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MERCURY DISTRIBUTION IN THE SOIL–PLANT–AIR SYSTEM AT THE WANSHAN MERCURY MINING DISTRICT IN GUIZHOU, SOUTHWEST CHINA

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Abstract—The level of mercury bioaccumulation in wild plants; the distribution of bioavailable Hg, elemental Hg, and total Hg in soil; and the concentration of total gaseous Hg (TGM) in ambient air was studied at three different mining sites (SiKeng [SK], WuKeng [WK], and GouXi [GX]) in the Wanshan mercury mining district of China. Results of the present study showed that the distribution of soil total Hg, elemental Hg, bioavailable Hg, and TGM varies across the three mining sites. Higher soil total Hg (29.4–1,972.3 mg/kg) and elemental Hg (19.03–443.8 mg/kg) concentrations were recorded for plots SK and WK than for plot GX. Bioavailable Hg was lower at plot SK and GX (SK, 3–12 ng/g; GX, 9–14 ng/g) than at plot WK (11–1,063 ng/g), although the TGM concentration in the ambient air was significantly higher for plot GX (52,723 ng/m^3) relative to WK (106 ng/m^3) and SK (43 ng/m^3). Mercury in sampled herbage was elevated and ranged from 0.8 to 4.75 mg/kg (SK), from 2.17 to 34.38 mg/kg (WK), and from 47.45 to 136.5 mg/kg (GX). Many of the sampled plants are used as fodder or for medicinal purposes. High shoot Hg concentrations may therefore pose an unacceptable human health risk. Statistical analysis of the recorded data showed that the Hg concentration in plant shoots was positively correlated with TGM and that the Hg concentration in roots was positively correlated with the bioavailable Hg concentration in the soil. The bioaccumulation factor (BAF) in the present study was defined with reference to the concentration of bioavailable Hg in the soil ($Hg_{[root]}/Hg_{[bioavail]}$). Three plant species, *Macleaya cordata* L., *Achillea millefolium* L., and *Pteris vittata* L., showed enhanced accumulation of Hg and therefore may have potential for use in the phytoremediation of soils of the Wanshan mining area. Environ. Toxicol. Chem. 2011;30:2725–2731. © 2011 SETAC

Keywords—Mercury pollution Plant uptake Total gaseous mercury Bioavailable mercury Human health risk

INTRODUCTION

Mercury (Hg) is a highly toxic trace element that is released to the environment through natural and human processes. Organic Hg, especially methylmercury (MeHg), is of great concern because of its potential to bioaccumulate in the food chain and its inherent neurotoxicity. Mercury is naturally present in soils with a concentration range between 0.01 and 0.2 mg/kg [1]. However, elevated Hg concentrations in soils have been found near Hg and gold mines and chlor-alkali plants [2].

The general population is exposed to MeHg primarily through the consumption of contaminated fish and marine mammals. However, Hg can also enter the food chain through the consumption of contaminated plants. Thus, for inland Hg mining districts, human exposure to MeHg occurs through pathways other than the consumption of fish. In particular, the ingestion of Hg through the consumption of contaminated rice has received scientific attention [3,4]. Therefore, in any risk assessment or toxicological study conducted at Hg mining sites, it is necessary to study the bioaccumulation of Hg in vegetation. Advances in understanding the cycling of Hg from soil to plants have made possible the identification of species that have a high capacity to extract Hg from soil. Plants that accumulate Hg in their aerial parts could subsequently be used to remediate Hg-contaminated land (phytoremediation).

The accumulation of Hg in terrestrial plants is related both to the concentration of the element in the soil and to the plant species [5]. The geochemical speciation of Hg in soil is also a key parameter controlling plant uptake. Generally, only a small fraction of the total metal in soil is bioavailable (water-soluble and exchangeable Hg and part of the carbonate bound soil fraction) [6]. Bioavailable Hg can be extracted by a single extractant such as dilute hydrochloric acid (HCl) [7]. In non-polluted soils, the bioavailable Hg fraction usually does not exceed 1% of the total Hg concentration [8]. In addition to root uptake from soil, Hg can enter the plant through aerial tissues [9]. Studies have demonstrated uptake of atmospheric Hg to be an important pathway for accumulation of Hg in foliage [10]. Patra and Sharma [11] believed that the Hg concentration in above-ground parts of plants appears to depend largely on foliar uptake of elemental Hg (Hg^0) volatilized from the soil. Su et al. [12] designed a sunlit chamber that was used to investigate whether Hg volatilized from Hg-elevated soil could be absorbed by the aerial parts of the fern *Pteris vittata* L. The results indicated that the Hg concentration in the leaf of the fern could reach 177 mg/kg and that foliar Hg uptake could be an important channel if the ambient air contains a high concentration of Hg vapor. Foliage can potentially absorb Hg^0 from the atmosphere through plant stomatal or nonstomatal pathways. The extent of these processes depends on the degree of air contamination, atmospheric aerosol deposition, CO_2 content of air, meteorologic conditions, and plant species [13–16].

