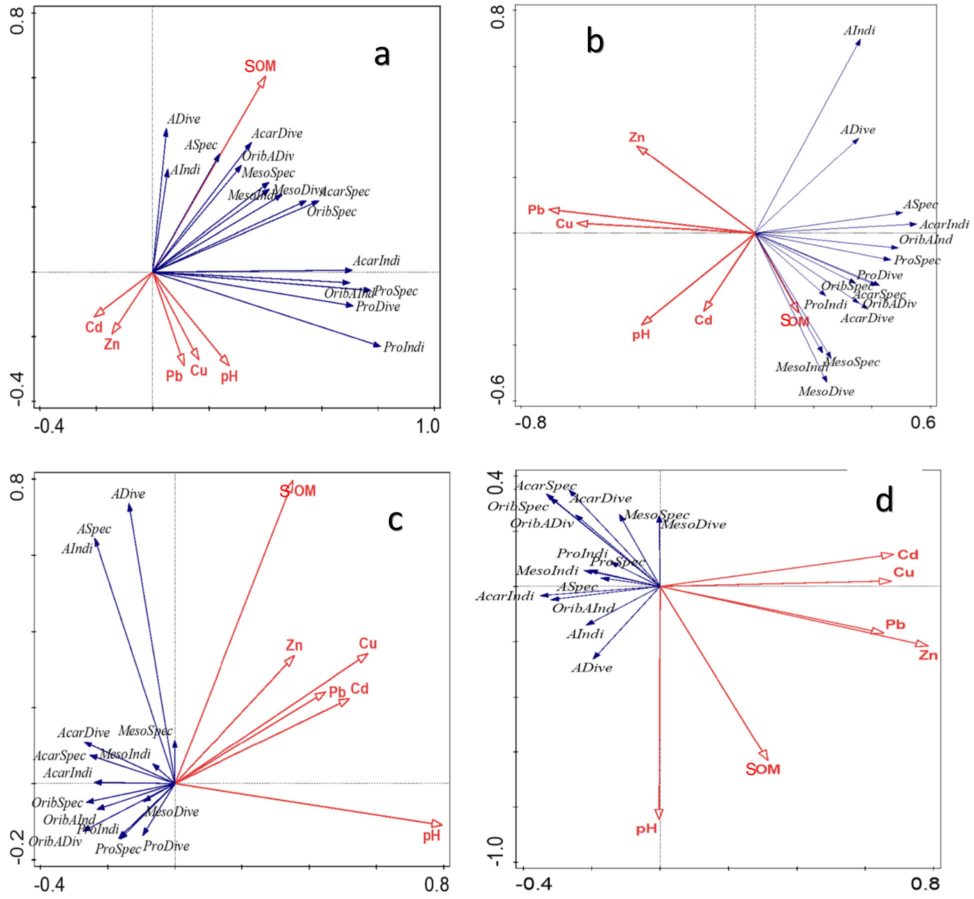


Fig. 8 Canonical correspondence analysis bi-plot of the correlations between mite properties (AcarSpec, AcarIndi, AcarDive, MesoSpec, MesoIndi, MesoDive, ProSpec, ProIndi, ProDive, ASpec, AIndi, ADive, OribSpec, OribIndi, OribDive) and the environmental factors (Cu, Zn, Pb, and Cd, and pH and SOM) for each land use type: woodlands (**a**), dry fields (**b**), paddy fields (**c**), and wastelands (**d**)

Table 8 Explanation (Expl), relative contribution (Cont), and *F*-values of the Monte Carlo Replacement test (number of permutations = 499) of the RDA relation analysis for correlations between each of the environmental factors (Cu, Zn, Pb, and Cd, and pH and SOM) and mite properties (AcarSpec, AcarIndi, AcarDive, MesoSpec, MesoIndi, MesoDive, ProSpec, ProIndi, ProDive, ASpec, AIndi, ADive, OribSpec, OribIndi, OribDive) for all land use types combined and each of the land use types

