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Cadmium accumulation in six common plant species associated with soils containing high geogenic cadmium concentrations at Le Gurnigel, Swiss Jura Mountains

Raul Quezada-Hinojosa [a,1], Karl B. Föllmi [b,*], François Gillet [c,d], Virginie Matera [e]

[a] Institut de Géologie, Université de Neuchâtel, rue Emile-Argand 11, CH-2000 Neuchâtel, Switzerland
[b] Institut des Sciences de la Terre, Université de Lausanne, Géopolis, CH-1015 Lausanne, Switzerland
[c] UMR 6249 Chrono-environnement, Université de Franche-Comté, CNRS, 16 route de Gray, 25030 Besançon cedex, France
[d] Laboratory of Ecological Systems, École Polytechnique Fédérale de Lausanne, Station 2, CH-1015 Lausanne, Switzerland
[e] Institut National de Recherche et Sécurité, Rue du Morvan, CS 60027, 54519 Vandoeuvre-Les-Nancy, France

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ABSTRACT

The uptake of cadmium (Cd) was analyzed for six different perennial plant species growing in a wooded pasture of the Swiss Jura Mountains, where the soils are geogenically enriched in Cd (4.58 $mg \cdot kg^{-1}$ on average ($n = 36$); maximal value: 16.3 $mg \cdot kg^{-1}$). The six selected plants — *Hypericum maculatum* (*Hypericaceae*), *Alchemilla xanthochlora* (*Rosaceae*), *Cynosurus cristatus* (*Poaceae*), *Ranunculus acris* (*Ranunculaceae*), *Dactylis glomerata* (*Poaceae*) and *Acer pseudoplatanus* (*Sapindaceae*) — show variable Cd contents among the species and among individuals from the same family (*Poaceae*). Average Cd concentrations in the selected plants are in the 2–6 $mg \cdot kg^{-1}$ range and exceed the maximal Cd concentration tolerated in vegetal feed for animals, which is established at 1 $mg \cdot kg^{-1}$. High Cd concentrations in the soil result in a reduction of Cd accumulation in the shoots and a corresponding increase in the roots. This implies that Cd transfer coefficients from the soil/rhizosphere to the plant are inversely proportional to the total Cd concentrations in soils and do not depend on plant species but instead on soil type. Sequential chemical extractions reveal that variations in Cd distribution between the bulk soil and the corresponding rhizospheric soil occur mainly in the Cd-bearing phases, which are exchangeable, bound to carbonates, and associated with organic matter. This is principally due to the incorporation of root exudates, which modify pH and redox conditions of the rhizosphere. Elevated Cd concentrations in the shoots of *A. xanthochlora* (up to 8 $mg \cdot kg^{-1}$), *C. cristatus* (9 $mg \cdot kg^{-1}$) and *H. maculatum* (3 $mg \cdot kg^{-1}$) may represent a long-term hazard for livestock and human health since these plants are used either by grazing cattle or for medicinal purposes. On the contrary, *R. acris*, *A. pseudoplatanus*, and especially *D. glomerata* show lower Cd concentrations and are of minor concern with regards to their environmental impact.

1. Introduction

Cadmium (Cd) is a highly toxic element due both to its enhanced solubility in water and resulting mobility, as well as the low concentrations implied in developing its toxicity (e.g., Benavides et al., 2005; Das et al., 1997; Haghiri, 1973; Lockwood, 1976; Sikka and Nayyar, 2012). Cd-enriched soils are well known to have deleterious effects both on organisms within the soils as well as on the associated vegetation cover, through which it may enter the food chain (e.g., Das et al., 1997; Wahid et al., 2009). Elevated concentrations of Cd and heavy metals in general may impede soil enzyme activity, soil mitochondria growth, litter decomposition and soil respiration (e.g., Lagriffoul et al., 1998; Tyler et al., 1989; Yao et al., 2003). Plants may suffer from stunting, chlorosis, necrosis, and root and shoot growth limitation through the negative impact of Cd on the uptake, transport and use of biophile elements such as phosphorus (P), calcium (Ca), potassium (K) and iron (Fe) (Das et al., 1997; Liu et al., 2003/2004; Paschalidis et al., 2013; Sikka and Nayyar, 2012). Furthermore, Cd may impede respiration, photosynthesis, water uptake, cell division and induce genetic defects (e.g., Liu et al., 2009; Mohammad et al., 2009; Prasad, 1995; Sanita di Toppi and Gabrielli, 1999).

