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RELATIONSHIPS BETWEEN SOIL PROPERTIES AND TOXICITY OF COPPER AND NICKEL TO BOK CHOY AND TOMATO IN CHINESE SOILS

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Abstract: The toxicity of copper (Cu) and nickel (Ni) to bok choy and tomato shoot growth was investigated in a wide range of Chinese soils with and without leaching with artificial rainwater. The results showed that the variations of Ni toxicity induced by soil properties were wider than those of Cu toxicity to both tomato and bok choy plant growth. Leaching generally decreased the toxicity of Cu and Ni added to soils, which also depended on soils, metals, and test plant species. Soil factors controlling metal phytotoxicity were found to be soil pH and soil organic carbon content for Cu, and soil pH for Ni. It was also found that soil pH had stronger effects on Ni toxicity than on Cu toxicity. Predictive toxicity models based on these soil factors were developed. These toxicity models for Cu and Ni toxicity to tomato plant growth were validated using an independent data set for European soils. These models could be applied to predict the Cu and Ni phytotoxicity in not only Chinese soils but also European soils. *Environ Toxicol Chem* 2013;32:2372–2378. © 2013 SETAC

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INTRODUCTION

Both soil properties and biotic responses have been taken into account in the terrestrial risk assessment and derivation of ecologically based soil-quality standards for metals [1]. The use of soil-modifying factors to explain the phytotoxicity of metals across different soils is one of the key steps in improving risk assessments of metals in soils [1–4]. Several studies have addressed the effect of soil factors on Cu and Ni toxicity to plant growth [2–9]. For example, Warne et al. [4] reported the toxicity of Cu to wheat with effect concentrations causing a 50% inhibition in growth (EC50s) ranging from 240 to 6680 mg Cu/kg in 14 Australian soils, and cation exchange capacity (CEC) and soil pH were deemed to be the most important soil factors for predicting Cu phytotoxicity across soils. In their studies of the EC50s of Cu and Ni for tomato shoot growth in a wide range of European soils Rooney et al. [2,3] found approximately 39-fold and 54-fold variations, respectively, and effective CEC (eCEC; measured at actual soil pH) was found to be the best single predictor for toxicity of Cu and Ni to tomato shoot growth. In these studies, the predictive phytotoxicity models were developed for European and Australian soils [2–4]. It is unknown, however, whether these phytotoxicity models can be applied to a wide range of soils from other regions, such as arid or subtropical and tropical regions in China. It is therefore necessary to validate phytotoxicity models of Cu and Ni in soils and to extend them across a wider range of soil environments.

The existence of differences in sensitivity to toxicity of metals in soils between plant species is well known [10]. Recently, Li [11] compared 8 Chinese plant species in 2 representative Chinese soils (red earth and fluvo-aquic soil) and found that bok choy was the most sensitive species to the Cu and Ni. Bok choy is an important agricultural food crop in Asia, and it is important to ensure that soil normalization models to predict metal toxicity across soils are applicable to relevant, sensitive crop species. Tomato shoot growth has been used as an ecotoxicological endpoint of Cu and Ni in European soils [2,3]. To compare toxicity thresholds in Chinese soils with those in European soils, plant shoot growth of tomato as well as that of bok choy, as a sensitive crop species, was used as a phytotoxicity endpoint to study the relationship between soil properties and phytotoxicity of Cu or Ni in a range of soils representing major soil types in China. The aims of the present study were to develop quantitative relationships between soil physicochemical properties and Cu or Ni phytotoxicity thresholds for tomato and bok choy shoot growth in a wide range of soils representing major soil types in China and to validate the phytotoxicity models for tomato shoot growth using an independent data set from European temperate soils.

MATERIALS AND METHODS

Soil samples and treatments

For the present study, 17 soil samples (S1–S17) from multiple locations in China were used. The soil properties and treatments have been described by Li et al. [12,13]. The ranges of soil properties were as follows: pH 4.93 to 8.90; organic carbon content (OC) 0.60% to 4.28%; eCEC 6.36 cmol^+/kg to 33.59 cmol^+/kg; and clay content 10% to 66%. Air-dried soil samples (<2 mm) were spiked with Cu (as $CuCl_2$) or Ni (as $NiCl_2$) at 8 dose rates (control plus 7 doses: 12.5–800 mg/kg for soils with $pH < 5$, 25–1600 mg/kg for soils with pH 5–7, and 37.5–2400 mg/kg for soils with $pH > 7$). The spiked soils were left to equilibrate for 2 d at 100% maximum water-holding capacity, then air-dried and sieved again through a 2-mm plastic mesh. Subsamples of spiked soils were leached with artificial rainwater consisting of 5×10^{-4} M calcium chloride, 5×10^{-4} M calcium nitrate, 5×10^{-4} M magnesium chloride, 10^{-4} M

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sodium sulfate, and 10^{-4} M potassium chloride at pH 5.9, according to Oorts et al. [14]. Leached soil samples were also air-dried and sieved through a 2-mm plastic mesh before use. Total Cu and Ni concentrations were then measured in both leached and unleached soils by atomic absorption spectroscopy (ZEEnit 700; Analytik Jena AG) according to Zarcinas et al. [15]. The unleached and leached soils were incubated and equilibrated for 1 wk at 70% of field capacity at pF 1.9 (log 80 cm water suction) before commencing plant growth assays.

