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Mercury uptake and phytotoxicity in terrestrial plants grown naturally in the Gumuskoy (Kutahya) mining area, Turkey

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ABSTRACT

This study investigated mercury (Hg) uptake and transport from the soil to different plant parts by documenting the distribution and accumulation of Hg in the roots and shoots of 12 terrestrial plant species, all of which grow naturally in surface soils of the Gumuskoy Pb-Ag mining area. Plant samples and their associated soils were collected and analyzed for Hg content by ICP-MS. Mean Hg values in the soils, roots, and shoots of all plants were 6.914, 460, and 206 $\mu\text{g kg}^{-1}$, respectively and lower than 1. The mean enrichment factors for the roots (ECR) and shoots (ECS) of these plants were 0.06 and 0.09, respectively and lower than 1. These results show that the roots of the studied plants prevented Hg from reaching the aerial parts of the plants. The mean translocation factor (TLF) was 1.29 and higher than 1. The mean TLF values indicated that all 12 plant species had the ability to transfer Hg from the roots to the shoots but that transfer was more efficient in plants with higher ECR and ECS. Therefore, these plants could be useful for the biomonitoring of environmental pollution and for rehabilitating areas contaminated by Hg.

KEYWORDS

mercury uptake; wild plants; enrichment coefficient; translocation factor; phytoremediation; mining area

Introduction

Mercury (Hg) is a naturally occurring element (a member along with zinc and cadmium of Group IIB on the periodic table) that is found in air, water and soil. It exists in several forms: elemental or metallic Hg, inorganic Hg compounds and organic Hg compounds. Elemental or metallic Hg is a shiny, silver-white metal that is liquid at room temperature. If heated, it becomes a colorless, odorless gas (U.S. EPA, 2006). Hg abundance is 400 $\mu\text{g kg}^{-1}$ in continental crust (Wedepohl 1995), 80 $\mu\text{g kg}^{-1}$ in acid rocks (granites and gneisses), 180–400 $\mu\text{g kg}^{-1}$ in shales and 0.04–0.05 $\mu\text{g kg}^{-1}$ in limestones (Kabata-Pendias and Pendias 2001). Background levels of Hg are not easy to estimate due to widespread Hg pollution. Nevertheless, data reported for various soils on a worldwide show that mean concentrations of Hg in surface soils do not exceed 400 $\mu\text{g kg}^{-1}$. The highest mean levels of Hg were reported for Canada (400 $\mu\text{g kg}^{-1}$), Japan (350 $\mu\text{g kg}^{-1}$), Vietnam (300 $\mu\text{g kg}^{-1}$), the U.S. (280 $\mu\text{g kg}^{-1}$), China (142 $\mu\text{g kg}^{-1}$), and Poland (61 $\mu\text{g kg}^{-1}$) (Kabata-Pendias and Pendias, 2001). Soils contaminated with Hg are related mainly to base metal processing industries and certain chemical works. The highest concentrations of Hg were found in Hg mining areas or their surroundings, ancient mining areas, areas subject to the application of fertilizers and pesticides and volcanic areas (Patra and Sharma 2000; Kabata-Pendias, and Pendias 2001; Millan *et al.* 2006; Moreno-Jiménez *et al.* 2006; Molina *et al.* 2006).

There is evidence that increasing Hg concentrations in the soil causes an increase in the Hg content of plants. The highest rates of increase for Hg content in plants when the soil was the only source of this metal was reported to be highest for roots,

but leaves and grains also accumulate Hg (Sorterberg 1980). These findings show that Hg is easily absorbed by the root system and is translocated within the plants. In Poland, the highest Hg concentrations in plants were recorded in greenhouse vegetables, followed by plants from industrialized areas. Lettuce and parsley leaves had the highest concentrations; tomatoes, potatoes, and cucumbers had the lowest. Fruits and grains bioaccumulated much less Hg than did vegetables. There was no clear correlation between the concentrations of Hg in the soil and in the plants grown in it (Szymczak and Grajeta 1992). But Molina *et al.* (2006) indicated that the Hg concentrations found in plants from the Almaden district of Spain clearly reflected the importance of contamination processes throughout the study region. Similarly, Crowder (1991) reported that Hg concentrations were related to both the concentration of the element in the soil and the plant species accumulating the Hg. Some studies have shown that plant uptake of Hg from the soil may be limited by the roots, which function as a barrier between the aboveground plant and the element in the soil (Patra and Sharma 2000). Schwesig and Krebs (2003) suggested, however that this mechanism may operate only in highly polluted soils. Molina *et al.* (2006) defined four well-differentiated patterns of Hg uptake in the Almaden district: 1) the rate of uptake is constant, independent of Hg concentration in the soil (Hg soil), 2) after an initial linear relationship between uptake and soil concentration, no further increase in Hg concentration in the plant (Hg-plant) is observed, 3) no increase in uptake is recorded until a threshold is surpassed, and thereafter a linear relationship between Hg-plant and Hg-soil is established and 4) there is no relationship between Hg-plant and Hg-soil. Overall, the

Hg concentrations found in plants from the Almaden district clearly reflect the importance of contamination processes throughout the study region.