Factors	All land uses			Woodlands			Dry fields			Paddy fields			Wastelands		
	Expl (%)	Cont (%)	*F*	Expl (%)	Cont (%)	*F*	Expl (%)	Cont (%)	*F*	Expl (%)	Cont (%)	*F*	Expl (%)	Cont (%)	*F*
Cu	< 0.1	0.1	< 0.1	20.7	42.2	9.4*	0.2	0.6	< 0.1	0.8	12.1	0.5	1.1	8.5	0.2
Zn	0.7	9.1	1.1	11.9	24.4	6.4*	13.4	46.5	2.2*	1.4	20.1	0.9	6.9	54	1.8
Pb	1.3	15.4	1.9	2.5	5.1	1.4	9	31	1.5	0.4	5.5	0.2	0.1	0.9	< 0.1
Cd	0.2	3	0.4	5.8	11.8	2.1	3	10.3	0.5	0.1	1.8	< 0.1	1	8.1	0.2
pH	4.7	58	6.9**	0.2	0.3	< 0.1	2.9	9.9	0.4	3.6	51.9	2.4	2.1	16.2	0.5
SOM	1.2	14.5	1.7	8	16.2	2.8	0.5	1.6	< 0.1	0.6	8.6	0.4	1.6	12.3	0.4

$^*P < 0.05$, $^{**}P < 0.01$

and were adopted as the background values in the present study. The results from this study indicated that the Cu smelting activities resulted in multiple metal pollution of the soils at very high concentrations. Many fields near the smelters had a slightly dark colored soil surface and did not support crop growth. These fields were allocated to the wastelands land use category and the soil concentrations of the metals were 2–5 times higher than those for the other three land use types. The wasteland study sites may have originally been dry fields, and there were no study sites in the dry field category where the soil Cu concentrations reached the level of the highest concentration group; i.e., there was no C4 concentration group in the dry fields. The soil Cu, Zn, and Pb concentrations were generally dependent on land use type. In the woodlands and the wastelands, the concentrations of the metals in

Table 9 Eigenvalues for axis 1 (Axis1) of the RDA relation analysis and *F*-values of the Monte Carlo Replacement test (number of permutations = 499) on axis 1 for correlations between each of the mite properties (AcarSpec, AcarIndi, AcarDive, MesoSpec, MesoIndi, MesoDive, ProSpec, ProIndi, ProDive, ASpec, AIndi, ADive, OribSpec, OribIndi, OribDive) and the environmental factors (Cu, Zn, Pb, and Cd, and pH and SOM) for the four land use types

Mites	Woodlands		Dry fields		Paddy fields		Wastelands	
	Axis1 (%)	*F*	Axis1 (%)	*F*	Axis1 (%)	*F*	Axis1 (%)	*F*
AcarSpec	40.0	17.7*	25.6	3.3	7.1	4.4	23.3	5.5
AcarIndi	50.0	27.2*	30.8	4	5.8	3.6	12.5	2.7
AcarDive	32.1	12.8	53.3	10.3	8.9	5.6	20.5	4.9
MesoSpec	25.3	9.1	41.1	6.3	13.3	8.9	22.2	5.4
MesoIndi	27.6	10.3	52	9.7	8.9	5.7	12.8	2.8
MesoDive	24.8	8.9	48.4	8.4	4.7	2.9	19.2	4.5
ProSpec	68.8	59.6*	32	4.2	8.9	5.6	22	5.4
ProIndi	73.8	76.1*	25.9	3.1	8.4	5.3	12.5	2.7
ProDive	61	42.2*	22.8	2.7	5.2	3.2	–	–
Aspec	29.6	11.3	30.9	4	53.8	67.6*	7.3	1.5
Aindi	23.9	8.5	62.2	14.8	54.8	67.7*	7.4	1.5
Adive	22.2	7.7	27.5	43.4	70.4	13.8*	11.2	2.4
OribSpec	34.9	14.4*	24.1	2.9	7.4	4.7	21.5	5.2
OribIndi	49.0	26.0*	24.8	3	5.9	3.6	8.5	2.2
OribDive	24.5	8.8	42.3	6.6	9.9	6.3	14.1	3.1

$^*P < 0.05$

"–" denotes no data

the highest concentration group (C4) were much higher than in the other three concentration groups (C1, C2, and C3), but these high concentrations did not occur or were less pronounced in the dry or paddy fields, suggesting that different land use types influenced the distribution of soil metal concentrations. However, the Cd concentrations were not significantly different among the four land uses and there was also no interaction effect between land use type and the metal concentration group, suggesting that Cd concentrations or pollution may not depend on land use.