Plant growth assays

The tomato (*Lycopersicon esculentum* cv. Meifen No. 1) and bok choy (*Brassica rapa* var. *chinensis* cv. Susheng 28) seeds were from Beijing Jiahe Seeds. The shoot growth assays were based on International Organisation for Standardization (ISO) 11269-2 [16]. Ten undressed seeds (the seeds were not treated with seed coatings) of bok choy or tomato (pregerminated with radicles <2 mm in length) were sown in each pot (approximately 10 cm inner diameter and 12 cm height), which contained an equivalent of 700 g oven-dried soil. After emergence, the number of plant seedlings per pot was thinned to 5. The plants were grown for 21 d from the time of emergence. Pots were placed randomly on racks inside a glass house with 25 ± 3 °C daytime and 20 ± 3 °C night temperatures and a natural light photoperiod. To maintain good plant growth and prevent possible nutrient deficiencies in soils, a dilute nutrient solution was added at 3 times during the plant growth period to preserve consistent nutrient status in soils. The nutrient solution contained 3 mM NH_4NO_3, 3 mM KNO_3, and 1 mM KH_2PO_4 and was applied in doses of 50 mL per pot [2].

The soil moisture content was maintained in the range of 75% to 90% of field capacity using deionized water during the whole plant growth period. At harvest, tomato and bok choy shoots were cut just above the soil surface, washed with deionized water, then dried at 65 °C for 48 h, and the weights of dry biomass were measured. Each replicate represented the mean dry weight of 5 plants per pot. The relative plant growth was expressed as a percentage of plant dry weight to control.

Statistical analysis

The dose−response data were fitted by a log−logistic curve

$$Y = \frac{Y_0}{1 + e^{b(X-M)}}$$

where Y is relative plant growth (%); X is $\log_{10}$ of metals added (mg/kg); M is the $\log_{10}$ of the effective concentration of added metal that decreases plant growth by a user-defined percentage (ECx), such as EC50; and Y_0 and b are curve fitting parameters [17,18]. The measured added Cu or Ni concentration was used as the metal dose, which is the measured total concentration of each soil sample minus the average metal concentration of the control treatments for each soil. The values of the EC50 and the measured added Ni or Cu concentration in soils causing a 10% inhibition in plant growth (EC10), along with their 95% confidence intervals, were derived from the fitted curve parameters and standard errors according to Haanstra et al. [17]. More details for analysis of the dose−response data were described by Li et al. [12]. Significant differences between EC10 values (or EC50 values) in unleached and leached soils were determined using the Student's *t* test. The adequacies of the predicted equations were checked by examining the distribution of the residuals and minimizing the calculated root mean squared error (RMSE) based on the difference between the observed and predicted values. Single and stepwise multiple linear regression analysis was employed using SPSS 12.0 for Windows to examine the relationships between the logarithms of toxicity thresholds and soil properties [19]. Relationships were deemed significant at $p \leq 0.05$.

RESULTS

Cu and Ni toxicity thresholds for tomato

The ranges and variation of Cu toxicity thresholds for the tomato shoot growth are shown in Figure 1A. Excluding the Guangzhou soil, for which an appropriate dose−response model could not be fitted, the mean and standard deviation of Cu EC10 values were 159 ± 71 mg/kg for unleached soils and 252 ± 183 mg/kg for leached soils. Average EC50 values for Cu were 464 ± 203 mg/kg for unleached soils and 651 ± 355 mg/kg for leached soils. The variation in EC10 and EC50 values for Cu was about 5-fold to 10-fold across soils. For Ni, the average EC10 values were 222 ± 221 mg/kg for unleached soils and >415 ± 476 mg/kg for leached soils. Average EC50 values for Ni were 561 ± 551 mg/kg for unleached soils and >1037 ± 969 mg/kg for leached soils (Figure 1B). Compared with the variations of Cu toxicity thresholds, a wider variation in toxicity of Ni across soils was observed (about 100-fold to >190-fold). A dramatic decrease in Ni toxicity to tomato shoot growth was found for 6 soils with pH values ≥8.2 after leaching (S11, S12, S13, S15, S16 and S17). Therefore, EC50 values could not be calculated for these soils after leaching despite added Ni concentrations being greater than 2000 mg/kg.