Mercury is one of the most toxic heavy metals and is considered a global contaminant. Its toxic level varies as a function of the exposure pathway and the chemical species in which it occurs (Ferrer, 2003; Rodriguez *et al.* 2003; Sierra *et al.* 2009). It is also very expensive to clean up, because of its accumulative and persistent character in the biota (Perez-Sanz *et al.* 2012). As a highly bio-accumulated toxic metal in the food chain, Hg represents and increasingly critical environmental concern worldwide. Many large Hg mines have been abandoned recently because of low Hg prices and decreasing demand. Abandoned Hg mines continue to impact local environments through mine wastes, drainage, and elemental Hg vapor. Because the ecological and toxicological effects of Hg are strongly dependent on the chemical species present, the primary concern about abandoned Hg mines is the biological accumulation (Qiu *et al.* 2006). Direct Hg contamination is usually the result of releases from abandoned Hg mines, gold/silver/thallium mining and other mining activities, or the chlorine-alkali industry, while indirect (non-point source) contamination is largely attributed to atmospheric deposition originating from coal-fired power plants (Ullrich *et al.* 2001; Xiao *et al.* 2004; Qiu *et al.* 2006; Chattopadhyay *et al.* 2012). It has been estimated that it would cost US\$40,000 to 70,000 to remove an average pound of Hg from the environment with currently available technologies (U.S. EPA 2006). Thus, there is an urgent need to develop alternative Hg remediation strategies. The potential application of phytoremediation to Hg contamination has been explored in several environmental settings. There is evidence that certain plant species have the ability to extract and accumulate Hg from atmospheric and soil sources, although no species with Hg hyperaccumulating properties has been identified (Rugh *et al.* 1999). The accumulation of Hg in terrestrial plants has been reported to be related to soil characteristics, including concentration of the element in the soil (Adriano 2001), but the uptake of Hg has also been found to be plant-specific (Crowder 1991; Molina *et al.* 2006). Soil characteristics such as high pH value, abundant lime, and accumulated salt reduce its uptake by plants. A highly significant correlation exists between Hg concentrations and the organic matter content in the top layer of forest soils (Lag and Steinnes 1978).

In Turkey, many researchers have studied the distribution and speciation of Hg and heavy metals in foods, drinking and river waters, agricultural soils, and other environmental samples (Tüzen and Soylak 2005; Tüzen *et al.* 2009a; Tüzen *et al.* 2009b). The aim of the present study was to investigate Hg uptake and transport from soil to plant parts by studying the distribution and accumulation of Hg in the roots and shoots of 12 wild plant species that grow naturally in the Hg-contaminated surface soils of the Gumuskoy Ag-Tl-As mining area (Fig. 1) in order to assess the area's degree of Hg pollution and to contribute to the knowledge of the Hg soil plant relationship.

Material and methods

Apparatus

A Perkin-Elmer ELAN 9000 (CT-USA) inductively coupled plasma mass spectrometer (ICP-MS) was used to determine of

Hg, following the operating conditions recommended by the manufacturer.

Study area

The study area was between 38° 96' and 39° 48' N latitude and between 29° 48' and 29° 71' E longitude. The altitude of the Gumuskoy mining area varies between 1100 and 1320 m above sea level. Kütahya is a transition zone between the continental climate of central Anatolia and the mild climate of the Aegean and Marmara regions because of the formation of the landscape and the altitude. In the eastern part of the area, the summers are hot and dry while winters are cold and rainy. The average temperature of Kütahya is 10.5°C. The hottest months are July and August, while the coldest months are January and February. The highest temperature that has been measured was 38.6°C while the lowest was -28.1°C. Temperature variation over the year is 66.7°C. Meteorology Directorate data and maps show the rainfall rate in Kütahya as irregular with wet and dry periods due to the continental climate, with an average yearly rainfall of 565 mm. Rainfall is greatest in December and least in August, with 38.8% coming in winter, 29.4% in spring, 12.5% in summer, and 19.3% in autumn. The average number of snow days is 19 and precipitation as snow is normal in winter owing to the landscape and altitude. Turkey has a unique flora and fauna, protected by the formation of national parks all around the country.