Apart from the initial Cd concentrations in soils and soil biogeochemical conditions, the accumulation, transport and distribution of Cd within plant systems is dependent on many different factors, such as plant species, root morphology, adsorption of Cd to chelators and peptides, exchange with zinc (Zn), Ca, and manganese (Mn), transpiration rates in leaves, etc. (Das et al., 1997; De Maria et al., 2013; Kashem and Singh, 2002; Tudoreanu and Phillips, 2004).

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* Corresponding author.
E-mail address: karl.foellmi@unil.ch (K.B. Föllmi).

[1] Present address: Caro 1070 y Velasco Galvaro, Oruro, Bolivia.

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In the French and Swiss Jura Mountains, Middle Jurassic (Bajocian) carbonates contain intervals, which are highly enriched in geogenic Cd (Quezada-Hinojosa et al., this volume). As a consequence, associated soils are naturally incorporating this element into their different mineralogical phases (Okopnik, 1997; Benitez, 1999; Prudente, 1999; Prudente et al., 2002; Dubois et al., 2002; Rambeau, 2006; Rambeau et al., 2010; Quezada-Hinojosa et al., 2009, this volume; Efimenko et al., 2014). This is the case at the site called "Le Gurnigel", which is located in the Jura Mountains, northeast of the "Col de la Vue des Alpes" (canton Neuchâtel, Switzerland). Soils at this site contain Cd concentrations with mean values around 4.6 mg·kg^{-1} ($n = 36$) and with a maximal value recorded in the subsoil of 16.3 mg·kg^{-1} (Quezada-Hinojosa et al., this volume). These values largely exceed the official Swiss indicative guideline value for soils fixed at 0.8 mg·kg^{-1} (Federal Authorities of the Swiss Confederation: OSol, 1998). As such, these soils may represent an environmental risk since the local herbaceous vegetation cover is susceptible to pump and stock this element both in roots and shoots, which are again used by grazing ungulate livestock. Consequently, Cd may gradually enter the food chain and jeopardize animal and human health.

Wermeille (1999) analyzed the total aerial biomass of a large set of local plant species from this area and reported Cd accumulations of up to 9 mg·kg^{-1} dry matter (DM), especially in some grass species. With this contribution, we follow up on this research and focus on the individual behavior of six different perennial plant species growing on soils with variable Cd concentrations at the Le Gurnigel site, and analyze Cd accumulations in roots and shoots separately for each species. *Hypericum maculatum* (*Hypericaceae*), *Alchemilla xanthochlora* (*Rosaceae*), *Cynosurus cristatus* (*Poaceae*), *Ranunculus acris* (*Ranunculaceae*), *Dactylis glomerata* (*Poaceae*) and *Acer pseudoplatanus* (*Sapindaceae*) were collected for this purpose. A statistical approach by means of ANOVA Kruskal–Wallis rank sum tests, is used to correlate the data and trace the variability in Cd behavior in plants.

The principal goal of this contribution is to evaluate the dependency of Cd concentrations in the selected plant species on the plant species itself, and on the Cd concentration in bulk and corresponding rhizospheric soils. For the speciation of the Cd concentrations in the soils, a sequential extraction method was used (Quezada-Hinojosa et al., this volume). A further goal was to estimate the degree of hazard each plant species represents for animal and human health.

2. Material and methods

2.1. Site description

The alpine meadow named "Le Gurnigel" (1300 m above sea level) is located on the northern face of the Mont d'Amin (canton Neuchâtel, Switzerland; Fig. 1). The majority of the site overlies Upper Bajocian oolitic limestone (Middle Jurassic). The geomorphology of the site consists of three main hillocks with slopes ranging from 20 to 30%. Soils at the site include thin solums (13–40 cm deep) formed mainly on top of the hill flanks, and deeper soils (80–140 cm deep), which are located in the accumulation zones or coombs formed by the conjunction of two hillocks. The soils at this site consist of Cambisols in general, and more specifically of Hypereutric Cambisols and Cambic Luvisols, which present strong signs of allochthony suggesting that they were formed on aeolian silt deposits of glacial origin (Okopnik, 1997; Quezada-Hinojosa et al., this volume). Fig. 2 shows the six selected soils classified according to the World Reference Base (IUSS Working Group WRB, 2006).