Cu and Ni toxicity thresholds for bok choy

The ranges and variations of Cu toxicity thresholds for the bok choy shoot growth are shown in Figure 1C, except for soil S2 (Qiyang, Hunan, China) in which the oxalate-extractable Al was 1326 mg/kg. Bok choy did not survive in S2, likely as a result of Al toxicity, as reported by Qin and Chen [20]. Similar to tomato shoot growth, the variation of Ni toxicity thresholds for bok choy plant growth across soils was also found to be wider than those for Cu (Figure 1D). Unlike tomato plant growth, however, Ni toxicity to bok choy was still seen in the 6 soils with pH values ≥8.2 after leaching, likely because bok choy is more sensitive to metals than tomato.

In both unleached and leached soils, almost all toxicity thresholds for Cu and Ni were significantly higher for tomato shoot growth than for bok choy ($p \leq 0.05$), which confirms that bok choy is generally more sensitive to Cu and Ni than is tomato. Overall, the statistical uncertainty of EC10 values was generally larger than that of EC50 values; thus, EC50 values were used to compare toxicity across species, soils, and leaching treatments. Unlike tomato, bok choy was more sensitive to Cu than Ni; for bok choy, the averages of Cu EC50 values in unleached and leached soils were 127 ± 83 mg/kg and 126 ± 70 mg/kg—lower than those for Ni, which were 359 ± 207 mg/kg in unleached soils and 606 ± 520 mg/kg in leached soils, respectively. The EC50 values for Cu and Ni to tomato were similar.

Effect of leaching on Cu and Ni toxicity

The leaching factor was defined as the ratio of ECx in leached soil (i.e., EC10 and EC50) to ECx in unleached soil. Leaching factors estimated by Cu EC10 values for tomato ranged from 0.75 to 2.77, with an average and standard deviation of 1.54 ± 0.62; for Ni, they ranged from 0.40 to >13.4, with an average of >2.98 ± 3.85. When EC50 values for tomato were

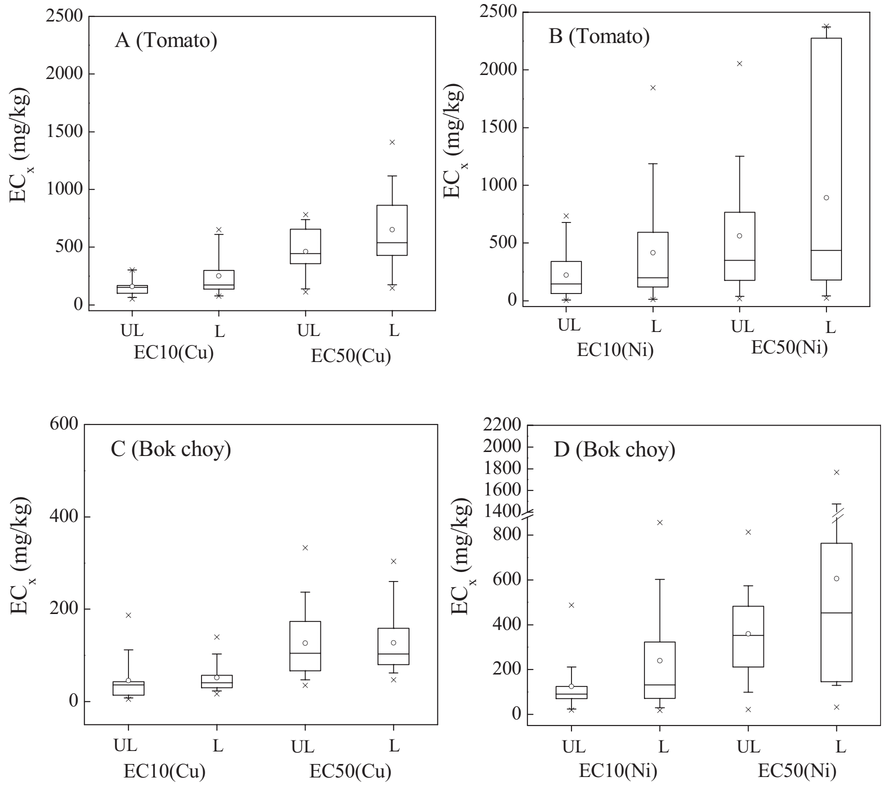

Figure 1. Ranges and variation of Cu and Ni toxicity thresholds for tomato shoot growth in Chinese soils. (**A**) Cu toxicity to tomato; (**B**) Ni toxicity to tomato; (**C**) Cu toxicity to bok choy; (**D**) for Ni toxicity to bok choy. UL = unleached soils; L = leached soils; ECx = effective concentration of added metal that decreases plant growth by a user-defined percentage; EC10 = concentration in soils causing a 10% inhibition in plant growth; EC50 = concentration in soils causing a 50% inhibition in plant growth; × = maximum and minimum; I = 10th–90th percentile; ▯ = 25th–75th percentile; — = median; ○ = average.