Although some studies have been conducted to investigate the distribution of Hg in wild plants growing in Hg mining districts [17,18], few studies have taken into consideration the role of atmospheric Hg in plant Hg concentration. Wanshan

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(WS), known as the mercury capital of China, is located in the southwest of China (Guizhou province) and extends over an area of approximately 174 km^2. Mining at WS was initiated in the Qin Dynasty (221 BC), but ceased in 2001. Because of the extensive mining and smelting works in the Wanshan area, approximately 125.8 million tons of calcines and over 20.2 billion cubic meters of exhaust gases containing Hg are estimated to have been dispersed into adjacent ecosystems. Many researchers have investigated Hg contamination of the local ecosystem [19–21]. However, the biogeochemical cycle of Hg in the soil–plant–air system remains poorly understood. Therefore, in the present study, the degree of contamination of vegetation with Hg was studied. In addition, a detailed investigation of local wild plant species was made. The aim of this secondary investigation was to identify species that have a high capacity to extract Hg from soil and to accumulate this metal in aerial tissues. Such identification is essential for any future implementation of phytoremediation in this area.

Three Hg mining sites were chosen for the preset study. The following parameters were determined at each site: the total, elemental, and bioavailable Hg concentration in the soil; the TGM concentration in the ambient air; and the Hg concentration in different plant species growing across each site.

MATERIALS AND METHODS

Study area

The climate of the Wanshan region is defined as humid subtropical, characterized by abundant precipitation (1,200–1,400 mm) and mild temperatures. The Wanshan Hg mining district is hilly and karstic, ranging in altitude between 270 and 1,149 m above sea level. The annual average minimum and maximum temperatures are 13 and 17°C, respectively, with the highest temperature of 33.5°C occurring in July. Most of the Hg mines and artisanal smelters (retorts) in this region are scattered in valleys. The typical vegetation in the area is secondary coniferous forest and deciduous broadleaf forest.

Sampling

Soil and plant samples were collected from three different plots (SiKeng [SK, E109°12′02.45″ N27°30′48.47″], WuKeng [WK, E109°14′04.57″ N27°32′12.04″], and GouXi [GX, E109°11′38.21″ N27°33′21.59″]) in the Wanshan Hg mining district (Fig. 1). Both SK and WK were located near the now inactive smelter. These plots are partially covered with smelting wastes such as residual Hg ore and mine-waste calcines. Plot GX was situated far from the Hg mine tailings and waste but near an active artisanal Hg smelter. Each plot covered 100 m^2. The collected plants were representative of the community of species growing in the plots under investigation. However, not every species was common for all of the three plots. The plant communities at both the SK and the WK plots were dominated by the following plant family and species: Asteracea (Canadian horseweed [*Conyza canadensis* L.], common yarrow [*Achillea millefolium* L.], Eastern daisy fleabane [*Erigeron annuus* L.]), Papaveraceae (plume poppy [*Macleaya cordata* L.]), Leguminosae (Lucerne, [*Medicago* spp.], sinuate-leaf tickclover [*Desmodium sequax* Wall.]), and Pteridaceae (brake fern [*Pteris vittata* L.]). Plot GX was covered primarily by species belonging to the family Asteraceae (*C. canadensis*, *A. millefolium*, and sweet wormwood [*Artemisia annua* L.]). Three samples for each plant species were collected, along with a corresponding sample of soil from the plant root zone (rhizosphere). In the laboratory, the plant samples were carefully washed with tap water, then rinsed with deionized water, and finally dried in an oven at 36°C for 48 h. When dry, the plants were separated into roots and shoots using stainless-steel scissors and then homogenized by grinding in preparation for analysis. All soil samples were air dried, ground in a ceramic disc mill, and sieved to 200 mesh.