In the present study, the plants and the associated soil samples were collected from an area of polymetallic ore deposits in the Gumuskoy mining district, Kutahya, Western Turkey (Fig. 1). In this region, outcrops metamorphic, volcanic and sedimentary rocks ranging from Permian to present-day eras are present. A number of polymetallic ore deposits represented by Ag, As, Tl, Pb, Zn, and Sb occur between the Gümüşköy and Şahin villages. Soil and plants in the study area are naturally polluted by these heavy metals. This region has at least 3534 ± 24 years of mining history, according to ^{14}C absolute age determinations from charcoal discovered in mining waste by Kartalkanat (2008). Consequently, the area has been heavily charged with different metals arising from both ancient and modern mining activities (Arik 2002; Arik and Nalbantçılar 2005; Arik and Yıldız 2010). Intensive mining operations continue in this region to the present day.

Plant and soil samples

The plant samples, consisting of their roots, shoots and associated soils, were taken from 41 sites in the study area. The plant species in the Gumuskoy region can grow under severe climate conditions due to their massive and deep-reaching root systems. These systems also give them the ability to live in areas deficient in organic matter. The Hg content was measured in 12 plant species that grow in the area: *Alyssum saxatile* L. (AL), *Anchusa arvensis* L. (AN), *Centaurea cyanus* L. (CE), *Carduus nutans* (CR), *Cynoglossum officinale* (CY), *Glaucium flavum* (GL), *Isatis* L. (IS), *Onosma* sp. (ON), *Phlomis* sp. (PH), *Silene compacta* (SL), *Tripleurospermum maritimum* (TR), and *Verbascum thapsus* L. (VR). These plants were chosen because they are native and dominant species in the study area.

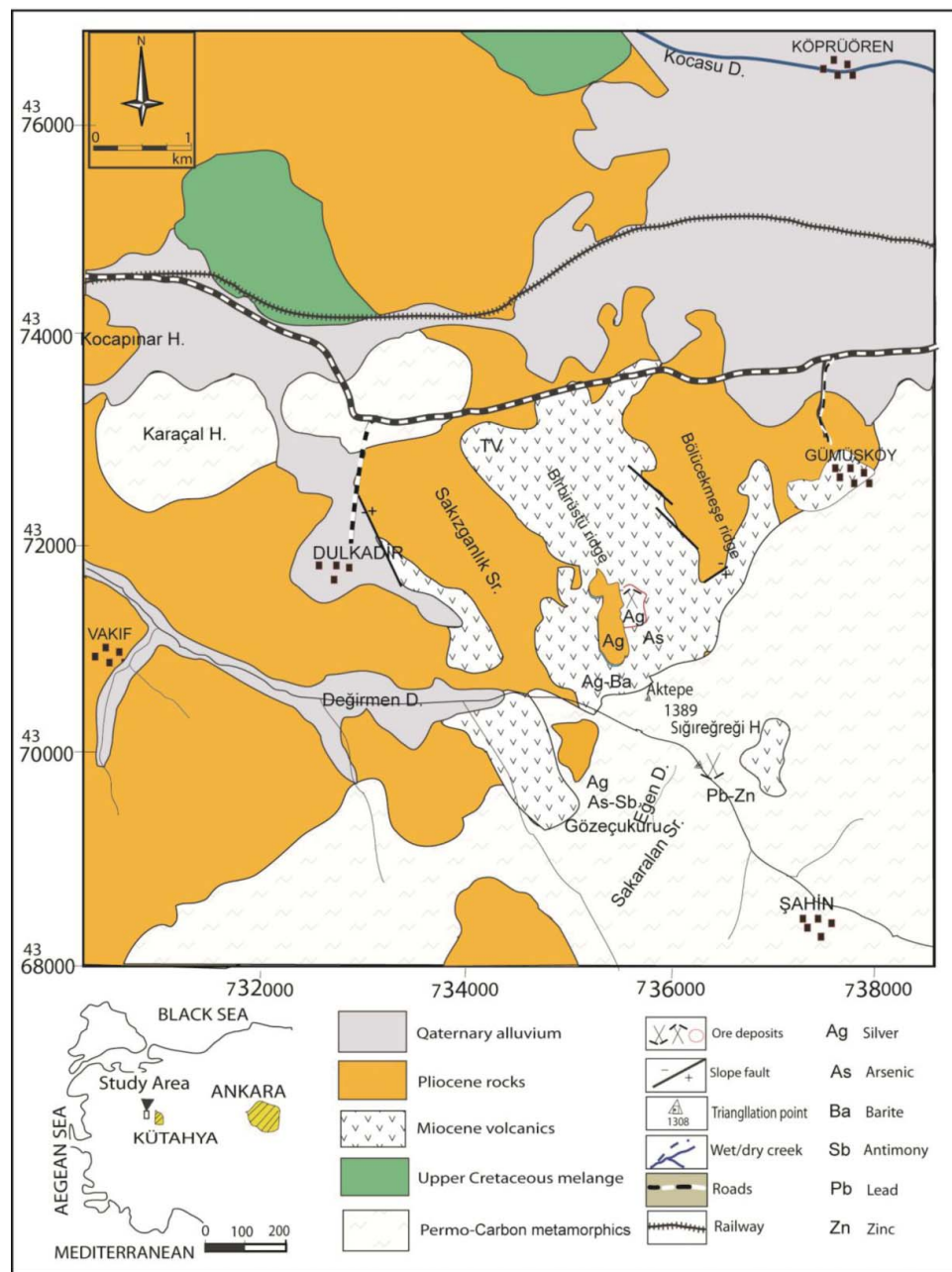


Figure 1. Geological and location map of the study area (simplified from Arik 2002).

