Rhizosphere Characteristics of the Arsenic Hyperaccumulator Pteris vittata L. and Monitoring of Phytoremoval Efficiency

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Recently discovered As-hyperaccumulator ferns hold promise for phytoremediation of As-polluted soils. We investigated changes in the rhizosphere characteristics of Pteris vittata (Chinese Brake fern) relevant for its use in phytoextraction. Plants were grown in rhizoboxes filled with soil containing 2270 mg Kg⁻¹ As. Dissolved organic carbon (DOC) concentrations in rhizosphere soil solution were increased by 86% and appeared to enhance total Fe solubility due to complexation reactions. Despite substantial removal of As by the fern, As was not significantly decreased in the rhizosphere soil solution after one cropping, apparently due to the large buffer capacity of the soil and possibly because of ion competition with DOC. However, the difference between 0.05 M (NH₄)₂SO₄-extractable labile As and rhizosphere soil accounted for 8.9% of total As accumulated in the fern, indicating that As was mainly taken from less available pools. Moreover, As depletion in the rhizosphere and limited resupply from less available pools were indicated by a 19.3% decreased As flux, measured using the technique of diffusive gradients in thin films (DGT). Modeling of the DGT—soil system was able to show that the rate of release from solid phase to solution in the rhizosphere was one-third of that in the bulk soil. Applying the remedial strategy of bioavailable contaminant stripping, which aims at diminishing the phytoavailable pollutant fraction, DGT can be used as a monitoring tool to evaluate the efficiency of phytoextraction and to study the potential resupply of bioavailable pools after phytoextraction has ceased.

Introduction

Arsenic is an ubiquitous trace metalloid and is found in virtually all environmental media. Concentrations of As in non-contaminated soils are typically below 10 mg kg⁻¹ (1). However, 41% of the Superfund sites in the United States, for which the U.S. EPA has signed records of decision, are contaminated with As (2), and more than 10,000 As-contaminated sites have been reported for Australia (3). Concentrations of As in fresh and (fodder) crops at such contaminated sites may exceed permissible limits (4, 5). Both, the European Union and the United States have lowered drinking water standards (6, 7), as it has been shown that inorganic As is toxic, even at lower concentrations than previously thought (8). Such legislative changes on As drinking water standards have consequences for As concentrations in soil that are acceptable for groundwater protection (5).

Technologies currently available for the remediation of As-contaminated soils are expensive and time-consuming, can create risks to workers, and can produce secondary waste (9). Phytotechnology, the use of green plants to clean up contaminated soil, has attracted attention as an environment-friendly low-input remediation technique. This technology uses hyperaccumulator plants that extract pollutants from the soil and accumulate them in the harvestable above-ground biomass (10). However, hyperaccumulation of As was discovered only recently, first in Pteris vittata L. (11), followed by Pityrogramma calomelanos L. (12) and four other species of the Pteris genus: P. cretica L., P. longifolia L., P. umbrosa L. (13), and to a lesser extent in P. argyreae L. (14). Arsenic concentrations in fronds of P. vittata reached up to 7526 mg kg⁻¹ when grown on a site contaminated with chromated copper arsenate and even 22630 mg kg⁻¹ on As-spiked soil (11).

Calculations suggest that phytoextraction to remedial targets based on total metal/metalloid concentrations would typically take several decades, depending on the level of pollution (10). Moreover, total pollutant concentrations are not a good measure for pollutant bioavailability and associated risks.

Phytotechnology employing the remedial strategy of “bioavailable contaminant stripping” (BCS) aims at removing only labile/bioavailable metal fractions (15). Whereas this risk-based approach would substantially reduce the time needed to clean up metal-polluted soils while minimizing the ecological risk, several issues relating to the remediation efficiency and longevity still need to be resolved. Figure 1 depicts schematically possible changes of the labile/bioavailable metal fraction during and after termination of phytoextraction using BCS. Labile metal/metalloid fractions are operationally defined as pools removable by mild extractants such as neutral salt solutions. However, such chemical extraction procedures are generally not good predictors of trace element concentrations in plants. Recently, the technique of diffusive gradients in thin films (DGT) was shown to be a promising alternative for risk assessment of metal-polluted soils in terms of predicting element concentrations in plants. Unlike commonly used chemical extractants, DGT is founded on kinetic rather than equilibrium principles, allowing the measurement of fluxes and interfacial concentrations. This is achieved by interposing a well-defined
of the As hyperaccumulator experiment aimed at assessing rhizosphere characteristics is the first use of DGT in rhizosphere research. This monitoring tool in BCS-based phytoextraction of As. This potential, and release of root exudates (mechanisms involved are acidification, decrease of redox potential, and release of root exudates (19). Monitoring changes of bioavailable pollutant fractions in the rhizosphere of phytoextraction crops is a basic requirement for the evaluation of the efficiency and longevity of remediation (18, 20).