Analytical methods

The pH of the soil was measured with deionized water 1:2.5 (w/w) using a pH meter. Organic matter (OM) was determined according to the potassium dichromate volumetric method [22]. For total Hg analysis, soil samples were digested in a water bath (95°C) using a fresh mixture of concentrated HCl and HNO_3 (3:1, v/v). Elemental Hg in the soil samples was evaluated according to the method of García-Sánchez et al. [17]. Bioavailable Hg in soil was determined according to the method of Jing et al. [7], which uses dilute hydrochloric acid to extract Hg. The total and bioavailable Hg concentration in the soil preparations was measured using cold vapor atomic absorption spectrometry with a F732-S spectrophotometer. The plant samples were directly measured (solid sample) using a Lumex RA915+ Hg analyzer equipped with a PYRO 915+ pyrolysis attachment by way of thermal decomposition to Hg^0. The detection limit of the instrument is 0.2 to 5 ng/g. The TGM concentration in the ambient air of each plot was measured with a portable atomic absorption spectrometer operating on the Zeeman principle (Lumex RA-915+). The detection limit of this instrument is 2 ng/m^3. A single concentration data point represents a sampling time interval of 20 s, and the measurements were carried out at each site for 30 min.

Quality control and quality assurance

The standard reference materials GBW (E) 070009 and GBW10020 (manufactured by the Institute of Geophysical and Geochemical Exploration, China) were used for soil and plant analytical quality control, respectively. The average total Hg concentration of the geological standard GBW07405 was 2.43 ± 0.15 mg/kg ($n = 5$), which is comparable with the certified value of 2.20 ± 0.40 mg/kg. The average total Hg concentration of the orange foliage standard GBW10020 was 0.16 ± 0.001 mg/kg ($n = 5$), which is comparable with the certified value of 0.15 ± 0.02 mg/kg. The relative percentage differences of sample replicates for soil and plant were $<8\%$ and $<5\%$ respectively.

Data analysis

Statistical analyses including Pearson's correlation analysis and Fisher's least significant difference test were performed using SPSS 17.0 for Windows.

RESULTS AND DISCUSSION

Mercury in soils

The concentration of total, elemental, and bioavailable Hg in the collected soil samples is presented in Table 1. The total Hg concentration in the soil ranged from 11.2 mg/kg to 1,972 mg/kg and for all sampling locations was significantly higher than the maximum upper limit for Hg concentration (1.5 mg/kg) in agricultural soils in China [23]. The highest recorded concentration was from plot SK (1,972 mg/kg). The reported concentrations are comparable to those previously reported for the Wanshan mining district [20] (5.1–790 mg/kg). Similar total Hg concentrations have been reported for other mining districts, such as the Almadén Hg mining district in Spain, where total Hg