Assessment of soil metal pollution

Assessment of the single and integrated pollution indices

The EP, PI, and Igeo indices assessment of the metals suggested that the indices were generally consistent each other and consistent with the concentrations of the metals in the soils. The indices can recognize that Cd pollution was the highest among the four metals because the indices are calculated according to the background data or by reference to soil quality standards (Chen et al. 2015; Islam et al. 2015a, b; Wu et al. 2015; Kowalska et al. 2016). The indices indicated that the pollution levels caused by each of the four metals were all highest in the wastelands, probably because the metal concentrations were highest in the wastelands where there was little plant growth. The pollution levels caused by the four individual metals were all lowest in the paddy fields, possibly because wet paddy field systems may contain more very fine particles and more clay and organic matter that can bind metals. The EP index can recognize whether a metal pollution type comes from anthropogenic or crusted sources. The Mn in soil was used in this study as the reference element for the EP calculation because its content does not generally change (Chen et al. 2015; Kowalska et al. 2016; Mazurek et al. 2017). In general, low EP enrichment values indicate a large contribution from crusted sources to the soil, while high EP values indicate a significant contribution from anthropogenic sources (Islam et. al 2015 a, b; Rashed 2016). In this study, the Cu, Zn, Pb, and Cd EP values for all the concentration groups under the four land use types were over the lowest index grade level, indicating that almost all the pollution in the study area came from the anthropogenic sources, i.e., metal smelting activities.

The values produced by three integrated indices: C_d, PLI, and $PI_{Nemerow}$, for the four heavy metals combined were all able to assess whether a certain area, such as study sites in different concentration groups, with different land uses, or the whole area of the present study, were contaminated. In the present study, the C_d index and the $PI_{Nemerow}$ values for concentration groups C2, C3, and C4 for all the land uses were basically at the highest contamination grades of the two indices. The PLI index has only two contamination grades (the perfection and contamination grades) and all the concentration groups for all land uses were over the contamination grade. These results suggested that the three indices recognized whether or not sites in an area were polluted and could assess the degree of pollution at lower concentrations, such as between C1 and C2 in the present study.

Assessment using the ecological risk indices

The ecological risk levels assessed by the single ecological risk factor E_r^i did not quite coincide with the pollution levels assessed by the EP or PI single pollution indices. All the Cu, Zn, and Pb pollution levels in contamination groups C4 or C3 for all land use types except the paddy fields were classified into the highest grades when assessed by the EP or PI methods, while only the Cu ecological risk level in the C4 group in wastelands was classified as being in the highest grade range according to the E_r^i value. For Cd, the pollution levels assessed by the EP or PI indices were similar to the ecological risk levels assessed by the E_r^i factor. The pollution levels assessed by the single pollution Igeo index were similar to the ecological risk levels assessed by the E_r^i factor for Cu, Zn, and Pb, but this was not the case for Cd.

The ecological risk levels assessed by the integrated ecological risk index RI were similar to the pollution levels assessed by the C_d or PI_{Nemerow} integrated pollution indices, although the RI index was more suitable for slightly higher concentration pollution areas than the C_d or the PI_{Nemerow} indices. The pollution levels of the metals in the concentration groups C2, C3, and C4 for all land uses were generally at the highest grades assessed by the C_d or the PI_{Nemerow} indices. Similarly, the ecological risk levels of the metals assessed by the RI index were also at the highest grade for C3 and C4 across all the land use types.

Soil mite community response to metal pollution

General mite community composition in the study area

In the present study, a total of 132 species of mites were identified, of which 44 were identified to the species name, 77 to genera, and 11 to families. Of the 77 species identified to genera, 65 belonged to 65 different genera; i.e., each of the 65 genera had only one species. For the remaining 12 species, four belonged to the four respective genera of Oribatida: *Brachioppiella*, *Oppiella*, *Perxylobates*, and *Lamellobates*, each of which contained two species and one of them was an identified species. Two species belonged to a genus of Prostigmata, *Eustigmaeus*, in which only these two species existed. Three species belonged to two genera of Oribatida, *Allonothrus*, and *Suctobelbella*, each of which consisted of three species; *Allonothrus* contained two of these species and one other identified species, and *Suctobelbella* contained one of these species and two other identified species. The last three of the 12 species belonged to a genus of Mesostigmata, *Amblyseius*, which contained four species, three of these species and one other identified species. Similarly, for the 11 species identified to the family level, all 11 species respectively belonged to 11 different families. The species above that had not been identified to the species name could be distinguished as distinct species by their distinct characteristics and then used in the community analysis (Holmstrup et al. 2007; Wahl et al. 2012).