In this paper, we describe the results of a rhizobox experiment aimed at assessing rhizosphere characteristics of the As hyperaccumulator P. vittata and at testing DGT as a monitoring tool in BCS-based phytoextraction of As. This is the first use of DGT in rhizosphere research.

Experimental Section

Rhizobox Experiment. The experimental soil (upper B horizon, Calcaric Cambisol), containing geogenic As, was collected near St. Margarethen/Carinthia, Austria (5). Important soil characteristics were determined following standard procedures (21); texture, sandy loam; clay content, 190 g kg⁻¹; pH (H₂O) 8.2; cation exchange capacity, 334 mmolc kg⁻¹; CaCO₃, 157 g kg⁻¹; total As, 2270 g kg⁻¹; total C, 27 g kg⁻¹; total N, 2.4 g kg⁻¹. Fresh soil was passed through a 2-mm sieve, homogenized, and frozen in plastic bags at −18 °C. Soil was thawed and equilibrated at room temperature for 14 d before being filled into rhizoboxes (bulk density, 1.2 g cm⁻³).

The rhizobox used is based on a previously published system (22). Adaptations were set as described in the following (Figure 2a). Root growth was restricted to the central compartment by nylon membranes with 0.45-μm pore size (Pall Europe Ltd., Portsmouth, England) to avoid growth of root hairs as well as mycorrhizal fungi into the adjacent 2-mm-thick root-free rhizosphere soil compartment. The root-free rhizosphere compartment was separated from bulk soil by a 30-μm mesh size nylon net (Haack, Vienna, Austria). The rhizoboxes were made of Perspex acrylic material, allowing observation of root growth. Rhizoboxes were wrapped with aluminum foil during the experiment to avoid algal growth and weed germination.

P. vittata (population from Florida) was propagated from spores (23) and pregrown on noncontaminated potting substrate until about 5 fronds had developed. Thereafter, one individual plant was transferred onto each of four replicate rhizoboxes and grown until the central compartments were densely rooted after 41 d.

Commercially available nylon-coated soil moisture samplers (Rhizosphere Research Products, Wageningen, The Netherlands) were placed in central and bulk soil compartments for collection of soil solution. Three days before harvest, all compartments of the rhizoboxes were uniformly watered from the top to increase the water content. Soil solution (~8 mL) was collected 1 d before harvest using syringes. The water content of the soil in the individual compartments (determined immediately after harvest) was about 48% of the maximum water holding capacity (MWHC). The experiment was carried out in summer (July/August) in a greenhouse at about 25–30 °C during the day and 19–20 °C at night. No fertilizer was applied to avoid artifacts due to P-induced As mobilization in the experimental soil (24). Three additional individuals of P. vittata were grown for 3 months in pots containing the same soil to observe long-term accumulation of As.

To complement the main experiment, a highly resolved gradient of DGT-induced As fluxes in the rhizosphere of P. vittata was assessed without replication using a recently developed rhizobox system (25). After 2 month of growth, a dense root monolayer developed in the root-only compartment. A 30-μm nylon net, permitting growth of root hairs into the rhizosphere soil, was employed. Rhizosphere soil was cut without freezing into root-parallel sections using a specially designed slicing device (26). DGT-induced fluxes of each soil layer were measured as described below.

Chemical and Biological Parameters. Harvested plants were divided into young fronds (developed during growth in rhizoboxes), old fronds, rhizomes (including some short stalks), and roots, which were thoroughly rinsed with deionized water and oven-dried for 24 h at 80 °C. After recording dry weights, the plant material was finely ground using a mortar and pestle. Subsamples (0.2 g) of the ground plant

FIGURE 1. Possible changes in the labile/bioavailable metal/metalloid pool during and after bioavailable contaminant stripping (BCS).