used to estimate leaching factors, they ranged from 1.01 to 1.80, with an average of 1.37 ± 0.22 for Cu; and for Ni they ranged from 0.73 to >3.10, with an average of >2.05 ± 1.91. A dramatic increase in Ni EC50s was observed in 6 soils with pH ≥ 8.2 (S11, S12, S13, S15, S16, and S17) after leaching (e.g., S17 soil; Figure 2A); however, for acidic and neutral soils, the leaching effect on decreasing Ni toxicity was comparatively weaker (e.g., S4 soil; Figure 2B).

For bok choy, leaching factors estimated by Cu EC10 values ranged from 0.48 to 6.00, with an average of 2.01 ± 1.54, whereas leaching factors estimated by Cu EC50 values ranged from 0.73 to 1.77, with an average of 1.13 ± 0.31. For Ni toxicity, leaching factors estimated by EC10 values ranged from 0.37 to 6.42, with an average of 2.18 ± 1.82; leaching factors estimated by EC50 values ranged from 0.53 to 3.43, with an average of 1.60 ± 0.88. Although the increases in Ni EC50 values resulting from leaching occurred mostly in calcareous soils for bok choy, leaching effects on Ni toxicity were obviously weaker for bok choy than for tomato shoot growth.

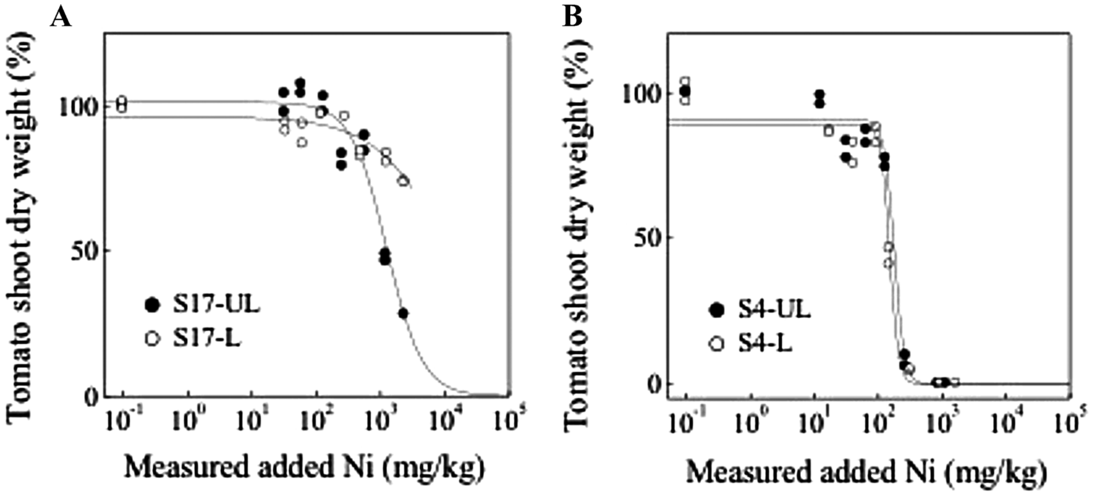

Figure 2. Examples of dose−response curves of measured added Ni concentrations for tomato shoot growth in soils with different pH: (**A**) soil S17 (Dezhou, Shangdong, China) with pH 8.9; (**B**) soil S4 (Jiaxing, Zhejiang, China) with pH 6.7. Symbols represent all replicated data points, and smooth lines were the fitted log-logistic curves. UL = unleached soils; L = leached soils.

Relationships between Cu and Ni toxicity thresholds and soil properties

Single and multiple stepwise regressions were carried out between Cu and Ni toxicity thresholds (i.e., EC10 and EC50 values; based on log-transformed data) and various soil properties. For tomato, there were poor single regression relationships between log EC50 for unleached soils and either soil pH or log OC (log EC50 = 1.715 + 0.118 pH, $r^2 = 0.37$; log EC50 = 0.368 + 2.563 log OC, $r^2 = 0.15$). With soil pH and log OC as 2 parameters in the regression equation, the model was improved significantly, explaining more than 79% of the variance in Cu toxicity in both leached and unleached soils (Equations 2 and 6 in Table 1), which suggested a strong interaction between soil pH and OC for controlling Cu toxicity across soils. For Ni toxicity to tomato, soil pH was also a very important factor, explaining 77% of the variance in toxicity across soils (unleached; Equation 8 in Table 1). Incorporating OC in the model had little effect on improving the model (Equation 9, Table 1).