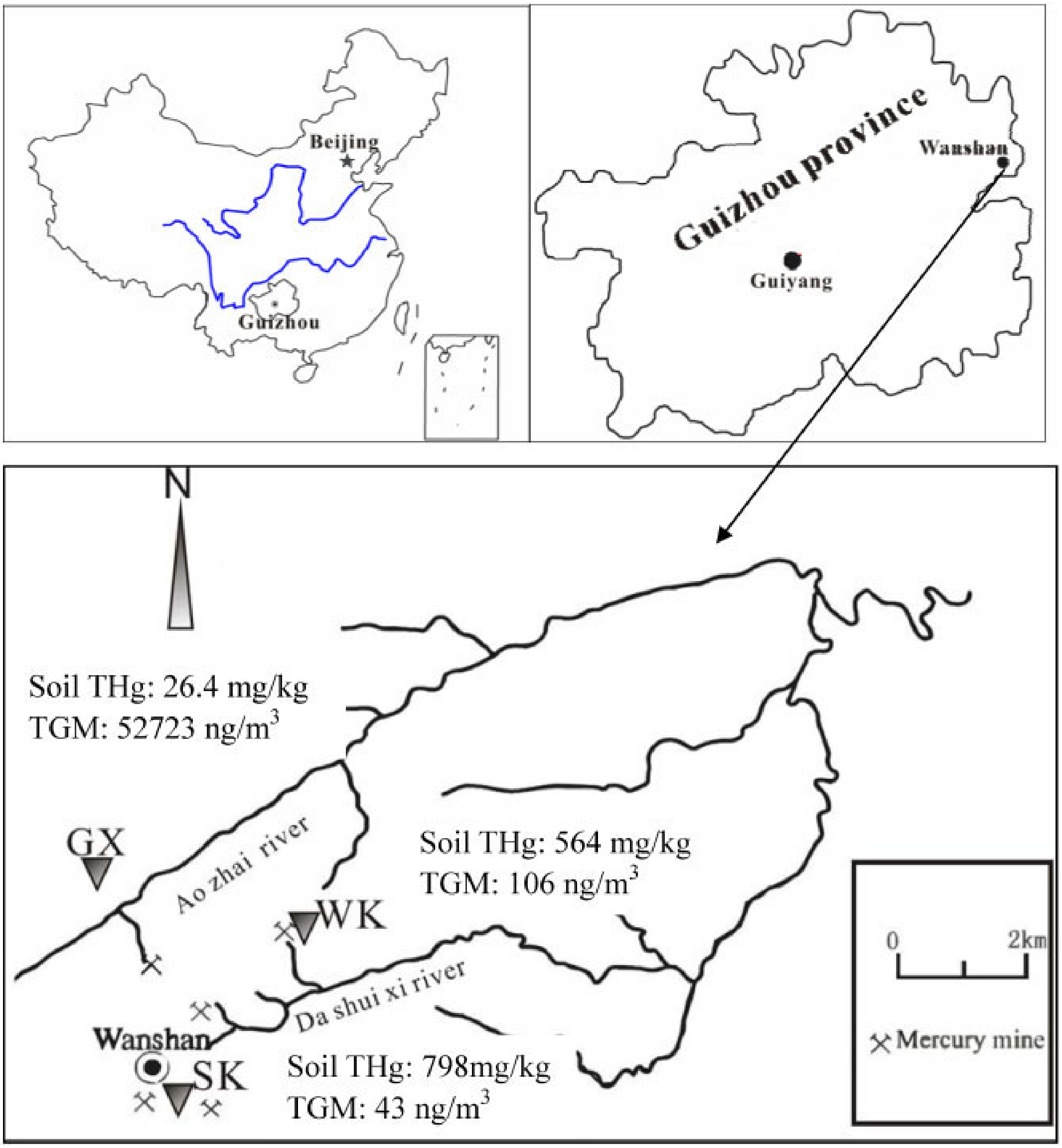

Fig. 1. Location of the SiKeng (SK), WuKeng (WK), and GouXi (GX) mining site in the Wanshan Hg mining district, China. Soil total Hg (THg) and total gaseous Hg (TGM) are average values. [Color figure can be seen in the online version of this article, available at wileyonlinelibrary.com]

concentrations associated with a closed Hg smelter and abandoned mine tailings range from 5 to 1,710 mg/kg [24]. Abandoned mine wastes are regarded as the main source of Hg in soil for the SK and WK plots. Mercury mine wastes in Wanshan usually contain a high residual Hg concentration because of inefficiencies in the smelting process [25]. Qiu et al. [20] reported that the total Hg concentration in mine wastes collected from the Wanshan mining area ranges from 5.7 to 4,400 mg/kg. The total Hg concentration in the soil at plot GX ranged from 11.2 to 45.3 mg/kg, which is significantly lower than that for plots SK and WK and is comparable to the Hg concentration in soil for the Tongren artisanal Hg mining site in Guizhou province, China, that has been reported in a previous study (0.8–48 mg/kg [25]). Artisanal Hg mining is recognized as a significant anthropogenic source of atmospheric Hg emission [25]. Atmospheric Hg may be deposited to soils as Hg^{2+}, either by the direct deposition of emitted Hg^{2+} or by conversion of emitted Hg^0 to Hg^{2+} through ozone-mediated processes [26]. Plot GX is located on the slope of a mountain and far from the Wanshan Hg tailings. The soil at plot GX is less impacted by Hg mining wastes, and the source of soil Hg may be atmospheric Hg deposition.

The soil Hg^0 concentration as a function of plot location follows the trend WK > SK > GX. For the WK and SK plots, the Hg^0 concentrations range from 19.03 to 444 mg/kg and 25.46 to 299 mg/kg, respectively. This represents 12.8 to 76.4% and 10.1 to 74.2% of the total Hg concentration at these plots, respectively. The Hg^0 concentration for plot GX is lower (7.47–28.26 mg/kg) but represents a greater fraction of total Hg load at this location (52–67%). The high proportion of Hg as Hg^0 at GX may be explained by the active deposition of atmospheric Hg (illegal smelting is ongoing at this location). The Hg^0 at the SK and WK plots likely originates from Hg^0 that condensed during the ore-roasting process before the smelter closed. These reported contents of Hg^0 are comparable to those found in other mining districts. For example, soils at the Hg mining district of Usagre, located in the south of Badajoz province (Spain), showed an Hg^0 content of 0.4 to 8% [17] of total Hg.