2.2. Plant sampling strategy

The three main soil types were sampled as a function of their degree in evolution, from poorly developed AC-horizon soils to better developed Cambic Luvisols. The three groups of soils were coded as follows: A = AC — soil horizons, C = Cambisols — Cambisols (Calcaric), and E = Cambisols — Cambic Luvisols. Okopnik (1997) determined the spatial distribution of Cd at the le Gurnigel site (Fig. 2c). Using the spatial Cd distribution map Okopnik (1997), two intervals of Cd concentrations were considered: interval X = 1–8 mg·kg^{-1} and interval Z = 8–16 mg·kg^{-1}. The sampling points were therefore coded as AX, AZ, CX, CZ, EX, and EZ (Quezada-Hinojosa et al., this volume: Fig. 1). The exact locations of these points were determined by means of a Garmin ETrex Summit GPS device. The selection of plant species was based on their ubiquity in each of the six sampling points in order to compare the behavior of the same species at each point whenever possible. Following this criterion, six major species of plants were collected (roots and shoots), which are presented in Table 1. In order to control the accuracy of the analyses, three individuals of each species were collected at each sampling point.

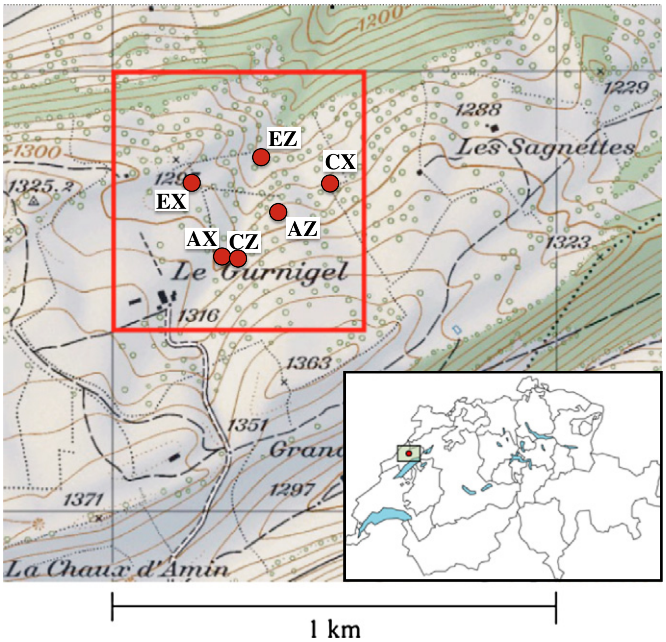

Fig. 1. Topographic map of the Le Gurnigel site with the six sampling points, reproduced with the permission of the Swiss Federal Office of Topography. Inset map of Switzerland is from Wikipedia.org.

All plant individuals were separated from other species, soil particles were washed away and roots were separated from shoots to analyze them individually. We also separated the bulk soil and the soils associated directly with the roots and carefully collected samples of the rhizospheric soil of each of the six plant species. Roots reached a maximal depth of 20 cm (Fig. 2).

2.3. Chemical analyses of trace metals in plants

Roots and shoots were freeze dried by lyophilisation during 63 h at −40 °C and a pressure of 0.05 Pa. Each part was weighed separately in order to measure its respective dried matter (DM) biomass.

Cd concentrations were determined separately in roots and shoots for each plant species as follows: Dried samples were milled using an agate mill and sieved through a 0.5 mm mesh. 150 mg of milled sample were subjected to microwave-assisted acid digestion in PTFE vessels under oxidizing conditions with a mixture composed of 6 ml of concentrated HNO_3 and 2 ml of H_2O_2. Dissolved samples were subsequently filtered through a 0.45 μm HVLP-Millipore filter before analysis. The filtered solutions were analyzed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS Perkin-Elmer Elan 6100).