For bok choy, OC was found to be the best single predictor for Cu toxicity, but it explained only 45% to 56% of the variance in toxicity across both unleached and leached soils. Soil pH could explain only 13% of the variance in EC50 values across leached soils. No other soil factor was able to improve the models. For Ni toxicity to bok choy, similarly to tomato, soil pH and OC were still the most important factors to predict Ni toxicity, and regression models based on these 2 factors could explain more than 84% of the variance in Ni EC50 values across unleached and leached soils (Equations 19 and 21, Table 1). There was no significant soil factor controlling Ni EC10 values, probably because of their high variation.

Validation of Cu and Ni phytotoxicity models

For tomato plant growth, the models developed from Chinese soils were validated by using the data set from European soils used by Rooney et al. [2,3]. Relationships for unleached soils were used (Equations 2 and 8, Table 1) to be comparable to those of Rooney et al. [2,3] (Figure 3). The results showed that Equation 2 in Table 1 for Cu toxicity could predict log (EC50) values for tomato shoot growth in 16 European soils (RMSE = 0.19; $r^2 = 0.69$; $n = 16$), except for the Houthalen soil, which has a very low pH (3.4), low eCEC (1.90 cmol^+/kg), and low clay content (5%), and the Vault de Lugny soil, to which the EC50s cannot be fit [2] (Figure 3A). For Ni toxicity, Equation 8 in Table 1 could predict Ni EC50 values for tomato shoot growth in European soils (RMSE = 0.23; $r^2 = 0.86$; $n = 14$), except for 2 high-OC soils (Rhydtalog and Zegveld, OC > 12%; Figure 3C).

DISCUSSION

It is well documented that the toxicity of soluble metal salts spiked freshly in soil is decreased by leaching treatments [13,14,21,22]. In the present study, leaching resulted in a

Table 1. Simple and multiple linear regressions between logarithm of EC50s or EC10s for tomato and bok choy and the properties of soils with and without leaching treatments[a]

Plant	Metal		Regression equation	r^2	RMSE
Tomato					
	Cu				
		Unleached soil ($n = 16$)			
		1	log EC50 = 1.715 + 0.118 pH	0.37	0.19
		2	log EC50 = 1.257 + 0.167 pH + 0.667 log OC	0.79	0.11
		Leached soil ($n = 16$)			
		3	log EC10 = 1.476 + 0.749 log eCEC	0.39	0.21
		4	log EC10 = 0.635 + 0.092 pH + 0.873 log eCEC	0.56	0.18
		5	log EC50 = 1.774 + 0.127 pH	0.34	0.22
		6	log EC50 = 1.236 + 0.185 pH + 0.783 log OC	0.81	0.12
	Ni				
		Unleached soil ($n = 17$)			
		7	log EC10 = − 0.967 + 0.398 pH	0.61	0.38
		8	log EC50 = − 0.393 + 0.383 pH	0.77	0.25
		9	log EC50 = − 0.786 + 0.425 pH + 0.571 log OC	0.83	0.22
		Leached soil ($n = 17$)			
		10	log EC10 = − 0.810 + 0.413 pH	0.71	0.33
Bok choy					
	Cu				
		Unleached soil ($n = 17$)			
		11	log EC10 = 1.319 + 1.158 log OC	0.50	0.28
		12	log EC50 = 1.913 + 0.770 log OC	0.47	0.20
		Leached soil ($n = 17$)			
		13	log EC10 = 1.554 + 0.706 log OC	0.56	0.15
		14	log EC50 = 1.972 + 0.600 log OC	0.45	0.21
		15	log EC50 = 1.419 + 0.726 log OC + 0.071 pH	0.58	0.13
	Ni				
		Unleached soil ($n = 16$)			
		16	log EC10 = 1.865 + 0.734 log OC	0.30	0.28
		17	log EC10 = 0.418 + 1.150 log OC + 0.180 pH	0.56	0.22
		18	log EC50 = 0.357 + 0.271 pH	0.64	0.16
		19	log EC50 = − 0.539 + 0.371 pH + 0.847 log OC	0.87	0.13
		Leached soil ($n = 16$)			
		20	log EC50 = − 0.173 + 0.358 pH	0.76	0.22
		21	log EC50 = − 0.815 + 0.430 pH + 0.607 log OC	0.84	0.18

[a] All independent variables in equations are significant at $p \leq 0.05$.

eEC50 = toxicity effect concentrations causing a 50% inhibition in growth; EC10 = toxicity effect concentrations causing a 10% inhibition in growth; eCEC = effective cation exchangeable capacity; OC = organic carbon content; RMSE = root mean squared error.