Table 1. Total Hg (THg), bioavailable Hg, and elemental Hg (Hg^0) concentration in the rhizosphere soil of plant species ($n = 3$) from three mining sites in China

Plots	Plant species	THg (mg/kg)	Bioavailable Hg (mg/kg)	Hg^0 (mg/kg)
SiKeng	*Conyza canadensis* L.	393.4 ± 230.0	0.012 ± 0.008	91.54 ± 37.6
	Achillea millefolium L.	1,972.3 ± 1054.9	0.004 ± 0.002	299.2 ± 23.9
	Macleaya cordata L.	350.0 ± 17.0	0.003 ± 0.0001	107.7 ± 12
	Medicago spp.	117.0 ± 141.0	0.003 ± 0.001	83 ± 110
	Pteris vittata L.	1137.2 ± 76.4	0.006 ± 0.004	25.46 ± 7.07
WuKeng	*C. canadensis*	932.5 ± 315.6	0.255 ± 0.02	219.4 ± 60.2
	A. millefolium	648.3 ± 336.1	0.132 ± 0.106	208 ± 75.2
	M. cordata	29.4 ± 28.4	0.011 ± 0.004	19.03 ± 18.60
	P. vittata	746.1 ± 314.5	0.417 ± 0.038	443.8 ± 256
	Erigeron annuus L.	526.9 ± 219.9	1.063 ± 0.734	220.5 ± 175
	Desmodium sequax Wall.	500.1 ± 22.9	0.501 ± 0.439	230.5 ± 124
GouXi	*C. canadensis*	22.7 ± 20.6	0.009 ± 0.005	11.76 ± 10.8
	A. millefolium	11.2 ± 2.6	0.012 ± 0.01	7.47 ± 0.54
	Artemisia annua L.	45.3 ± 11.9	0.014 ± 0.004	28.26 ± 8.54

The concentration of bioavailable Hg for each of the studied plots is lower than the corresponding concentration of Hg^0 and ranges from 0.003 to 1.06 mg/kg. This is consistent with the conclusion that nonbioavailable forms of Hg are the dominant forms present in the soil (cinnabar for the SK and WK plots and Hg^0 for the GX plot). Higher concentrations of bioavailable Hg were found in the soils of the WK plot, with an average value of 0.35 mg/kg (0.01–1.06 mg/kg). Although both the SK and the WK plots were located near the inactive smelter, the SK plot shows a lower concentration of bioavailable Hg. This may be due to the location of SK, which is also near the Wanshan mine tailings, where the pH of the soil is significantly elevated (Table 2; pH 8.74). In addition, the average organic matter content in this plot is higher than that in the other two plots (Table 2). It is reported that organic matter plays an important role in capturing and immobilizing Hg in soils [27]. For all plots, bioavailable Hg accounted for less than 0.01% of the total Hg concentration in the soil. This result is comparable to that of a previous study [28] on the geochemical speciation of Hg in soil collected from the Wanshan mining area.

Mercury in air

Table 3 presents the concentration of TGM in the ambient air at the SK, WK, and GX plots. The highest TGM concentration was found near the active artisanal smelter at GX, with an average value of 53 μg/m^3. This concentration exceeds the limit for Hg in air for industrial workshops set by the Chinese National Standard Agency (20 μg/m^3) [29]. For the SK and WK plots, the average TGM concentration in the ambient air was 43 and 106 ng/m^3 respectively, values that are comparable to those in other studies of the same area (17.8–102 ng/m^3) [30]. The TGM concentrations at SK and WK were significantly higher than the annual average value (8.4 ng/m^3) in Guiyang, the capital city of Guizhou province [31,32].

Table 2. pH and organic matter content of the rhizosphere soil samples collected from the research plots at the SiKeng (SK) ($n = 15$), WuKeng (WK) ($n = 18$), and GouXi (GX) ($n = 9$) mining sites, China

Sample sites	pH			Organic matter (%)		
	Maximum	Minimum	Average	Maximum	Minimum	Average
SK	9.19	8.24	8.74	10.30	3.87	6.40
WK	8.67	7.98	8.32	7.00	2.90	4.54
GX	8.26	5.84	7.09	4.45	0.97	2.44