Preparation of samples

Soil Samples

Soil thicknesses in the study area vary between 30 cm. and 6 m. The soils are generally light to dark brown and black in color, with a loamy and peaty clay texture (23.6% sand, 51.4% silt, and 19.3% clay), with a pH of 6.4–7.2 and with an organic matter content of 2.32–6.48%. An X-ray diffraction study of the clay minerals was not performed. Soil samples were collected from around the roots of the plants at a depth of 30–40 cm. After the soil samples dried in an oven at 100°C for 4 hours, rocks were removed and the soil samples were ground using hand mortars. Soil samples were digested in a mixture of HCl:HNO₃:H₂O (1:1:1, v/v; 6 ml per 1.0 g of soil) for 1 hour at 95°C. This treatment dissolved all soil samples except for silicates,

and the digests were analyzed using ICP/AES-MS techniques for Hg at the ACME Analytical Labs, Vancouver, Canada (www.acmelab.com).

Plant samples

Plant samples were randomly collected from sites that were chosen based on representative characteristics of the Gumuskoy mining area. Three samples of shoots and roots were taken from each sampling site. The root samples were taken at a depth of 30–40 cm below the surface. The shoot and root samples of the studied plants were thoroughly washed with tap water, rinsed with distilled water, and dried at 60°C for 24 hours. A chelating EDTA wash was applied, and no differences were observed between EDTA washed and unwashed

samples. The dried samples were digested in HNO₃ (Merck, Darmstadt, Germany) for 1 hour, followed by digestion in a mixture of HCl:HNO₃: H₂O (1:1:1, v/v; 6 ml per 1.0 g of the dried sample for 1 hour at 95°C. The digests were analyzed using ICP/AES-MS techniques for Hg (www.acmelab.com).

Enrichment coefficients of roots (ECR)

Enrichment coefficients were calculated using the ratios of specific activities in plant roots and soils (root concentration in $\mu\text{g kg}^{-1}$ divided by soil concentration in $\mu\text{g kg}^{-1}$ of soil). This value was used as an index to determine accumulation of trace elements in plant parts or to establish the transfer of elements from the soil to the plant roots (Chen *et al.* 2005).

Enrichment coefficient for shoots (ECS)

Enrichment coefficients were also calculated for the shoots (ECS) (shoot concentration in $\mu\text{g kg}^{-1}$ divided by soil concentration in $\mu\text{g kg}^{-1}$ of soil). The ECS is a very important factor, as it indicates the phytoremediation capacity of a given species (Zhao *et al.* 2003). This value is also used as an index to characterize the transfer of elements from the soil to the plant shoots. The ECS therefore characterizes the capability of a plant to absorb and transport metals from sediment and then to store them in the above-ground parts (Baker *et al.* 1994; Brown *et al.* 1994; Wei *et al.* 2002).

Translocation factors (TLF)

Translocation factors (TLF) were obtained by calculating the ratio of metal in the plant shoots to that in the plant roots (shoot concentration in $\mu\text{g kg}^{-1}$ divided by root concentration in $\mu\text{g kg}^{-1}$). In a metal accumulator species, a translocation factor greater than 1 is common, whereas in metal excluder species, translocation factors are typically lower than 1 (Zu *et al.* 2005).

Results and discussion

Hg concentrations in the soils

The soil samples were collected from the Aktepe and Gözeçukuru areas in the study area and its surroundings (Fig. 1). Hg concentrations in the soil samples were found to be between 79 and 50,000 $\mu\text{g kg}^{-1}$ (mean: 6,609 $\mu\text{g kg}^{-1}$). Hg concentrations in similar mining areas range from 8,400 to 610,000 $\mu\text{g kg}^{-1}$ in the Lanmuchang, Guizhou (southwestern China) Hg–Tl ore deposits (Qiu *et al.*, 2006); 5 to 1,710,000 $\mu\text{g kg}^{-1}$ in Almadén mine (Spain) (Millán *et al.*, 2006); 12,000 to 100,000 $\mu\text{g kg}^{-1}$ in Türkönü mercury mine, Turkey (Gemici and Tarcan 2007); 210 to 3,400 $\mu\text{g kg}^{-1}$ in an ancient mining area of England (Davies 1976); 200 to 1,900 $\mu\text{g kg}^{-1}$ in a Hg mining area of Canada; 2,600 to 2,900 $\mu\text{g kg}^{-1}$ in Hg mining area of France; 90 to 220 $\mu\text{g kg}^{-1}$ in Hg mining area of Brasil (Kabata-Pendias and Pendias 2001). The mean value of Hg in the study area was lower than that of the soils around these Hg deposits but many times higher than average Hg concentrations in the lithosphere (50 $\mu\text{g kg}^{-1}$) and unpolluted soils