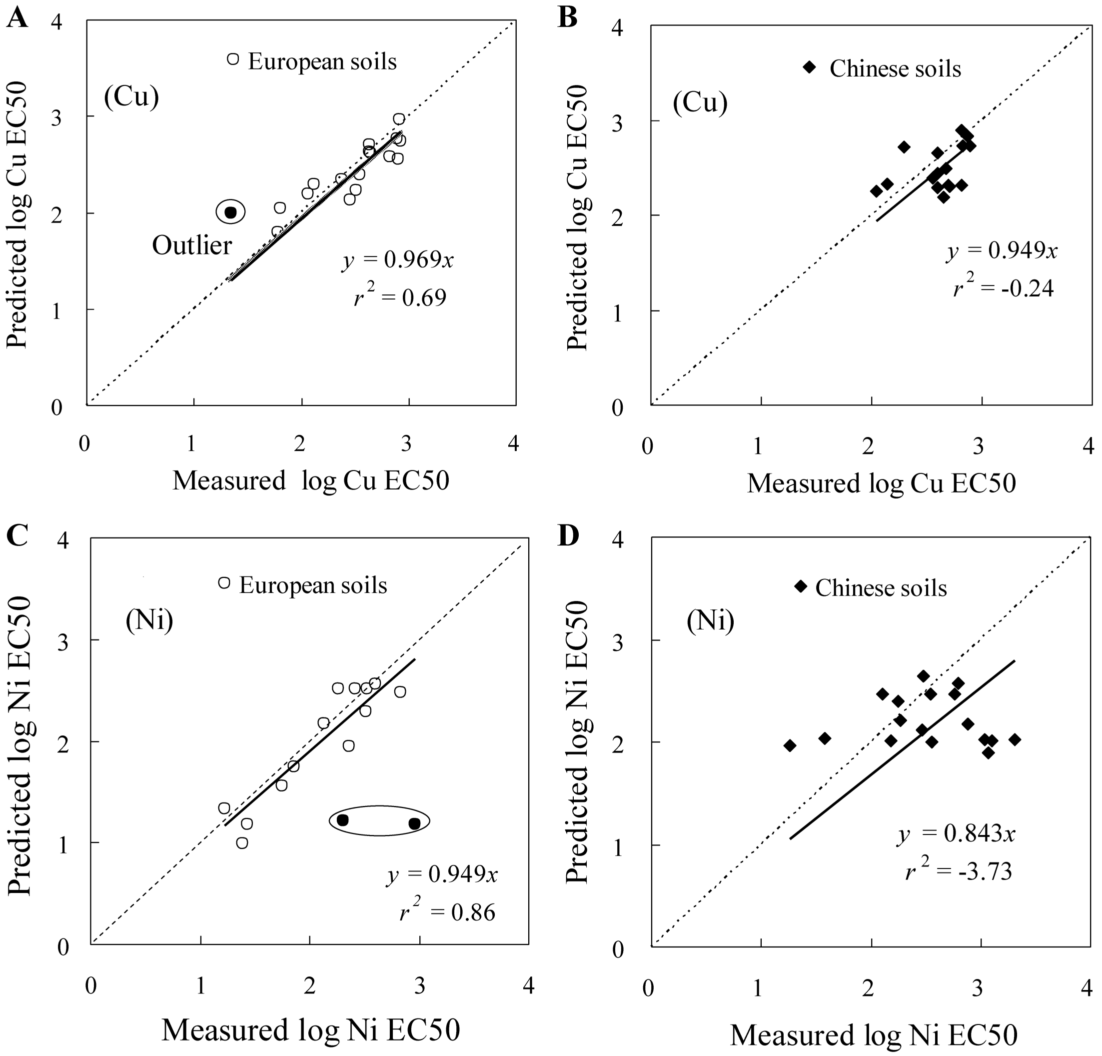

Figure 3. Measured toxicity effect concentrations causing a 50% inhibition in growth (EC50) values versus the EC50 values for tomato plant growth predicted using the models developed from Chinese soils in the present study and from European soils [2,3]. (**A**) Cu EC50s for European soils (Equation 2 in Table 1); (**B**) Cu EC50s for Chinese soils ($\log EC50 = 1.410 + 0.970 \log$ effective cation exchange capacity (eCEC) [2]); (**C**) Ni EC50s for European soils (Equation 8 in Table 1); (**D**) Ni EC50s for Chinese soils ($\log EC50 = 1.410 + 0.970 \log eCEC$ [3]). The point marked as an outlier in (A) is the Houthalen soil, and the points marked as outliers in (C) are Zegveld and Rhydtalog soils with organic carbon $> 12\%$.