The source of atmospheric Hg for plot GX is likely the smelting process used to recover Hg from ore. However, for plots SK and WK, which were located far from an active artisanal smelter, the source of atmospheric Hg may be Hg emission from the soil. It is reported that Hg volatilization from Hg-enriched soil is the primary source of atmospheric Hg contamination [33]. The average Hg emission flux from soil in the Wanshan mining area has been previously reported to range from 1.42 to 243.7 mg/m^2 per year [30]. Many studies have proven that various factors can influence the exchange of Hg between soil and air. These include the total soil Hg concentration [34], solar irradiation [35], humidity of soil [36], soil temperature [37], TGM concentration in the air [35], and vegetation [36]. Among these factors, the total soil Hg concentration may be the main factor that controls the magnitude of Hg flux [30]. Soil with a higher total Hg concentration has higher potential for Hg emission to the atmosphere. Furthermore, Kocman and Horvat [38] have reported that Hg emission will occur more readily from soils in which Hg is in a more mobile form relative to sites containing insoluble cinnabar. In the context of the present study, the SK plot had higher total Hg content but relatively lower TGM compared with plot WK. This apparent anomaly may be attributed to the higher percentage of Hg in the bioavailable fraction for the soil collected from plot WK.

Mercury in plants

The Hg concentration in the shoots and roots of the wild plant species collected from the SK, WK, and GX plots is presented in Figure 2. Mercury uptake was both species and plot specific. The highest concentration of Hg in plants was recorded for the GX plot, with a reported concentration range from 47.45 (*A. millefolium*) to 136.5 (*C. canadensis*) mg/kg. For the SK plot, the reported range is 0.80 (*Medicago* spp.) to 4.75 (*C. canadensis*) mg/kg and, for the WK plot, from 2.17

Table 3. Total gaseous Hg concentration (ng/m^3) in the air for plots at the SiKeng (SK), WuKeng (WK), and GouXi (GX) mining sites, China

Sample sites	Maximum	Minimum	Average	Sample numbers (n)
SK	51	37	43	90
WK	131	88	106	90
GX	172,400	11,200	52,723	90

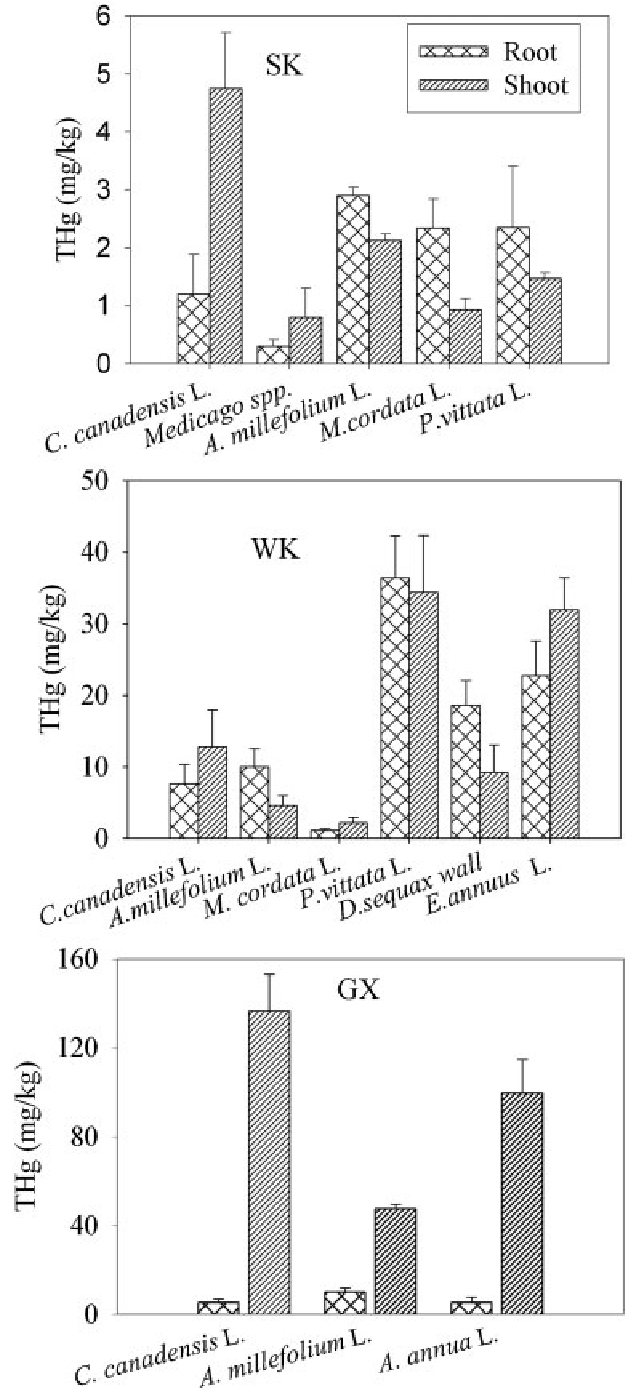

Fig. 2. Mercury concentrations in the roots and shoots of plant species collected from the SiKeng mining site (SK), WuKeng mining site (WK), and GouXi mining site (GX) in China. Bars denote standard deviation from the mean of three replicates.

