Effect of soil characteristics on Cd uptake by the hyperaccumulator *Thlaspi caerulescens*

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Higher total/extractable Cd in soil, lower pH and coarser texture were associated with higher Cd concentration by *Thlaspi caerulescens*.

Abstract

The influence of soil characteristics on the phytoremediation potential of *Thlaspi caerulescens* is not well understood. We investigated the effect of soil pH and Cd concentration on plant Cd uptake on one soil type, and the variation in Cd uptake using a range of field contaminated soils. On soils with total Cd concentrations of 0.6–3.7 mg kg⁻¹, *T. caerulescens* (the Ganges ecotype) produced greater biomass in the pH range 5.1–7.6 than at pH 4.4. The highest plant Cd concentration (236 mg kg⁻¹) and Cd uptake (228 mg pot⁻¹) were observed at pH 5.1. On soils with total Cd concentrations of 2.6–314.8 mg kg⁻¹, shoot Cd concentrations were 10.9–1196 mg kg⁻¹. Multiple regression analysis indicated that higher Cd in soil, low pH (within the range of > 5) and coarser texture were associated with higher Cd concentration and Cd uptake by *T. caerulescens*.

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Keywords: Cadmium; Hyperaccumulator; Phytoremediation; Contaminated soil; *Thlaspi caerulescens*

1. Introduction

Soil pollution with heavy metals is a major environmental problem worldwide. Since the beginning of the industrial revolution, pollution of the environment, including soil, with toxic metals has accelerated dramatically. About 90% of the anthropogenic emissions of heavy metals have occurred since 1900 AD (Nriagu, 1996). Accordingly, it is now well recognized that human activities lead to a substantial accumulation of heavy metals in soils on a global scale, e.g. 5.6–38×10⁶ kg Cd year⁻¹ (Nriagu and Pacyna, 1988). Toxic heavy metals accumulate in soils due to many processes such as atmospheric deposition from industrial activities or power generation; disposal of wastes such as sewage sludge, animal manures, ash, domestic wastes or by-products; irrigation and flood or seepage waters and the utilization of fertilizers, lime, or agrochemicals. Their accumulation in soil can result in a decrease in soil microbial activity, biodiversity and soil fertility, yield losses of crops, and even damage on animal and human health through the food chain (McLaughlin and Singh, 1999). This applies especially to Cd, since this element is extremely toxic to humans, as evidenced in “Itai-itai” disease in Japan (Kobayashi, 1978). To protect the food...
chain from Cd contamination, therefore, national and international criteria for Cd concentrations in crops and soil have been established. Examples of these include the maximum allowed value of 1.0 mg Cd kg$^{-1}$ for rice grain used to designate contaminated farmland in Japan (the Agricultural land soil pollution prevention law, 1971) and the 0.2 mg Cd kg$^{-1}$ upper limit for rice and wheat grain (European Commission, 2001). In this context, remediation of soils polluted with Cd is far more necessary than ever, as is the prevention of soil pollution with Cd.