The numbers of species of soil mites in the study area were comparable to those obtained in forest soils from the Tianmu mountains in the same province (Zhejiang Province) (total 104 genera, 112 species) (Yin 1992). However, the numbers of species were much higher than those obtained from organic chemical (PAH) disturbed vegetable field soils in Jiangsu Province, eastern China (total 54 species, i.e., 27 Oribatida species with 3500–9292 individuals, 14 Mesostigmata species with 1208–2042 individuals, 11 Prostigmata species with 250–625 individuals, and two Astigmata species with 250–2542 individuals m^{-2}) (Liu et al. 2013). In contrast, the individual abundances were comparable to vegetable field soils. The numbers of species were also higher than those obtained from soils from grazing prairies in Hebei Province, Northern China (total 46 species, i.e., 25 Oribatida species with 2720–2850 individuals, eight Mesostigmata species with 975–1560 individuals, six Prostigmata species with 200–340 individuals, and seven Astigmata species with 220–300 individuals m^{-2}), but the individual abundances were comparable with Hebei Province (Liu et al. 2016). Finally, the numbers of species were also higher than those obtained in soils from urban weed green belts in Shanghai city, close to Zhejiang Province (total 46 species, i.e., 26 Oribatida species with 991–11,536 individuals, eight Mesostigmata species with 71–1486 individuals, and two Astigmata species 0–920 individuals m^{-2}), whereas the number of individuals was similar (Liu et al. 2007).

Impact of metal pollution and the effect of land use type on mite community properties

The community property values for the Acari and the four orders gradually deceased as the concentration groups increased, and this decrease was more pronounced for the Acari as a whole, and the orders Oribatida and Astigmata. This suggested that soil mite communities can be affected by metal pollution and that their community property values gradually decrease as the pollution concentration increases. Other studies have also shown that soil mites significantly decreased as the concentration of heavy metals increased (Seniczak et al. 2002; Skubala and Kafel 2004; Ivan and Vasiliu. 2009; Santamaria et al. 2012; Skubala and Zaleski 2012; Wahl et al. 2012). However, there were differences between the present study and previous studies, and this probably because of the very high concentrations of the heavy metals in this study. It seems that the community properties of the Acari and order Oribatida are more sensitive to both land use differences and the metal concentrations than the other three orders. Because the Oribatida accounted for the major proportion of Acari (over 66% of species richness and 78% of individual abundance), the community properties of Acari and Oribatida are similar in sensitivity and the Oribatida can be considered as the most sensitive group to land use type and metal concentration. Order Prostigmata also seemed to be sensitive to the different land uses but not to metal concentration, while the Astigmata seemed to be sensitive to metal concentration but not to land use type. However, there were fewer Astigmata species and not many individuals. For Mesostigmata, the species richness and the individual abundance numbers among the land use types and the metal concentrations were not statistically different, which was not consistent with the results of many other studies in which Mesostigmata was more or most sensitive to environmental or pollution impacts. This is thought to be because Mesostigmata species are predators that are generally sensitive to environmental changes (Liu et al. 2013; Manu et al. 2019). Therefore, mite species richness and individual abundance are strongly reduced in very serious pollution areas, such as the present study area. This is especially true for the orders containing more species that are sensitive to metal pollutants, resulting in low species richness and individual abundances for these species. Therefore, when investigating metal pollution of soil, mites from all four orders need to be assessed and studies on seriously polluted areas must include the rare species.