(*M. cordata*) to 34.38 (*P. vittata*) mg/kg. The root Hg concentration for plants sampled from the WK plot was elevated, ranging from 1.12 (*M. cordata*) to 36.40 (*P. vittata*) mg/kg. At the SK plot, root Hg concentrations did not exceed 2.90 mg/kg. The three species collected from the GX plot showed root Hg concentrations below 10 mg/kg.

In general, the background Hg concentration in the aerial parts of wild plants is below 0.1 mg/kg dry weight [1]. The recorded concentrations of Hg in the plants collected for the current study attest to the extent of Hg contamination across the Wanshan mining area. Despite the high Hg concentrations, no visual symptoms of Hg toxicity were observed in any of the sampled plants. The species *C. canadensis*, *E. annuus*, *Medicago* spp., *D. sequax*, and *A. annua* are employed as feedstuffs or feed additives for livestock. According to Standard GB13078-2001 on the limit of toxic substances permitted in feedstuffs or feed additives, the maximum Hg concentration allowed in animal feed is 0.1 mg/kg [39]. Therefore, in all locations, the surveyed plant species show Hg concentrations in shoots that are well in excess of environmental guideline values. Substantially higher Hg concentrations in duck livers and pig brains have been reported in the Wanshan mining area for livestock that depend on crops or wild plants as their primary foodstuffs [40]. The risk that may be apparent through the incorporation of Hg into the food chain through the consumption of these Hg-contaminated plants should be taken into consideration. Consequently, mandatory controls on the use of such fodder plants may be necessary. In addition, the seeds of these wild plants could be used as food for birds or other animals. In this case, Hg would likely be incorporated into the food chain and induce environment risk. Meng et al. [41] showed that MeHg translocates to the seed of rice plants during ripening. Under the assumption that Hg behaves as a mobile nutrient in other plant species, further distribution of Hg through the food chain may be occurring as birds and other animals ingest Hg-contaminated seed. Zhang et al. [42] investigated the distribution and bioaccumulation of Hg in the soil–plant–grasshopper–spider food chain system at an urban location in China. This study indicated that the Hg concentration in grasshoppers was highly correlated with the Hg concentration in plant leaves, suggesting that Hg in grasshoppers came from the ingestion of plant leaves. The plant species *C. canadensis*, *A. millefolium*, *E. annuus*, *A. annua*, and *M. cordata* are widely used as medicinal plants. Poisonings attributed to the presence of toxic metals in medicinal plants have been reported [43]. According to the green standards of medicinal plants and preparations for foreign trade and economy (WM/T2-2004) that seeks to regulate toxic substances in medicinal plants, the maximum Hg concentration allowed in medicinal plants is 0.2 mg/kg [44]. An apparent human risk exists for the use of medicinal plants collected from the Wanshan mining area, and this risk should again be taken into consideration.

A significant correlation was recorded in the present study between the concentration of bioavailable Hg in the soil and the Hg concentration in roots ($p < 0.01$), but no correlation was found between this soil parameter and the concentration of Hg in shoots (Table 4). Statistical interpretation of the data suggests that mobile Hg in soil can be easily absorbed into the roots but that Hg translocation inside the plants, from the root to the shoot, is a very slow process.

In the present study, plants containing the highest shoot Hg concentration were recorded for the site with the highest TGM concentration (GX) in ambient air, and the correlation between TGM and the shoot Hg concentration (Table 4) was significant. This indicates that the elevated shoot Hg concentration may be due to stomatal or foliar absorption of Hg from the atmosphere, and not to uptake and translocation of Hg from soil.