Against this background, phytoremediation, defined as the use of green plants to remEDIATE contaminated soils or waters, has been highlighted as a promising technique for the removal of heavy metals from soils (McGrath et al., 2002; Salt et al., 1995). For heavy metals including Cd, phytoextraction, in which metal-accumulating plants are used to transport and concentrate metals from the soil into the harvestable parts of plants, is considered to be a promising method because it offers the benefits of operating in situ, being low cost and environmentally sustainable because the soil can be reclaimed without a concommitant decrease in soil fertility (Ebbs et al., 1997; McGrath et al., 2002). One approach for phytoextraction is to use hyperaccumulator plants with exceptional metal-accumulating capacity to extract metals from the soil (Brown et al., 1995; McGrath et al., 1993). One of these species, *Thlaspi caerulescens*, is known to be a hyperaccumulator of Cd and Zn (Baker et al., 1994; Brown et al., 1995; Robinson et al., 1998; Lombi et al., 2000; Schwartz et al., 2003; Zhao et al., 2003). Due to the promising potential of natural hyperaccumulators such as *T. caerulescens* for phytoextraction, many studies have been carried out on the physiological mechanisms of the hyperaccumulation, especially in relation to secretion of root exudates (Zhao et al., 2001), the response of root growth to heterogenous Zn or Cd patches (Schwartz et al., 1999; Whiting et al., 2000; Yanai et al., 2003), and physiological and molecular characterisation of Zn and Cd transporters in roots (Assunção et al., 2001; Lasat et al., 1996; Lombi et al., 2001, 2002; Pence et al., 2000). Limited information is available, however, on the relationship between Cd uptake by *T. caerulescens* and soil characteristics, even though it is well known that soil properties have a large influence on metal bioavailability (Adams et al., 2004; Alloway, 1995; Yanai et al., 2004). As a consequence, basic information is needed for the establishment of rational phytoremediation for field conditions and with different soil types.

The objectives of this research were, therefore, to (1) investigate the effect of soil pH and Cd concentration on plant Cd concentration and the amount of Cd accumulated in the shoots, and (2) evaluate such plant performance based on soil total/extractable Cd concentration and other soil characteristics using a wide range of contaminated soils.

## 2. Materials and methods

### 2.1. Soil preparation

In the first experiment, soils were collected from the top 20 cm layer from the field plots of a long-term liming experiment at Rothamsted, England (Sanders et al., 1986). Soil pH was maintained at four levels of around 4, 5, 6 and 7.5 in the field for some 30 years. Samples of these four soils were then taken and each was amended with three levels of Cd (as CdSO$_4$): 0, 1.5 and 3.0 mg kg$^{-1}$ 10 years ago and used to grow ryegrass for one season in a glasshouse (Knight, 1996). After the ryegrass was harvested, soils were air-dried and stored at room temperature for over 7 years before being used in the present study. For the second experiment, 14 soils were collected from the top 20 cm layer from contaminated sites or experimental plots in UK, Belgium and France. These soils contained elevated levels of heavy metals for geogenic reasons or due to anthropogenic contamination. All soils were air-dried, and sieved to < 2 mm before use. Detailed information of the soil samples and their physico-chemical characteristics are shown in Table 1.

### 2.2. Pot experiment

Plastic pots 8.4 cm in height and 9.6 cm in diameter were used. Air-dried soil equivalent to 300 g of oven dry soil was placed into each pot after fertilization at the rates of 100, 50 and 100 mg kg$^{-1}$ of N, P and K, respectively, as NH$_4$NO$_3$, K$_2$HPO$_4$ and KCl. Each soil, including 14 European contaminated soils and 12 Rothamsted soils of different pH and Cd amendment combinations, was replicated in three pots. Soil solution samplers (Eijkelkamp, Rhizon SMS-MOS-F) were installed in one pot of each soil.

Three seedlings of *T. caerulescens* (the Ganges ecotype), which were 3 weeks old after germination, were transplanted into each pot and grown in a glasshouse for 40 days. The Ganges ecotype from southern France was used in this experiment because it possesses a superior ability to hyperaccumulate Cd compared to populations from other regions (Lombi et al., 2000; Zhao et al., 2003). Deionised water was added every 1 or 2 days throughout the experiment to keep the water content near to field capacity. Soil solution samples were collected at 7 days after transplanting at field capacity, 12 h after watering. At the end of the experiment, plant shoots were harvested, washed with deionised water, and dried at 70 °C for 24 h.