All the community property values were generally higher in the woodlands and dry fields than in the paddy fields and wastelands. The lowest values were recorded in paddy fields, suggesting that soil mite communities are affected by land use type. A possible reason why the paddy field system reduced all the mite community properties was because it was a water farming system and anoxic habitats occurred where non-aquatic and aerobic organisms such as mites found it difficult to survive. In the wastelands, all the community property values were lower than those in the woodlands and dry fields, probably because the wastelands consisted of fields that were originally dry fields and occasionally woodlands, but with much higher metal concentrations than the dry fields and woodlands. The high metal concentrations prevented crop growth in the wastelands and destroyed the habitat and nutrient conditions that the mites rely on. Metal pollution may cause mite communities to decrease faster in the land use types that are more advantageous to mite habitats and contain more sensitive species and individuals, such as in the woodlands and dry fields, than in the land use types that are less favorable to mites, such as the paddy fields and wastelands. These results may be inconsistent with the suggestions that the influence of soil properties on survival is modulated by toxicodynamics rather than toxicokinetics. Furthermore, restoring habitat quality may be more important for soil invertebrate protection than metal concentration at contaminated sites (Jegede et al. 2019). In addition, the quality and amount of leaf litter from standing crops may differentially affect terrestrial fauna in the ecosystems found on different land use types (Wallace et al. 1999). Early studies also showed that Oribatid mite spatial patterns, such as assemblages, and latitudinal and longitudinal gradients, may be affected by other factors, such as other soil environmental factors or organisms that may also be indirectly influenced by metals (Caruso et al. 2009).

Distribution association between mites and metal pollutants

The numbers of mite species and individuals appeared to be lower along the midline and gradually increased from the line to the edges of the area, which was opposite to the metal concentration trend. The local spatial distribution analysis by SADIE showed that there were more negative correlations between the distribution of soil mites and soil metal concentration than positive correlations, and that these correlations depended on soil properties or environmental factors. A study of the responses of oribatid communities along a gradient of heavy metal pollution in forests showed that small concentrations of heavy metals were positively correlated with the development of saprophagous oribatid mite communities (Skubala and Kafel 2004). The stimulation of a low concentration of heavy metals on the rate of reproduction was recognized and was called hormesis (Denneman and Van Straalen 1991; Skubala and Kafel 2004). Denneman and Van Straalen (1991) reported that both copper and lead stimulated reproduction in the low concentration range (Skubala and Kafel 2004). The finding in the present study of a positive association between the mite species number and Cu concentration might also be due to the stimulatory effect of the metals on mites, which was reflected in the distribution analysis. The results also suggested that a higher percentage or a stronger negative association between the mite and metal distributions may lead to more favorable mite habitats, such as in woodlands or dry fields, where the more favorable soil properties or environmental factors may attract more sensitive mite species compared to less favorable areas, such as paddy fields or wastelands.

Correlations between mite community properties and metal concentrations

Correlations between all the mite community properties and all the metals

The correlation analysis between all the mite community properties as a whole unit and all the environmental factors as a whole unit showed that the community properties were generally negatively correlated to the metal concentrations and that this was statistically significant for woodlands but not for the other land uses. This was probably because woodlands are a natural ecosystem where mite community diversity is greater, although the woodland ecosystems were damaged due to poor tree growth, sparse trees, and weeds being generally scarce due to the heavy metal pollution (Skubala and Kafel 2004). Among the other three land use types, the dry field and wasteland community properties were more correlated with the metals than the paddy fields because the dry fields and the wastelands are dry lands where soil mites normally live, whereas the paddy fields are water cultivation systems where soil mites find it difficult to live (see above) (Skubala and Kafel 2004; Yao et al. 2006; Navarrete and Tsutsuki 2008). However, the waste land community properties were less correlated to the metals than the dry field properties, probably because the metal pollution concentrations in the wastelands were higher than those in the dry land, which caused a decline in the populations of the more sensitive species in the wastelands (Skubala and Kafel 2004; Salminen et al. 2001).