Although no correlation was observed between the Hg concentration in the soil and that in the shoot, this does not discount Hg transport from roots to shoots. The concentration of bioavailable Hg at plot WK was significantly higher than that at plot SK, an observation that was in turn a function of soil chemistry. Increased Hg bioavailability at plot WK appears to have increased the root to shoot translocation of Hg for plants

Table 4. Pearson's correlation matrix, giving the linear correlation coefficients (*r*) among the total Hg (THg) concentration in plant tissues (root and shoot), air (total gaseous Hg [TGM]), and the soil (elemental Hg [Hg^0], THg, and bioavailable Hg; $n = 14$)

	Hg root	Soil bioavailable Hg	Soil Hg^0	Soil THg	TGM
Hg shoot	0.13	−0.02	−0.19	−0.41	0.87[a]
Hg root		0.72[a]	0.74[a]	0.20	−0.08
Soil bioavailable Hg			0.50	0.18	−0.26
Soil Hg^0				0.65[a]	−0.42
Soil THg					−0.51

[a] $p < 0.01$.

growing at this location. In the present study, the bioaccumulation factor (BAF) is defined to be the ratio between the Hg concentration in root and the bioavailable Hg concentration in soil ($Hg_{[root]}/Hg_{[bioavail]}$) and is used to evaluate the capacity of the surveyed plant species to take up Hg from the soil. Because of the apparent differences in TGM concentration for the ambient air at the SK, WK, and GX plots, the BAF of each collected plant species was evaluated for each plot (Fig. 3). The highest BAFs were recorded for the GX plot, with a reported value range from 311 (*A. annua*) to 1,225 (*A. millefolium*), but statistical analysis showed that no significant difference ($P > 0.05$) was observed among the three plant species collected from this plot. For the WK plot, the BAF for each plant species followed the trend *M. cordata* > *P. vittata* > *A. millefolium* > *C. canadensis* ≈ *D. sequax* > *E. annuus*. Among these plant species, *M. cordata* shows a BAF that is dramatically ($p < 0.05$) higher than that of other plant species. For the SK plot, the BAF for each plant species followed the trend *M. cordata* > *A. millefolium* > *P. vittata* > *Medicago* spp. > *C. canadensis*. However, the differences among *A. millefolium*, *M. cordata*, *Medicago* spp., and *P. vittata* are statistically insignificant ($p > 0.05$). Based on this analysis, the plant species *M. cordata*, *A. millefolium*, and *P. vittata* showed enhanced ability to take up and translocate more Hg than the other plant species if Hg availability was of the same order in the soil. In any application of phytotechnologies in the future for the remediation of the Wanshan mining area, manipulation of Hg solubility in the plant root zone will be essential if plants are to remove this metal efficiently from soil.

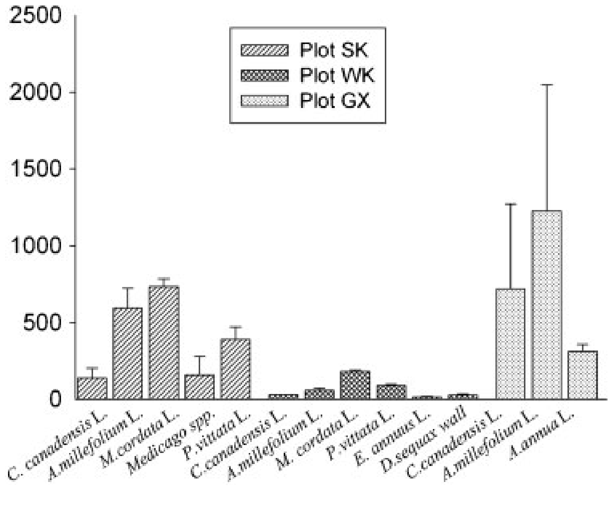

Fig. 3. The bioaccumulation factor (BAF) of each plant species ($n = 3$). Significant differences within each plot are indicated by different lowercase letters ($p < 0.05$). SiKeng (SK), WuKeng (WK), and GouXi (GX) mining sites in China. Bars denote standard deviation from the mean of three replicates.

CONCLUSIONS

The Wanshan Hg mining district shows great variability in the distribution of THg and Hg^0 concentrations in soil. Plots SK and WK located close to a now-closed Hg smelter display high THg and Hg^0 relative to plot GX, which is located near an active (illegal) Hg smelter. The concentration of bioavailable Hg at all plots is low but is elevated at WK. The total gaseous Hg (TGM) concentration is similar for plots SK and WK but orders of magnitude higher for plot GX. The recorded Hg concentration in a range of native plant species collected from the three research plots highlights the extent of serious Hg contamination throughout the Wanshan mining district. The incorporation of Hg into the food chain through the consumption of these Hg-contaminated plants should be taken into consideration. Mercury concentrations in collected plant material exceed permissible limits for the safe use of herbage for fodder and medicinal purposes. The species *M. cordata*, *A. millefolium*, and *P. vittata* show a relatively high BAF across the three plots. These species could potentially be used for the phytoremediation of Hg-contaminated soils.

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