![FIGURE 1. Possible changes in the labile/bioavailable metal/metalloid pool during and after bioavailable contaminant stripping (BCS).](image)

![FIGURE 2. Cross section of (a) the rhizobox-design used and (b) a DGT device deployed on soil using an acrylic plate (gels are shown proportionally larger for illustrative purposes).](image)
material were digested in a microwave (mls 1200 mega, Milestone) using a mixture of H₂O₂/HClO₂/HNO₃ (0.5/1/6 mol).

Unlike most hyperaccumulators that belong to the Brassica family (10), ferns (Pteridophyta) including P. vittata may exhibit symbiosis with mycorrhizal fungi (18, 23). Hence, a randomized sample of the fresh root material (one-third of fresh weight) was screened for potential mycorrhizal infections following standard procedures (27).

A five-step sequential extraction procedure (SEP) for As (28) was performed on soil of all compartments. The first extraction step, 0.05 M (NH₄)₂SO₄, represents the most labile As of the scheme. For the second extraction, 0.05 M NH₄H₂PO₄ was used to assess As that can be specifically replaced by phosphate. Although not as easily released as the first fraction, this can also be considered as labile. The following three steps (targeted at As bonded to amorphous and crystalline hydrous oxides of Fe and Al, residual) can be considered as nonlabile under aerated conditions. Supernatants of the extracts were centrifuged (1700g) and filtered through 0.45-μm hydrophilic cellulose acetate membrane filters (Sartorius). Soil pore water and extracts were frozen at −18 °C until analysis.

Redox potentials of bulk and rhizosphere soil were measured in soil slurries (10 g/50 mL of deionized water) continuously stirred with a magnetic stirrer using a commercially available Pt-redox electrode fitted with a Ag/AgCl reference electrode (SenTix ORP, WTW). Gaseous He was used for protection. This membrane material had been shown to be an effective concentration (Cₑ) using eq 3 (16):

\[ Cₑ = \frac{C/Dk}{\ln (t)} \]  
(3)

where \( Cₑ \) is the concentration that would have to be present in soil solution to supply the measured mass of metal accumulated by DGT if it was supplied solely by diffusion. It is therefore larger than the concentration in soil solution. Here it represents, as a simple effective concentration, the available As concentration from both soil solution and solid-phase labile pool. \( R_{\text{diff}} \) is the ratio of the mean interfacial concentration due to supply by diffusion only to the initial or bulk concentration in soil solution. It was calculated using the numerical model of the DGT—soil system, DIFS (17). Input parameters to this model of soil porosity (\( \psi \)) and diffusion coefficient in soil solution (\( Dₛ \)) were calculated using eqs 4 and 5 (37):

\[ \psi = \frac{\text{volume of porewater}}{\text{volume of solid phase + porewater volume}} \]  
(4)

\[ Dₛ = Dγ/(1 - \ln \phi^2) \]  
(5)

where \( Dₛ \) is the diffusion coefficient in water. As DIFS is a 1-D model, a correction factor derived from a 2-D model was applied to obtain the value of \( R_{\text{diff}} \) for 2-D diffusion.
As the DGT device continuously takes metals out of the soil system during deployment, it is inevitable that for most cases some depletion of the concentration of metal in soil solution at the interface of the DGT device and soil will occur (38). The extent of the depletion is indicated using the ratio (R) of \( C_{\text{DGT}} \) to the independently measured initial concentration (using rhizon samplers) of As in the soil solution (\( C_{\text{soln}} \)):

\[
R = \frac{C_{\text{DGT}}}{C_{\text{soln}}}
\]  

The value of R is affected by the solid-phase labile pool size (\( K_d \)) and the response time of the soil to the depletion (\( T_r \)) (17). The DIFS model quantifies the relationship between R, \( K_{\text{uv}} \), and \( T_r \). As \( T_r \) is directly related to the rate constant of the supply process from solid phase to solution (\( k_{-1} \), \( k_{-2} \) can be obtained if \( R \) and \( K_d \) are known.