(30 $\mu\text{g kg}^{-1}$) (Pais and Jones 2000). Hg concentrations outside of mining areas were also observed in soils around coal power stations and metallurgy plants (400–7,550 $\mu\text{g kg}^{-1}$), in some chemical works (Henry *et al.* 1999), and at a former battery recycling facility (Lis and Pasieczna 1995).

Tufite and aglomera, with rhyolite and dacite composition, are widespread in the Gumuskoy mining area and its surroundings (Fig. 1). These rocks are acidic with high silica and have much lower Hg content than other rocks (Kabata-Pendias and Pendias 2001). The higher Hg concentrations may be related to the Ag, Tl, As, and Pb deposits of the Gumuskoy region, because the presence of Hg showed a linear correlation with the occurrence of certain heavy metals (Table 1). These linear correlations ($r = 0.48$ – 0.54) were observed between Hg and the heavy metals Pb, As, U, Sb, Tl, and Ba, whereas weak linear correlations ($r = 0.04$ – 0.10) were observed between Hg and the heavy metals Sr, Cd, Ca, and P (Table 1). The linear correlations between Hg and the heavy metals Pb, As, U, Sb, Tl, and Ba supported the idea that Hg and those heavy metals were geologically transported jointly to the soil of the study area in hydrothermal solutions.

Xiong *et al.* (2013) stated that there are several potential causes for the soil-independent accumulation of heavy metals in plant roots. First plant species have the potential to defend against heavy metal stress. Given high levels of heavy metals in the growth environment, the plant may activate defense mechanisms to reject or excrete heavy metal elements thereby avoid cell toxicity caused by extreme levels of heavy metals. Second heavy metal pollution generally occurs in the form of compound pollutants (Damian *et al.* 2010). The heavy metals in the soil were shown to be jointly correlated with each other, by which one type of heavy metal in the soil may regulate the absorption and accumulation of other types of heavy metals by plants. Third, once absorbed, the heavy metals may be transferred from the plant roots to different organs or tissues.

Significant relationships were detected between Hg content in all plant samples and in the soils in this study (Fig. 2). Hg in the roots changes as a second degree polynomial in regard to the soil (Fig. 2). This means that the more Hg in soil, the more Hg accumulates in the roots Figure 3 also clearly shows that Hg content in the shoots increases exponentially with a decreasing slope. This indicates that the roots function as a barrier to the movement of Hg to the shoots by accumulating more Hg as soil Hg concentrations increase (see Fig. 2). The mechanisms for absorption and transport of Hg differed among the plants in the study area. These variations in Hg content in the various plants and plant tissues might be genetically controlled by the genotype of the plants (Li and Cao, 2006).

The highest Hg concentration in all analyzed soils were 62,532 and 49,871 $\mu\text{g kg}^{-1}$ in the GL-01 and GL-02 samples,

Table 1. Correlations between Hg and other heavy metals in soils of the Gumuskoy mining area.

	Cu	Pb	Zn	Ag	Mn	Fe	As	U	Sr	Cd
Hg	−0.01	0.48	−0.07	−0.12	0.06	0.09	0.51	0.48	0.36	0.19
	Sb	Ca	P	Ba	Hg	Na	K	Sc	Tl	Se
Hg	0.52	0.25	0.19	0.54	1.00	−0.18	−0.35	−0.33	0.52	0.04