Correlations between all mite community properties and each of the metals

The relationship analysis between all the community properties as a whole unit and each of the environmental factors showed that the community properties were significantly negatively correlated to Cu and Zn in woodlands and to Zn in the dry fields, although the community properties were generally negatively correlated to all four metals across all land use types. These results suggested that mite communities responded differently to the four metals with a greater response to Cu and Zn than Cd and Pb. These responses also depended on land use because there was a more pronounced response in the woodlands and dry fields than in paddy fields and wastelands. Other studies have also found that Oribatid species diversity differentially responded to Zn, Cd, and Cu concentrations (Jamshidian et al. 2015; Skubala et al. 2016). The responses of the mite community to metal pollution did not appear to coincide with the toxicity of the metals to mite species in the laboratory. In the present study, CANOCO analysis showed that the response of the mite communities to the four metals varied, with greater response to Cu and Zn, when compared with that to Cd and Pb. However, laboratory tests with the oribatid mite *Oppia nitens* revealed that Cd had higher toxicity than Cu and Zn, while Cu and Zn had higher toxicity than Pb (Owojori and Siciliano 2012). The reason for this observation may be the difference in the metal sensitivity of the mite community comprising diverse species in field, which is influenced by fluctuations in environmental factors, whereas only the population of one species was examined under controlled laboratory conditions. Scott-Fordsmand et al. (2000) also indicated that the field effects are much lower because bioavailability largely depends on aging and sorption processes. Moreover, the response may not completely depend on the specific metal toxicity to mites, but on the correlation degree between mites and metal concentration, i.e., low toxicity of metals to mites could have high correlation degree between them, and vice versa. The highly toxic metals could essentially reduce the soil mite abundance, leaving only some tolerant individuals in the high metal concentration ranges. This could result in low variation in the mite population with the changes in the metal concentration; i.e., the response of the mites to highly toxic metals might be low in high metal concentration ranges. However, in low metal concentration ranges, numerous mites, including the sensitive individuals, could survive because the low metal concentration exerted lower toxicity to mites. Nevertheless, as some metals are highly toxic, even lower metal concentrations could still be toxic to mites, resulting in greater variation in mite population with the changes in metal concentration; in other words, the response of mites to highly toxic metals in low concentration ranges might be higher. In contrast, low toxic metals could not essentially reduce the mite abundance, with quite a few individual mites, including the sensitive ones, surviving in high metal concentration ranges, and the mites exhibiting higher variation with the changes in the high metal concentration ranges. However, in low concentration ranges, the metals might not be toxic enough to significantly reduce the mite abundance, with the mite population presenting lower or no variation with the change in metal concentration. Therefore, the response of mites to low toxic metals in high concentration ranges might be high, whereas that in low metal concentration ranges might be low. Accordingly, it can be presumed that the response of soil mites to different toxic metals might vary depending on the metal concentration ranges and type of metal in the polluted area.

Correlations between each of the mite community properties and all the metals

The correlation analysis between each of the mite community properties and all the environmental factors as a whole unit showed that the species richness and individual abundances of Acari and Oribatida, and the species richness, individual abundance, and diversity of Prostigmata in the woodlands were significantly negatively correlated to the metals, although all the community properties were only generally negatively correlated to the metals for the land use types. This suggested that Oribatida and Prostigmata species were more correlated to the metals than the other variables. The species richness, individual abundance, and diversity index for Astigmata also statistically responded to the metals in paddy fields, although there were not many individuals, more than half were hypopus, and all the Astigmata species that appeared in the present study were cosmopolitan and parasite pest mites generally found in cropping systems. The Mesostigmata species are almost all predatory, which means that they are generally sensitive to soil pollution (Manu et al. 2018, 2019), but in the present study, their community properties showed low correlations with the metals. This might be because the study area was too seriously polluted for most of the Mesostigmata species and only the metal pollution tolerant species could survive (e.g. *Hypoaspis queerlandicus*, *Asca aphidiodes*, and *Cheiroseius nepalensis*). The Oribatida species were mainly saprophytic forms that live on plant debris in soil and can find debris food in very seriously polluted soils (Skubala and Zaleski 2012; Iglesias et al. 2019). In this study, there were many Gynmonota species of the order Oribatida, such as *Scheloribates latipes*, *Scheloribates oryzea*, and *Xylobates tenuis*, which are generally ubiquitous species and can often be found in disturbed ecosystems, such as urban green belts and farmland ecosystems. These kind of species are generally dominant in polluted soils (Skubala and Kafel 2004; Khalil et al. 2009; Skubala and Zaleski 2012; Liu et al. 2013; Iglesias et al. 2019; Manu et al. 2019) and might help maintain sufficient Oribatida species richness and individual abundance numbers to allow differences between the concentration groups or between the land use types to be apparent. The community properties of some of the Prostigmata species could be sensitive to heavy metal pollution at very high concentrations in the present study area because Prostigmata contains many species that have different sensitivities including some that are tolerant to very high concentrations of metal pollutants. Other studies have also found that Prostigmata responded to heavy metal pollution (Wahl et al. 2012). The Prostigmata consists of diverse forms of species, including predatory, saprophytic, and parasitic species. In this study, the Tarsonemidae species and the *Mahunkania* sp. included pest mites that feed on plant roots, free-living species, and parasite forms that feed on microorganisms, such as alga and plants. Species of the genus *Scutacarus* are saprophytic or parasitic, *Bdella muscorum* and species of the genus *Eustigmaeus* are phytophagous, and Erythraeidae and Trombidiidae species are predatory. The diverse species in the order Prostigmata allow Prostigmata to endure serious pollution and could be used to evaluate the impacts of environmental factors.