### 2.3. Plant and soil analysis

Plant samples were digested with a mixture of concentrated HNO$_3$ and HClO$_4$, and their Cd and Zn...
concentrations determined by ICP-AES (Applied Research Laboratories, Accuris). The concentrations of Cd and Zn in soil solutions were measured by ICP-AES. Soil total Cd and Zn were determined by ICP-AES after wet digestion with aqua regia. Extractable Cd and Zn were extracted with 1M NH₄NO₃ at a soil:solution ratio of 1:10 (Symeonides and McRae, 1977) and determined by ICP-AES. Soil pH and EC were determined electrochemically. Organic carbon content was determined by the dichromate oxidation method (Tyurin, 1931). Clay, silt and sand content were determined by the sieving and pipette method.

Table 1
General information, metal concentrations, pH and other physico-chemical properties of the soils

<table>
<thead>
<tr>
<th>Site</th>
<th>Source of contamination</th>
<th>Total Cd mg/kg</th>
<th>Total Zn mg/kg</th>
<th>Ex-Cd mg/kg</th>
<th>Ex-Zn mg/kg</th>
<th>Solution Cd mg/L</th>
<th>Solution Zn mg/L</th>
<th>pH</th>
<th>EC µS/cm</th>
<th>Organic C %</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
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<td>1.39</td>
<td>4.40</td>
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<td>1.5</td>
<td>56.9</td>
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<td>22.4</td>
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<td>7.6</td>
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<td>1.09</td>
<td>4.39</td>
<td>505</td>
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<td>56.9</td>
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<td>0.443</td>
<td>1.78</td>
<td>4.38</td>
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<td>0.000</td>
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<td>0.006</td>
<td>0.04</td>
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<td>59.3</td>
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<td>7.55</td>
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<td>1.6</td>
<td>59.3</td>
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</table>

2.4. Statistical analysis

In addition to descriptive statistics, correlation analysis was also carried out. Stepwise multiple regression analysis was also carried out using selected soil properties as independent variables and Cd-related plant data as the dependent variable, respectively. The statistical software SYSTAT 8.0 was used in the analysis (SPSS Inc., 1998).

3. Results and discussion

3.1. Effect of pH and Cd concentration in soil on Cd uptake by T. caerulescens (Experiment 1)

The concentrations of total and NH₄NO₃ extractable Cd and Zn, as well as some physico-chemical properties of the 12 soils from the Rothamsted long-term liming experiment are shown in Table 1. The soils had similar general properties because the experiment was carried out in a relatively small area: clay loam texture with about 20% of clay, 1.6% organic C and moderate electrical conductivity. There was a slight increase in total soil Cd with increasing soil pH (Fig. 1a). As expected, soil pH had large influence on the extractability of Cd by NH₄NO₃ (Fig. 1b). For example, in the high Cd (3 mg kg⁻¹) treatments, extractable Cd decreased by 50-fold when soil pH increased from 4.4 to 7.8. Similar trends were also observed for the relationship between pH and Cd concentration in the soil solution (Fig. 1c).

Plant biomass, Cd concentration and Cd uptake by T. caerulescens are shown in Fig. 2a–c. Fig. 3 also shows the appearance of plant growth at the end of the experiment. The growth was relatively stable (not...
significantly different) in the soil pH range 5–7.6, i.e. 734–1426 mg pot$^{-1}$, which is equivalent to 1–2 ton ha$^{-1}$ based on the surface area of each pot (Fig. 2a). Plant growth was drastically reduced in the soil pH of 4.4. At pH 6 and 7.6, plant growth on the high Cd treatment was significantly higher than that in the control treatment ($p<0.01$). Roosen et al. (2003) showed that the effect of Cd on the growth of *T. caerulescens* was population dependent, with the positive effect only being observed in the populations from southern France. This positive effect suggests some unknown physiological role of Cd in the Ganges ecotype in addition to its extraordinary Cd tolerance. The patterns for Cd concentration in the shoots were very different from those of extractable Cd in soil. For example, Cd concentrations in shoots were less than 50 mg kg$^{-1}$ at
pH 4.4 and 7.6, irrespective of Cd concentration in soil (Fig. 2b). Concentrations were up to 236 and 121 mg kg$^{-1}$ at pH 5.1 and 6.1, respectively, suggesting considerable bioaccumulation of Cd from soil even in soils with relatively low Cd concentrations. This trend of decreasing Cd concentration with soil pH between the pH range of 5 and 7, also shown by Brown et al. (1994), was similar to that of extractable Cd in soil. The discrepancy at pH 4.4 is due to poor growth.