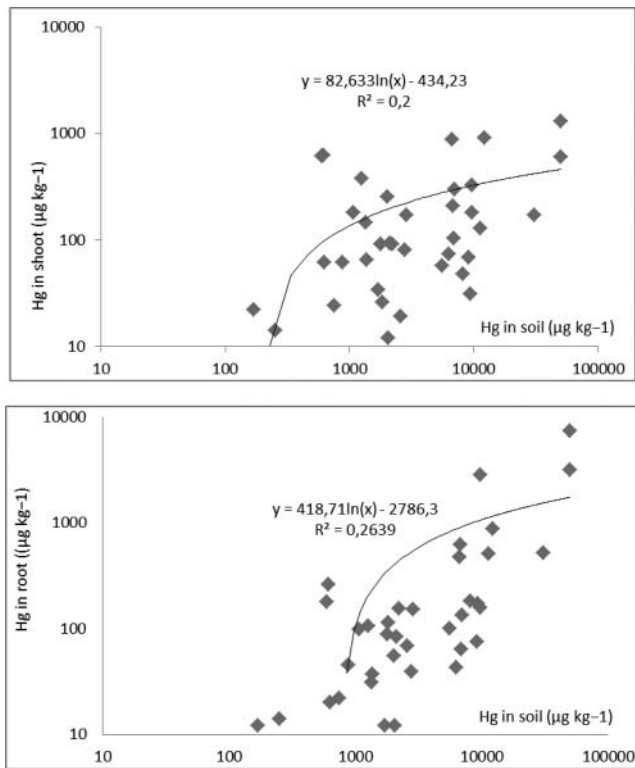


Figure 2. Correlations between Hg in plant roots and shoots with Hg in soil in the Gumuskoy mining area.

respectively (Fig. 3), which were collected from a mineralized area. These soils also had high As, Sb, Tl, Pb, and Ba concentrations. Hg mobility in the soil is believed to be medium in oxidizing conditions but high in acidic and humid environments (Plant *et al.* 2001). In the soils of the Gumuskoy study area, the maximum concentrations of Hg were found either at the surface or close to the surface. The soils with maximum Hg concentrations, like the soils with large concentrations of other heavy metals (Pb, Ag, Zn, Se, Sb, and Tl), were generally dark

brown in color and contained relatively large proportions of clay and organic matter. The Hg content decreased sharply with increasing depth in the soil profile, where the soils were generally light brown in color and contained more sand and rock and less organic matter.

Hg concentrations in the Plants

In the Gumuskoy mining area, 12 plant species were selected for the determination of Hg content. The chosen plants grow indigenously in the mining area and generally live for 1 year or 2 years (they are annuals and biennials). The Hg content of the plants in the study area varied considerably, but the average Hg concentrations for the plant roots and shoots were 460 and 206 $\mu\text{g kg}^{-1}$, respectively. Hg concentrations of the 41 plant samples, however, ranged from a minimum of 2 and 1 $\mu\text{g kg}^{-1}$ for the plant roots and shoots respectively, to a maximum of 7,328 and 1,299 $\mu\text{g kg}^{-1}$ for the plant roots and shoots, respectively. Hg concentrations ($\mu\text{g kg}^{-1}$ dry weight) of plant parts are given in Figure 3, together with Hg concentrations of the associated soils.

The mean Hg values for the soil, roots and shoots of *Alyssum saxatile* (AL), were 5,243, 746, and 155 $\mu\text{g kg}^{-1}$, respectively. The Hg levels in the soil around AL plants were significantly higher than the mean Hg values in AL shoots and roots. The Hg levels for all AL samples ranged between 45 and 2,813 $\mu\text{g kg}^{-1}$ for the roots, and between 26 and 300 $\mu\text{g kg}^{-1}$ for the shoots on a dry weight basis (Fig. 3). The Hg enrichment coefficients (ECR and ECS) for AL roots and shoots are shown in Figure 4; the mean ECR and ECS values were 0.10 and 0.04, respectively. Translocation factors (TLFs) for Hg in AL were between 0.06 and 2.26 (mean: 0.85) (Fig. 4), which indicates that Hg was only weakly transferred to the shoot following uptake from the soil to the root.

Hg concentrations in the soil, roots and shoots of *Anchusa arvensis* (AN) are given in Figure 3. Mean Hg values in the soil,