**Elemental Analysis and As Speciation.** Total elemental concentrations of extracts and digests were determined by inductively coupled plasma sector field mass spectrometry (ICP–SFMS; Element, Finnigan MAT, Bremen, Germany). Plant digests, samples of the SEP, and iron oxide digests of DGT were analyzed for As, and soil pore water was for As and Fe. Analysis of the As species As\( ^{VI} \), As\( ^{III} \), monomethylarsonate (MMA), dimethylarsinate (DMA), and arsenobetain (AB) in soil pore water was performed by HPIC–ICP–SFMS (39). Soil pore water was also analyzed for dissolved organic carbon (DOC) using a total C/N analyzer (DIMA-TOC 100, Dimatec, Essen, Germany).

**Results and Discussion**

**Arsenic Accumulation in P. vittata.** Mean As concentrations in various plant parts of P. vittata followed the order young fronds > old fronds > rhizomes > roots. Young fronds accumulated 2580 mg of As kg\(^{-1}\) whereas As concentration in roots was only 119 mg kg\(^{-1}\). The concentration factor (ratio young fronds: roots) for As was 22, revealing true hyperaccumulation (40). Ferns grown for 3 months in pots containing the same soil accumulated 8250 mg of As kg\(^{-1}\), confirming that As concentrations in fronds of P. vittata increase during growth time (11). Arsenic hyperaccumulation in the rhizob oxes occurred in the absence of mycorrhizal associations as none of the ferns were infected with arbuscular mycorrhizal fungi.

**Rhizosphere Manipulation by P. vittata.** Expectedly, pH was not affected by root activities of P. vittata. The high buffer capacity of the soil for protons is evident from its carbonate content, so no changes in pH were anticipated. Other studies also suggest that root-induced pH changes are not involved in the phenomenon of metal hyperaccumulation (41).

The redox potential in the rhizosphere decreased by 25.5 mV relative to bulk soil (Figure 3a). Iron concentration in the rhizosphere soil solution increased 2.8-fold relative to bulk soil (Figure 3b). Iron oxides/hydroxides are the primary sorption site of As in soils (1, 28, 42). Increased Fe solubility along with lower redox potential in the rhizosphere suggests root-induced reductive co-dissolution of As from iron oxides/hydroxides. However, a decrease in redox potential by 25.5 mV appears to be too small to explain the drastic increase in Fe solubility. The latter seems rather related to the almost doubled DOC concentrations in the rhizosphere soil solution (Figure 3c), causing Fe complexation and, hence, higher total concentrations of Fe in solution. Iron-efficient plants, exhibiting specific response mechanisms such as enhanced root exudation, are particularly known from calcareous environments where Fe availability is low (19, 43). The natural occurrence of P. vittata is mainly confined to calcareous soils (23). Hence, root–response mechanisms to improve Fe uptake may play a role in Fe acquisition by P. vittata grown on the calcareous experimental soil.

**Depletion of Labile Arsenic in the Rhizosphere and As Speciation.** Despite the large uptake of As in P. vittata, concentration of As in the soil solution was not significantly decreased in the rhizosphere as compared to bulk soil (Figure 3d). The sustained concentration of As in soil solution seems to be related to the large buffer capacity for As of the experimental soil. Assessment of As speciation revealed that only As\( ^{V} \) was present in bulk and rhizosphere soil solution. Hence, no root–microbe-induced transformation processes of As\( ^{V} \) to any other species (As\( ^{III} \), MMA, DMA, AB) occurred.
The observed decrease of the redox potential was not sufficient to cause a reduction of $As^{3+}$ to the more mobile and bioavailable $As^{5+}$ species. P-deficient plants show enhanced exudation of organic compounds, such as citric and malic acid (13, 44). Similarly, the observed increase of DOC in the rhizosphere may have caused $As$ desorption from the labile pools by ion competition (18), contributing to virtually sustained $As$ concentrations in the rhizosphere soil solution.