dramatic decrease in soluble Cu (up to 75%) and Ni (up to 95%) in soil and not much decrease in total Cu and Ni concentrations (less than 12% for Cu and 13% for Ni), expect for S14 soil (Langfang soil), in which total Ni concentrations decreased by up to 25%. To overcome the effects of loss of Cu and Ni on their toxicity, the concentrations of total Cu or Ni were used to calculate the values of ECx. Overall, the decrease in toxicity of soils with added Ni by leaching was greater than that in the soils with added Cu for both plant species, especially for high-pH or calcareous soils. Similarly, Oorts et al. [14,22] found that the decrease in Ni toxicity to potential nitrification rate and C mineralization by leaching was greater in an alkaline soil (pH 7.6) than that in acidic and neutral soils (pH $4.5 - 6.1$). The difference in leaching effect on toxicity of Ni added to soils may be the result of the different characteristics of release of Ni between alkaline/calcareous and acidic/neutral soils. Ponizovsky et al. [23] reported that the release of soluble Ni in noncalcareous soils could be described by an adsorption equation and in calcareous soil may be controlled by dissolution of a surface precipitate either on the surface of soil carbonates [$NiCO_3$ or $NiCO_3 \cdot 2Ni(OH)_2$] or on the surface of clay minerals (Ni-Al double-layer hydroxide).

Furthermore, the effect of leaching on Cu and Ni toxicity was obviously weaker for bok choy. It was reported that averages and standard deviations of leaching factors estimated by Cu and Ni EC50s across these Chinese soils were 1.81 ± 1.20 and 3.07 ± 4.87 for nitrification assay [24,25], 1.15 ± 0.26 and >1.67 ± 0.65 for barley root elongation [12,13], and 1.37 ± 0.22 and >2.05 ± 1.91 for tomato shoot growth in the present study, respectively, which are all higher than those of bok choy shoot growth (1.13 ± 0.31 and 1.60 ± 0.88). It could be concluded that the effect of leaching on decreasing metal toxicity depends on the ecotoxicological endpoints.

The correlation between leaching factors and soil properties was analyzed, and we found that leaching factors estimated by Cu EC10 or EC50 values for bok choy shoot growth are significantly correlated with electrical conductivity, both with r^2 of 0.37 when we exclude S9 with higher electrical conductivity (888 μS/cm; Figure 4); for tomato shoot growth, leaching factors estimated by Cu EC50 values are significantly correlated with OC, with r^2 of 0.42 (Figure 5). For Ni, we found a dramatic effect of leaching on high-pH or calcareous soils; also, there was no significant correlation between other soil properties and leaching factors for the 2 plant species. There was, however, a significant correlation between soil OC and leaching factors estimated by Ni EC50 values for nitrification assay ($r^2 = 0.39$) [25]. These results suggested that the leaching effect varied not only with ecotoxicological endpoints but also with soil properties.

Soil pH and OC were the most important soil properties controlling toxicity of Cu and Ni to tomato and bok choy shoot growth. The effect of pH in mitigating metal toxicity to tomato was slightly stronger for Ni than for Cu, as evidenced by the slope values for soil pH in the models (from 0.38 to 0.43 for Ni and from 0.09 to 0.19 for Cu). Sauvé et al. [26] showed that the effect of pH on Ni partitioning in soil was stronger than that for Cu. Ma et al. [27] demonstrated that the extent of Ni aging in soils depends on soil pH more than the extent of Cu aging in soils. Either through chemical behavior or through toxicity of Ni, the extent (such as the slope value for soil pH in the toxicity models) affected by soil pH is greater than that of Cu [28]. However, soil OC content played a more important role in mitigating Cu toxicity than for Ni, because the variation explained by the toxicity models by introducing OC into the relationships was more significantly improved for Cu (Table 1).