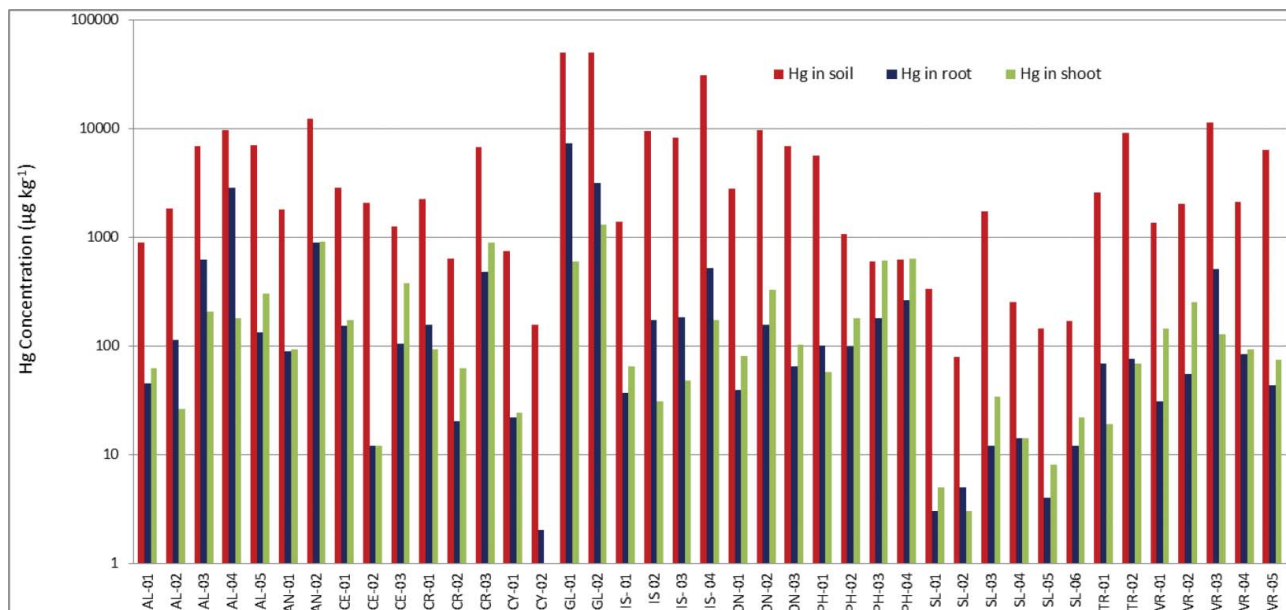


Figure 3. The Hg concentrations of the soils, roots, and shoots of 12 plant species.

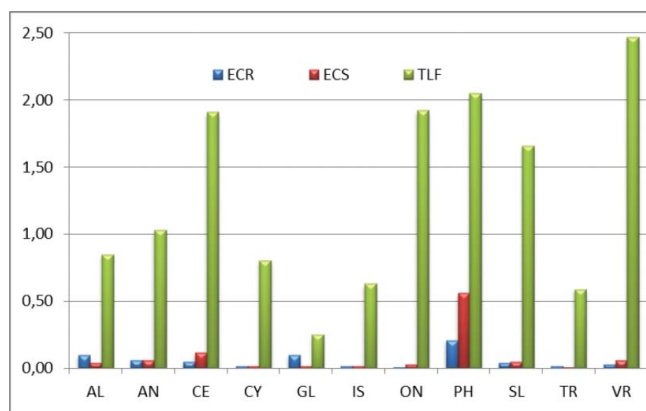


Figure 4. Mean translocation factors (TLF) and enrichment coefficients for the roots (ECR) and shoots (ECS) of plant species in the study area.

roots and shoots for AN were similar, at 6,959, 485, and 500 $\mu\text{g kg}^{-1}$, respectively, on a dry weight basis (Fig. 3). The enrichment coefficients (ECR and ECS) for Se in the roots and shoots of AN are shown in Figure 3. The mean values of 0.06 and 0.06 for ECR and ECS, respectively, indicated that Hg taken up from the soil by AN was transferred to the root. The translocation factor (TLF) for two samples of AN was 1.03 (Fig. 4), which means that the AN translocation factor was more than 1. This result indicates that AN has a relatively high transporting capacity for Hg in semi-arid environments or continental climates.

The mean Hg concentrations in the soil, roots, and shoots of *Centaurea cyanus* (CE) were 2052, 90, and 187 $\mu\text{g kg}^{-1}$, respectively (Fig. 3). The mean Hg values in the shoots of two CE samples were higher than the mean Hg values in the roots, but equal in one sample. The mean ECR and ECS of all samples were very low, but the TLFs of CE samples were higher than 1 for two samples and equal for one sample (Fig. 4). This value indicates that CE is not a very efficient bioaccumulator plant for Hg when growing in a similar environment and climate.

The mean Hg concentrations in the soil, roots and shoots of *Cynoglossum officinale* (CY) were 452, 12, and 13 $\mu\text{g kg}^{-1}$, respectively. The Hg values in the soil were higher than in the CY roots and shoots. The ECR, ECS, and TLF values for CY were lower than 1. Consequently, Hg is weakly transferred from the soil to CY roots and shoots (Fig. 4).

The mean Hg concentrations in the soil, roots, and shoots of *Glaucium flavum* (GL) were 56,202, 5,245, and 950 $\mu\text{g kg}^{-1}$, respectively (Fig. 3). The ECR, ECS, and TLF values for GL (mean = 0.09, 0.02, and 0.25 respectively) were less than 1 (Fig. 4).

The Hg content of the soil, roots, and shoots were analyzed in four samples of *Isatis* (IS). The soil, roots, and shoots contained an average of 12,404, 227, and 79 $\mu\text{g kg}^{-1}$ of Hg, respectively. Thus, the Hg concentrations in IS shoots and roots were substantially lower than the Hg concentrations in the soil, except for the IS-01 sample. The Hg content of IS-01 shoot was higher than Hg content of IS-01 root. The mean ECR, ECS, and TLF values for IS were 0.02, 0.02, and 0.63, respectively (Fig. 4).