Correlations between each of the mite community properties and each of the metals

The correlation analysis between each of the community properties and each of the environmental factors determined whether the different mite community properties had different responses to certain metals. In woodlands, species richness, individual abundance, and the diversity index for Prostigmata were statistically related to Zn, Pb, and Cd, to Cu, Zn, Pb, and Cd, and only to Zn, respectively, and Oribatida species richness and individual abundance were statistically related to Cu and Zn. In the paddy fields, Mesostigmata species richness and individual abundance were statistically related to Zn and Prostigmata species richness was statistically related to Pb. These results suggest that the different mite properties were more inclined to respond to certain metals, or that certain mite community properties were specifically related to certain metal pollutants, even if the whole mite community or the mite community properties as a whole unit may not be statistically related to the metals. This result can be help reveal the specific relationship between mite community features and heavy metal pollutants.

Effects of soil pH and SOM

Both soil pH and SOM content significantly differed among the four land use types. The pH values were lowest in the woodlands and generally neutral in the mainly arable dry fields, paddy fields, and wastelands. The average SOM content was lower in woodlands and dry fields, and higher in paddy fields and wastelands. In the woodlands, trees and grasses grew poorly with a sparse distribution, partly because the dust or ash from the smelting deposited on surface of leaves and branches, reducing the rate of photosynthesis. There was little litter fall on the soil surface. The soil appeared barren and contained large amounts of sand and stones, which could even lead to sampling difficulties when tools need to be pushed into the soil. Dry fields, wastelands, and paddy fields were the three land uses where crop cultivation occurred. The pH results were consistent with those of other studies, with the pH in secondary forest or brushland being lower than the pH in land used for growing crops or grassland previously used for crops (Navarrete and Tsutsuki 2008). The authors hypothesized a possible soil rejuvenation process through soil erosion (i.e., the direct effect of land use change). Common farm management activities, such as burning leaf litter and the application of mineral fertilizer (e.g., Ca, K, and Na) may also cause the soil pH to increase (Navarrete and Tsutsuki 2008; Wang et al. 2017). The SOM was also influenced by land use type. The soil carbon content varied depending on the type of land use change. Land use change can have either a positive or negative impact on soil and does not always result in a decline in soil fertility (Navarrete and Tsutsuki 2008). In the present study, the lack of fallen leaves and root exudates and exfoliation due to the poorly grown and sparse vegetation in the woodlands could cause the SOM content to be lower compared to common types of woodlands. For the other three types of land use, in which crops were grown, farming management practices such as the periodic addition of organic fertilizer might result in a slightly higher soil carbon content (Navarrete and Tsutsuki 2008). The SOM content was greatest in the paddy fields, which probably reflects the anoxic conditions in wet paddy soils.