The amounts of Cd taken up by plants were calculated by multiplying plant biomass with Cd concentration in plant. As shown in Fig. 2c, they were less than 5 and 61 μg pot$^{-1}$ at pH 4.4 and 7.6, respectively, but as high as 228 and 169 μg pot$^{-1}$ at the pH 5.1 and 6.1, respectively, which are equivalent to 315 and 233 g Cd ha$^{-1}$. The decreasing trend of Cd uptake with pH at the range of 5.1 and 7.6 reflected the same trend as extractable Cd in soil. The bioaccumulation factor for Cd, calculated as the ratio of concentration in shoots to that of soil, was also soil pH and soil Cd dependent, with the highest value of 69 at pH 5.1 and total Cd 3.4 mg kg$^{-1}$ (Table 2). Bioaccumulation factors for Cd were generally 5–10 times higher than those for Zn, partly due to high affinity to Cd of the Ganges ecotype, as discussed in Zhao et al. (2003), and due to application of only Cd salt in this experiment (Zn was not added).

Based on these results, it is concluded that the favourable pH range for T. caerulescens to take up Cd would be between pH 5 and 6, and that the efficiency of phytoremediation of Cd contaminated soils using the hyperaccumulator T. caerulescens depends on soil pH and the extractable and total Cd in soil.

3.2. Cd uptake by T. caerulescens from field contaminated soils (Experiment 2)

The concentrations of Cd and Zn and other physicochemical properties of 14 contaminated soils collected in some European countries are shown in Table 1. The soils used had a wide range of properties: textural classes ranging from sand to light clay, organic C from 1.2 to 14.6% and pH from 4.3 to 7.6. Total and NH$_4$NO$_3$ extractable Cd concentrations also varied greatly, ranging from 2.6 to 314.8 mg kg$^{-1}$ and from 0.02 to 7.35 mg kg$^{-1}$, respectively. It should be noted that there was a strong correlation between Cd and Zn concentrations ($p<0.01$), reflecting the history of artificial or geogenic contamination.

Shoot biomass, the concentrations and uptakes of Cd and Zn by T. caerulescens from the contaminated soils are shown in Table 2. Shoot biomass ranged from 250 to 2812 mg pot$^{-1}$ (equivalent to 0.35 to 3.89 t ha$^{-1}$), suggesting highly variable growth depending on the soil type. Cd concentration in the shoots ranged from 10.9 mg kg$^{-1}$ to 1196 mg kg$^{-1}$, reflecting the Cd concentration in the soils as well as their physicochemical characteristics. The lowest concentration was obtained from the soil in Avonmouth, UK, which had very low pH (4.3) and the highest clay content (44%) as well as relatively low Cd concentration (5.6 mg kg$^{-1}$). The highest concentration was obtained from the soil from Shipham, UK, which had the highest Cd concentration (314.8 mg kg$^{-1}$), relatively high pH (6.6) and a medium texture. The amounts of Cd taken up into the shoots reflected both biomass and Cd concentrations, ranging from 2.7 to 3364 μg pot$^{-1}$ (equivalent to
Large Cd uptakes were generally associated with higher total and extractable Cd in soil. However, lower Cd uptake was not necessarily associated with lower total Cd in soil. This was because plant growth and Cd uptake were reduced by other factors such as the low pH of the Avonmouth soil, low extractable Cd in combination with very high pH of the Bridgets soil and very coarse texture probably associated with poor nutrient supply in the Budel soil. Nevertheless, there were significant positive relationships between log-transformed Cd concentration in soil and log-transformed Cd concentration or content in shoots, as shown in Fig. 4a and b. This result indicates the general potential of *T. caerulescens* to remediate soils under the field conditions with variable soil characteristics. It should be also noted that there was no significant relationship between soil Zn concentration and Cd/Zn ratio in shoots, suggesting no inhibition of Zn on Cd uptake by the Ganges ecotype. This is consistent with the finding from a hydroponic study (Lombi et al., 2001). In addition, considering only moderately Cd contaminated soils (1–5 mg Cd kg⁻¹) with moderate pH range (5–7), and assuming an average biomass and Cd concentration of 1124 mg pot⁻¹ (equivalent to 1.55 ton ha⁻¹) and 138 mg Cd kg⁻¹, respectively, the average Cd content in plant shoots amounted to 145.1 μg pot⁻¹ (201 g ha⁻¹) with a bioaccumulation factor of 46.6. Accordingly, an average 17% of the total soil Cd was removed in 40 days, suggesting the potential of this plant for the phytoremediation of moderately contaminated soils.