In contrast, $P$. vittata significantly decreased the most labile $As$ fraction (0.05 M ($NH_4$)$_2$SO$_4$ extractable) of the SEP in the rhizosphere (central compartment) relative to bulk soil by 30% (Figure 3e). A similar decrease in the 2-mm compartment, free of root hairs, demonstrates that root hair-derived artifacts due to disruption of root hairs and concomitant release of ions as previously shown for $K$ (45) did not occur. The difference in the most labile $As$ fraction between bulk and rhizosphere soil accounted only for 8.9% of total $As$ accumulated in the ferns, indicating that $As$ was primarily acquired from less available pools. This may also include $As$ resupplied from such pools into more available fractions. However, total $As$ accumulation in the fern was exceeded by the 0.05 M NH$_4$H$_2$PO$_4$-extractable pool (second step of the SEP) by a factor of 15. Hence, $As$ depletion in the latter and in pools obtained in consecutive steps of the SEP was not detectable after only one cropping. Figure 3f shows a mass balance of the NH$_4$H$_2$PO$_4$, (NH$_4$)$_2$SO$_4$, soil solution, and total plant pools (mg kg$^{-1}$), illustrating the considerations above. The pool ratios, normalized to the soil solution pool, were 3531, 88, 1, and 234. These numbers reveal that the soil solution and (NH$_4$)$_2$SO$_4$ pools were too small to explain the total accumulation of $As$ in the fern. The white bar of the (NH$_4$)$_2$SO$_4$ pool (Figure 3f) represents the reduction in the rhizosphere relative to bulk soil, indicating that resupply from labile pools could not sustain the mobilization of the most mobile (NH$_4$)$_2$SO$_4$ pool size. Similar to the NH$_4$H$_2$PO$_4$ pool and consecutive fractions, a reduction of the total $As$ pool could not be detected as it exceeded total plant uptake by a factor of 187. However, total $As$ concentrations in soil solution were virtually sustained, even though the most labile $As$ pool of the SEP extracted by 0.05 M ($NH_4$)$_2$SO$_4$ was depleted. From adsorption studies on soils, it is known that organic acids are rapidly adsorbed on mineral surfaces after addition. Hence, large quantities of organic compounds need to be exuded by plant roots in order to cause a substantial increase of rhizosphere solution concentrations (46, 47) and to displace adsorbed anions such as phosphate and arsenate (46, 48). Therefore, the increased concentrations of DOC in the rhizosphere of $P$. vittata suggest that arsenate was desorbed from the solid phase by ion competition, contributing to the sustained $As$ concentrations in the rhizosphere soil solution. We hypothesize that sites that previously adsorbed arsenate were successively occupied by organic compounds released by roots of $P$. vittata. This process does not necessarily represent active mobilization to enhance $As$ uptake by $As$ hyperaccumulators. It could be also a mere side effect in response to Fe and P nutrition. Increased concentrations of DOC (1.86-fold) along with enhanced Fe solubility (2.8-fold) in the rhizosphere suggests DOC-triggered dissolution of Fe from iron hydroxide surfaces, which may have resulted in co-dissolution of $As$ (18). Both processes can explain the observed reduction of ($NH_4$)$_2$SO$_4$-extractable $As$ and sustained $As$ in soil solution.

**Reduction of DGT-Induced Arsenic Fluxes in the Rhizosphere.** DGT deployments locally lower metal/metalloid concentrations in the soil solution at the DGT–soil interface. Unlike soil solution measurements, the accumulated mass of metals/metalloids in DGT depends on both soil solution concentration and the kinetics of resupply from labile pools in the solid phase (16, 17). The DGT measurement can be interpreted as an effective concentration ($C_E$), which accounts for the enhancement in the solution concentration that a plant effectively experiences due to supply from the solid phase. For Cu, it was shown that the DGT–soil system, represented by $C_E$, could best mimic uptake in Lepidium heterophyllum Benth. as compared to measurements of Cu by EDTA extraction in soil solution and as free Cu$^{2+}$ activity (16).

Here we used DGT for the first time to study elemental depletion in the rhizosphere. Though no reduction of As pools other than the most labile fraction could be detected, depletion and limited resupply of As from labile pools in the solid phase were indicated by a 19.3 % decrease of As fluxes to DGT after only one cropping (Figure 4a). This was confirmed by a reduction of the DGT-induced As flux toward the root surface using a rhizobox system that allows the assessment of gradients in the rhizosphere (Figure 4b). The As flux was about 55% reduced in a zone within 3 mm from the root surface, followed by a steep gradient to bulk soil. The thickness of this zone corresponds very well to the length of the majority of the root hairs (some were even up to 6 mm long). In accordance to all plants investigated so far, physiological evidence has shown that arsenate uptake by $P$. vittata occurs via P transport systems (49). Therefore, the long root hairs of $P$. vittata very likely contribute also to the large As uptake capacity of this fern, similar to P uptake in P-efficient barley cultivars (50).