For Cu toxicity to tomato plant growth, the model developed from Chinese soils based on soil pH and OC could be used to predict EC50 values in both Chinese and European soils (Figure 3A). Nevertheless, the regression equation based on European soils (log EC50 = 1. 410 + 0. 970 log eCEC [2]) could not be used for prediction of Cu toxicity to tomato shoot growth in Chinese soils with $r^2 < 0.01$ (Fig. 3B). As reported previously by Li et al. [12] for barley root elongation, these results indicated that soil pH and OC content are important factors in predicting Cu toxicity thresholds across a very wide range of soils. However, Cu toxicity models developed using eCEC and Fe oxide by Rooney et al. [2] for European soils (e.g., log EC50 = 0.855 + 0.869 log eCEC + 0.216 log Fe oxide) were found to predict the phytotoxicity of Cu in Chinese soils poorly, despite the same method of determining eCEC being used [29]. Li et al. [12] indicated that the EC50 values for the European soils can be predicted by eCEC, probably because the eCEC values [2] could be calculated by soil pH, OC content, and clay content. However, the eCEC values cannot be calculated based on soil properties for the Chinese soils, likely because of the differences in clay mineralogy in the range of Chinese soils used, so that Cu toxicity models developed for the European soils are unable to predict the phytotoxicity of Cu in Chinese soils. Similarly, for Ni toxicity to tomato plant growth, soil eCEC was also not a good predictor for Chinese soils, and the regression equation in the paper of Rooney et al. [3] (log EC50 = 1. 410 + 0. 970 log eCEC) was found to predict Ni phytotoxicity poorly in Chinese soils, with $r^2 < 0.01$ (Figure 3D). Nevertheless, Equation 8 (log EC50 = − 0.393 + 0.383 pH) in Table 1 could be used to predict Ni toxicity to tomato shoot growth in European soils (RMSE = 0.23; $r^2 = 0.86$), except in 2 high-OC soils (OC > 12%; Figure 3C). When incorporating 2 factors (soil pH and log OC) together into the regression model (Equation 9 in Table 1), the model was not further improved for Ni toxicity to tomato shoot growth in European soils. These results indicate that soil pH is the most important factor for predicting Ni toxicity to tomato shoot growth.

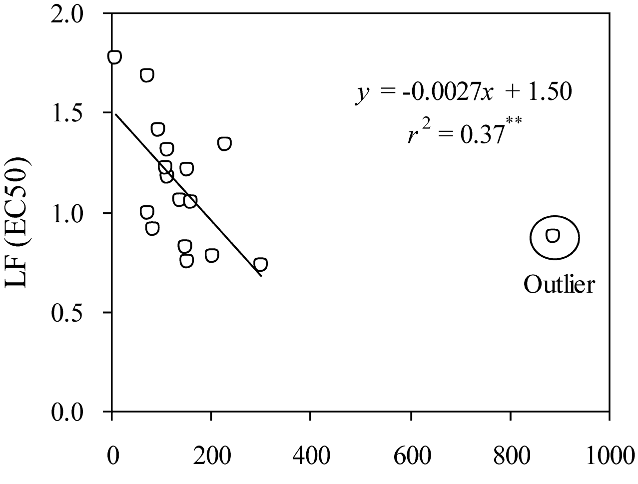

Figure 4. Change of leaching factors (LF) estimated by Cu toxicity effect concentrations causing a 50% inhibition in growth (EC50) for bok choy plant growth in all Chinese soils in response to soil electrical conductivity. Asterisks indicate regression coefficient significance at $p \leq 0.01$.

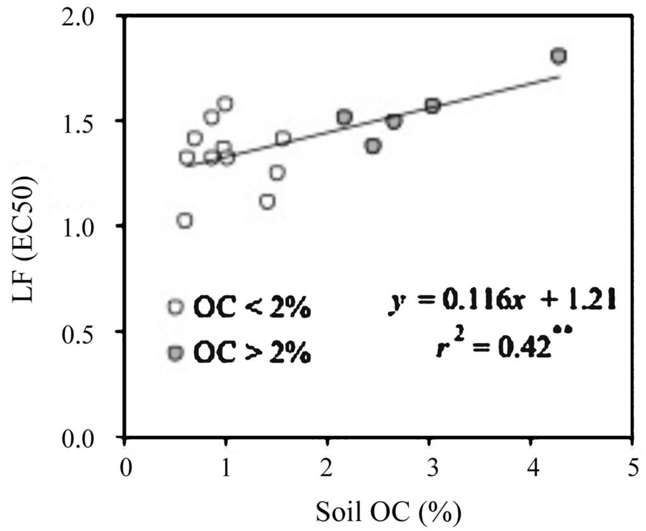

Figure 5. Change of leaching factors (LF) estimated by Cu toxicity effect concentrations causing a 50% inhibition in growth (EC50) for tomato plant growth in all Chinese soils, except for Guangzhou soil in response to soil organic carbon. Asterisks indicate regression coefficient significance at $p \leq 0.01$.

CONCLUSIONS

The variations of Ni toxicity induced by soil properties were wider than those for Cu toxicity to both tomato and bok choy plant growth. Leaching generally decreased the toxicity of Cu and Ni added to soils, which also depended on soils, metals, and test plant species. In high-pH soils, Ni toxicity to tomato growth was dramatically decreased by leaching. The most important and significant soil factors controlling Cu and Ni phytotoxicity in Chinese soils were found to be soil pH and soil OC for Cu and soil pH for Ni. Furthermore, the extent of Ni toxicity affected by soil pH was found to be greater than that of Cu. However, soil OC content played a more important role in mitigating Cu toxicity than Ni. Regression models of toxicity thresholds based on these soil factors were developed and validated against an independent data set from Europe. Hence, toxicity relationships developed for these metals in soils appear to have wide applicability.

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