### 3.3. Estimation of Cd uptake by *T. caerulescens* based on selected soil characteristics

Stepwise multiple regression analysis was performed to obtain the optimal model for predicting Cd concentration in and the amount of Cd uptake by *T. caerulescens*. The analysis was restricted to 22 soils from both experiments with pH above 5, because pHs below this affected plant growth severely, as discussed in the previous sections. Total and NH₄NO₃-extractable Cd in soil ranged from 0.6 to 314.8 mg kg⁻¹ and from 0.02 to 7.35 mg kg⁻¹, respectively, and Cd concentration and Cd content in the shoots ranged from 4.9 to 1196 mg kg⁻¹ and from 4.3 to 3364 μg pot⁻¹ (equivalent to 6–4650 g ha⁻¹), respectively. Log-transformed Cd concentration or Cd uptake was, therefore, used as dependent variable, and four soil characteristics; i.e. log-transformed total Cd or extractable Cd, pH, organic C and clay content were considered as independent variables.
used as independent variables. These soil characteristics were chosen to minimize co-linearity among the independent variables. Since no a priori information was available about the regression model, a linear combination of the first degree terms of the variables was assumed. As a result, the following equations were obtained with significance levels of $\alpha = 0.15$:

Predicted (log-shoot Cd concentration)

\[ \text{Predicted} = 0.709 \times (\log\text{-total soil Cd}) + 1.41 \quad R^2 = 0.60 \]
\[ = 0.641 \times (\log\text{-extractable Cd}) + 0.187 \times (\text{pH}) + 1.17 \quad R^2 = 0.64 \]

Predicted (log-Cd uptake)

\[ \text{Predicted} = 0.876 \times (\log\text{-total soil Cd}) + 0.029 \times (\text{clay}) + 1.000 \quad R^2 = 0.59 \]
\[ = 0.795 \times (\log\text{-extractable Cd}) + 0.034 \times (\text{clay}) + 0.222 \times (\text{pH}) + 0.529 \quad R^2 = 0.63 \]

These results suggest that log-transformed total or extractable Cd in combination with pH and clay content explained about 60% of the total variance of the log-transformed Cd concentration or Cd uptake in shoots. In general, total and extractable Cd in soil contributed more than 80% of the variances the equations explained, suggesting their importance as the determining factors. This would be because soil samples used in this experiment varied widely in their Cd concentration.