The DGT measurement also allows calculation of the concentration of As at the surface of the device ($C_{DGT}$) and of $C_E$. Like the concentration in the soil solution, both $C_{DGT}$ and $C_E$ were diminished in the rhizosphere (Table 1). The ratio (R) of $C_{DGT}$ to the concentration in the soil solution is sustained by resupply from the solid phase (16, 17). The slightly lower R value for the rhizosphere combined with a lower in soil solution indicates an appreciably poorer supply from the solid phase to the solution in the rhizosphere. The dynamic model DIFS of the soil–DGT system can be used to obtain information on the kinetics of supply from solid phase to solution (17). Information is

![Figure 4](https://example.com/figure4.jpg)

**TABLE 1. DGT-Interpreted Properties of the Rhizosphere and Bulk Soil**

<table>
<thead>
<tr>
<th>Property</th>
<th>bulk soil</th>
<th>rhizosphere soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_E$ (µg L$^{-1}$)$^a$</td>
<td>829</td>
<td>667</td>
</tr>
<tr>
<td>$C_{DGT}$ (µg L$^{-1}$)$^b$</td>
<td>92.8</td>
<td>74.7</td>
</tr>
<tr>
<td>$R^c$</td>
<td>0.74</td>
<td>0.68</td>
</tr>
<tr>
<td>$K_d$ (L kg$^{-1}$)$^d$</td>
<td>1140</td>
<td>1340</td>
</tr>
<tr>
<td>$T_s$ (s)$^e$</td>
<td>36.7</td>
<td>99.8</td>
</tr>
<tr>
<td>$k_1$ (s$^{-1}$)$^f$</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$4.4 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

*a Effective concentration. b Concentration of As at the interface of the DGT device and the soil. c $R = C_{DGT}/C_E$. d Distribution coefficient of the labile solid-phase pool ($NH_4$H$_2$PO$_4$ pool)/soil solution concentration. e Response time of the soil to As depletion. f First-order rate constant of As supply from solid phase to solution.

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**FIGURE 4. Reduction of DGT-induced As fluxes in the rhizosphere:** (a) main experiment and (b) highly resolved gradient in the rhizosphere of additional experiment. Error bars represent SEs.
required about the labile solid-phase pool in the form of a distribution coefficient ($K_d$). The plant uptake studies suggested that the fraction of $As$ released by $NH_2HPO_4$ is likely to be available to an $As$ sink such as DGT. This was used to estimate $K_d$ values for the rhizosphere and bulk soil of $1340$ (SE $\pm 100$) and $1140$ (SE $\pm 190$) L kg$^{-1}$, respectively. These values, along with the measured values of $R$ and other soil parameters (17), were used to calculate the response time of the soil system ($T_r$) and the first-order rate constant for release from the solid phase to solution ($k_-$) (Table 1). The response of the rhizosphere soil is about two-thirds slower than the response of the bulk soil, due almost entirely to the slower rate of release. This finding is consistent with the kinetic most available $As$ being used initially by the plant such that the residual $As$ cannot be supplied so quickly.

Because total concentrations are not a good measure for pollutant bioavailability, a remediation strategy to improve, for example, crop quality may not necessitate the reduction of total concentrations down to threshold values. A sustained decrease in the phytoavailable fraction may be sufficient. This remediation strategy, termed BCS, may be used for phytoextraction (15). Diminished trace element fluxes as measured by DGT have been shown to correspond to lower uptake by plants (16). Hence, DGT holds promise as a powerful tool for monitoring the progress of BCS-based phytoextraction. Application of BCS as a remediation strategy will require also quality control of the remediation process with respect to its longevity. Though reductions of phytoavailable pools may be achieved quite rapidly, as shown in our experiment, its resupply from less available pools by, for example, buffer reactions has to be also considered (Figure 1). This depends on the total pollutant concentration in soil and on a range of soil properties (e.g., texture, organic matter, pH, oxides concentrations) that modify pollutant bioavailability. DGT-based risk assessment lumps all these properties to one single key parameter, is more sensitive and meaningful to root-induced changes than chemical extraction, and represents therefore an effective means to study pollutant bioavailability during and after phytoextraction has ceased. This will be crucial for the future development of BCS-based phytoextraction and its implementation into a common cleanup practice.

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**Note Added after ASAP Posting**

This paper was released ASAP on 10/11/2003 with an error in the caption to Figure 3. The correct version was posted on 10/14/2003.

**Literature Cited**


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