The correlation analysis between the mite community properties and the environmental factors showed that the soil pH and SOM made large contributions to the environmental factor effects, but they depended on the mite community properties and land use type. This indicated that the mite communities correlated with the soil pH values and SOM. The mite community properties were basically negatively correlated with the soil pH, indicating that higher soil pH could be disadvantageous to mite communities. The pH values were generally over 5.0 in the study area. The soil pH values had a generally negative influence on the mite communities, particularly in the dry fields (pH 5.0–8.3), paddy fields (pH 4.7–8.1), and wastelands (pH 5.0–8.2), but not in woodlands (pH 4.1–7.4). This was probably because the pH values in woodlands were lower than those in the other three land use types and soil microarthropods usually live within a soil pH range of 4.0–8.0 (Ke et al. 2002, 2004a, b). The pH values also increased as the metal concentration groups rose from C1 to C4, probably because the pollution in the present study area was mainly derived from air pollution and the emitted pollutants from the refining chimney were mainly metal oxides, which would increase the soil pH values. The results suggest that higher metal concentration pollutions could be accompanied by higher soil pH values, which may have accelerated the decline seen in the mite communities. The correlations between the mite community properties and SOM content were generally weak and not as strong as the correlations with soil pH. They were also dependent on land use type. The mite communities were positively related to SOM in the woodlands but negatively related in the paddy fields and wastelands. However, these relationships were not statistically significant.

Conclusions

The present study was located in a relatively isolated arable area of ~ 11 km^2 that was enclosed by surrounding mountains. It contained different land use types and was contaminated with Cu, Zn, Pb, and Cd derived from Cu smelting that was practiced for over 10 years. Therefore, the study area was an ideal place for ecological studies on the relationships between soil mites and metal pollutants.

Zinc, Pb, and Cd, are byproducts of Cu smelting and are soil pollutants. Furthermore, their metal concentrations are highly correlated with each other. The Cu smelting activities has caused severe pollution in the study area with concentrations reaching up to 31.0–275.0 times the background values for the four metals. A total of 98.5% and 34.6% of all the study sites exceeded the lowest and the highest pollution grades of the Chinese Soil Quality Standard, respectively.

The pollution and ecological risk indices could more precisely and meaningfully separate the metal pollutants into definite pollution degrees, but they had different applications depending on the level of pollution, although the indices had generally similar tendencies in the overall assessment. The combined pollution level of the four metals assessed by the pollution and ecological risk indices showed that the pollution level of Cd was higher than those of the other three metals. In general, the metal pollution levels presented the following trend depending on the land use type and different indices: Cd > Cu > Zn > Pb.

The distributions of soil mite species richness and individual abundance were generally negatively associated to the distribution of metal concentrations. The local distribution associations between mites and metals included both negative and positive associations, but the negative associations were dominant. All these associations depended on the land use type and negative associations occurred more frequently in habitats that were more favorable to soil mites. The mite community properties strongly negatively responded and correlated to the four metal pollutant concentrations and the pollution degrees assessed by the pollution and ecological risk indices, but these correlations depended on mite community properties, metal pollutants, and land use type. Generally, the mite community properties of Acari (all mites) and order Oribatida were more strongly related to Cu and Zn than to Pb and Cd, and the responses were more pronounced in the woodlands and dry fields than in paddy fields and wastelands. The mite community properties of the other three orders also strongly negatively responded to the metals, but only for certain land use types. Furthermore, only some mite properties responded to certain metals. Land use type could strongly affect mite communities and mediate the impact of metals on mites.

Community property and species diversity assessment is an important approach because it can directly, objectively, and synthetically reflect the soil situation and the impacts of pollution on soil organisms and ecosystems. The findings of this study will help to understand the interactions between microarthropods and pollutants in soil ecosystems involving many environmental factors in a highly polluted area, and will also aid in improving assessment methods and strategies for the protection and recovery of soil mites and other soil organisms.

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Data availability This manuscript consists of 41 pages in text, nine tables, eight figures, and five supplementary materials (Online Resource 1, Online Resource 2, Online Resource 3, Online Resource 4, and Online Resource 5), which were submitted through the submission system. The raw data of two files in ".CSV" format (Data S1, and Data S2) are provided as private-for-peer review via the following link: https://figshare.com/s/873bbc94e4b841bd68c8, where the data will be permanently archived if the paper is accepted for publication.

Declarations

Original work and only journal submitted The submitted work is original and has not been published elsewhere in any form or language (partially or in full), and is not under consideration by any other journal.

Single and whole work The submitted work is a single and whole research project. It has not been split into several parts to increase the quantity of submissions.

Presentation of results The results in the manuscript are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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