Similar multiple regression analysis for Zn in shoot produced the following equations:

![Fig. 4. Relationship between total Cd concentration in soil and plant performance on the field contaminated soils. (a) Cd concentration in shoots; (b) Cd uptake into shoots.](image-url)
Predicted (log-shoot Zn concentration)
\[ = 0.569 \times (\text{total soil Zn}) - 0.252 \times (\text{pH}) + 3.00 \]
\[ = 0.335 \times (\text{extractable Zn}) + 0.021 \times (\text{organic C}) + 2.62 \]
\[ R^2 = 0.80 \]
\[ R^2 = 0.86 \]

Predicted (log-Zn uptake)
\[ = 0.629 \times (\text{total soil Zn}) - 0.232 \times (\text{pH}) + 2.87 \]
\[ = 0.414 \times (\text{extractable Zn}) + 0.024 \times (\text{clay}) + 2.435 \]
\[ R^2 = 0.76 \]
\[ R^2 = 0.76 \]

These results suggest that about 80% of the total variance of the log-transformed Zn concentration or Zn uptake in shoots were explained with similar equations to those for Cd, suggesting similar controlling mechanisms of Cd and Zn in soil-plant system.

To investigate the relationship under relatively low to moderate Cd contamination, stepwise multiple regression analysis was performed for the 14 soils with total Cd concentration in soil less than 5 mg kg\(^{-1}\) with soil pH > 5. In this case Cd concentration and amount of Cd uptake in the shoots and soil total and extractable Cd concentration were not log-transformed because the ranges of the variables were generally within one order of magnitude. As a result, the following equations were obtained with significance levels of \(\alpha = 0.15\):

Predicted shoot Cd concentration
\[ = 34.8 \times (\text{total soil Cd}) - 37.2 \times (\text{pH}) - 8.5 \times (\text{clay}) + 383.4 \]
\[ = 200.9 \times (\text{extractable Cd}) - 11.6 \times (\text{clay}) + 11.7 \times (\text{organic C}) + 231.3 \]
\[ R^2 = 0.70 \]
\[ R^2 = 0.85 \]

Predicted Cd uptake
\[ = 48.8 \times (\text{total soil Cd}) - 46.1 \times (\text{pH}) + 257.9 \]
\[ = 192.9 \times (\text{extractable Cd}) - 7.21 \times (\text{clay}) + 181.8 \]
\[ R^2 = 0.73 \]
\[ R^2 = 0.66 \]

In this case, total or extractable Cd in combination with pH, clay content and organic C explained about 70–80% of the total variance of the measured Cd concentration or Cd uptake in shoots. Again, total and extractable Cd in soil had the greatest contributions to the prediction, but in this case, soil total Cd or extractable Cd contributed to about 50% and 80% of the explained variance by the equations, respectively. In this sense, extractable soil Cd can be a good indicator by itself, but total soil Cd can be used with pH and clay content for more reliable prediction. It should also be noted that pH and clay content had a negative relationship with predicted Cd concentration and Cd uptake in plant, suggesting lower pH (within the range above 5) and coarser texture are generally associated with higher Cd concentration and Cd uptake by \(T. caerulescens\). In conclusion, total or extractable Cd concentration in soil was the dominant factor for the prediction of Cd concentration and Cd uptake in plant, and soil characteristics such as pH, clay content and organic C should be taken into account for the evaluation of the phytoremediation potential of \(T. caerulescens\) on contaminated soils with different soil characteristics.

4. Conclusions

Soil characteristics affected the performance of \(T. caerulescens\) (the Ganges ecotype) in hyperaccumulation of Cd from soil. The most favourable pH range for maximum Cd uptake was between 5 and 6. Cd addition up to 3.7 mg kg\(^{-1}\) had a significant positive effect on growth. In general, there was a positive relationship between log-transformed Cd concentration in soil and in shoots. Multiple regression analysis further indicated that lower pH (but not below 5) and coarser texture are generally associated with higher Cd concentration and Cd uptake by \(T. caerulescens\), as well as higher total or extractable Cd in soil. In conclusion, the potential of the hyperaccumulator \(T. caerulescens\) for phytoremediation was validated for a variety of soils and soil characteristics. The main characteristics that should be taken into account for the evaluation of the phytoremediation potential of \(T. caerulescens\) on contaminated soils were characterised.

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References