The mean Hg concentrations in the soil, roots, and shoots of *Onosma* (ON) were 6,455, 87, and 171 $\mu\text{g kg}^{-1}$, respectively

(Fig. 3). The Hg values in the shoots of all ON samples were higher than the Hg values in the roots, but lower than the Hg values in the soils. Therefore, the ECR and ECS values for ON were lower than 1, but the TLF values were higher than 1. These values indicate that the ON root does not efficiently accumulate Hg from the soil, but does efficiently transfer Hg to the shoot.

The Hg content of the soil, roots, and shoots of *Phlomis* (PH) were examined in four samples. The mean Hg concentration of the soil, roots, and shoots of PH were 1960, 160, and 369 $\mu\text{g kg}^{-1}$, respectively. The Hg concentrations in the shoots of two PH samples were higher than the Hg concentrations in the soil, but the other two samples had Hg concentrations lower than their soils. The mean ECR, ECS, and TLF values for PH were 0.21, 0.56, and 2.05, respectively. The ECS and TLF of the PH-03 and the PH-04 samples were higher than 1 (ECS: 1.03 and TLF: 3.39 for the PH-03 sample; ECS: 1.02, and TLF: 2.40 for the PH-04 sample). These values indicate that PH would be effective at cleaning or rehabilitating soils in areas contaminated by Hg.

The mean Hg concentrations in the soil, roots, and shoots of *Silene compacta* (SL) were 448, 8 and 14 $\mu\text{g kg}^{-1}$, respectively (Fig. 3). The Hg values in the soil were higher than in SL roots and shoots. The mean ECR and ECS values for this plant were lower than 1. The TLFs of SL were generally higher than 1 (mean 1.66), except for one sample. This means that Hg was not transferred from the soil to the root or the shoot by this plant (Fig. 4). This indicates that SL cannot act as a Hg bioaccumulator plant.

The Hg contents of the soil, roots, and shoots were investigated in two samples of *Tripleurospermum maritimum* (TR). The soil, roots, and shoots of TR contained an average of 5,846, 72 and 44 $\mu\text{g kg}^{-1}$ of Hg, respectively. The Hg concentrations in TR soils were higher than those in the roots and the shoots. The mean ECR, ECS, and TLF values for TR were 0.02, 0.01, and 0.59, respectively (Fig. 4). These low ECR, ECS and TLF values indicate that TR could not be a Hg bioaccumulator/hyperaccumulator plant.

The Hg content of the soil, roots, and shoots were analyzed in five samples of *Verbascum thapsus* (VR). The mean Hg concentrations in the soil, roots, and shoots of VR were 4625, 145, and 139 $\mu\text{g kg}^{-1}$, respectively. The Hg concentrations in VR shoots and roots were lower than the Hg concentrations in the soil, but the Hg concentrations in shoots of VR were higher than the Hg concentrations in roots of VR, except for one sample (Fig. 3). The mean ECR, ECS and TLF values for VR were 0.03, 0.06, and 2.47, respectively (Fig. 4). The mean TLF value (2.47) was higher than 1 and this value indicates that VR has the ability to transport Hg from the roots to the shoots.

Conclusions

The Hg levels in soils from the Gumuskoy Ag-As mining area varied between 79 and 62,532 $\mu\text{g kg}^{-1}$ (mean: 6,914 $\mu\text{g kg}^{-1}$), which are somewhat higher than those of uncontaminated surface soils reported in other countries. The distribution and accumulation of Hg was examined in the roots and shoots of 12 plant species that grow naturally in the Gumuskoy soils. The mean concentrations of Hg in the roots and shoots of these

plants were found $460 \mu\text{g kg}^{-1}$ and $206 \mu\text{g kg}^{-1}$, respectively. These results show that the fraction of available Hg for plants in soils of the Gumuskoy mining zone was lower than in the soils, but higher than Hg concentrations of plants grown in uncontaminated areas, despite the toxic levels of Hg found in these soils. Hg concentrations in the studied plants grown in these soils can be considered as phytotoxic, although no symptoms of Hg toxicity were observed in any of the studied plant species. The main reason for this is that the roots of the studied plants functioned as a barrier, preventing Hg from reaching the aerial parts of plants. According to the TLF values, however, *A. arvensis* (AN), *C. cyanus* (CE), *Onosma* sp. (ON), *Phlomis* sp. (PH), *S. compacta* (SL), and *V. thapsus* L. (VR) showed a greater ability to transport Hg from the roots to the shoots. These results indicate that they would be good candidates for Hg phytoremediation of contaminated soils. *A. saxatile* L. (AL), *C. officinale* (CY), *G. flavum* (GL), *Isatis* L. (IS), and *T. maritimum* (TR) had a lower ability to transport Hg from the roots to the shoots because these plants behaved as excluders of Hg, storing the metal mainly in the root.

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