



HAL
open science

Fate of cadmium in the rhizosphere of *Arabidopsis halleri* grown in a contaminated dredged sediment

Stéphanie Huguet, M.-P. Isaure, Valérie Bert, Agnès Laboudigue, Olivier Proux, Delphine Vantelon, Anne-Marie Flank, Géraldine Sarret

► **To cite this version:**

Stéphanie Huguet, M.-P. Isaure, Valérie Bert, Agnès Laboudigue, Olivier Proux, et al.. Fate of cadmium in the rhizosphere of *Arabidopsis halleri* grown in a contaminated dredged sediment. *Science of the Total Environment*, 2015, 10.1016/j.scitotenv.2015.07.026 . hal-01256222

HAL Id: hal-01256222

<https://minesparis-psl.hal.science/hal-01256222>

Submitted on 18 Jan 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1
2
3 **Fate of cadmium in the rhizosphere of *Arabidopsis halleri* grown in a**
4 **contaminated dredged sediment.**
5
6

7
8 Huguet Séphanie^{a,b,c,d}, Isaure Marie-Pierre^b, Bert Valérie^c, Laboudigue Agnès^{d,1},
9
10 Proux Olivier^e, Flank Anne-Marie^{f,g}, Vantelon Delphine^{f,g} and Sarret Géraldine^a
11
12
13
14
15

16 ^a ISTERre, Université Grenoble Alpes, CNRS, F-38041 Grenoble, France.
17

18 ^b Laboratoire de Chimie Analytique Bio-Inorganique et Environnement (LCABIE), Institut
19 des sciences analytiques et de physico-chimie pour l'environnement et les matériaux (IPREM
20 UMR 5254), Université de Pau et des Pays de l'Adour and CNRS, Hélioparc, 2 Av. Pierre
21 Angot, 64053 Pau Cedex 9, France.
22
23
24
25
26

27 ^c INERIS, Parc technologique Alata, 60550 Verneuil-en-Halatte, France.
28

29 ^d EMDouai, MPE-GCE, 930 Boulevard Lahure, 59500 Douai, France.
30

31 ^e OSUG, UMS832 CNRS/UJF, 414 rue de la piscine, 38400 Saint –Martin d'Hères, France.
32

33 ^f Beamline LUCIA, SLS, Swiss Light Source, CH-5232 Villigen, Switzerland.
34

35 ^g Synchrotron SOLEIL, F-91192 Gif Sur Yvette, France.
36
37

38 ¹ Present address: Ecole des Mines de Paris, 60 boulevard St Michel 75272 Paris Cedex 06,
39 France
40
41

42
43
44
45 **Corresponding authors:**
46

47 huguet.st@gmail.com
48

49 geraldine.sarret@ujf-grenoble.fr
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2 **Keywords:** Cadmium (Cd), sediment, *Arabidopsis halleri*, speciation, EXAFS, μ XANES,
3 μ XRF, SEM-EDS, phytoavailability, DGT, leachates.
4
5
6

7 **Abstract**

8
9

10 In regions impacted by mining and smelting activities, dredged sediments are often
11 contaminated with metals. Phytotechnologies could be used for their management, but more
12 knowledge on the speciation of metals in the sediment and on their fate after colonization by
13 plant roots is needed. This work was focused on a Zn, Cd-contaminated contaminated
14 dredged sediment from the Scarpe river (North of France). Zn, Cd hyperaccumulating plants
15 *Arabidopsis halleri* from metallicolous and non metallicolous origin were grown on the
16 sediment for five months in a pot experiment. The nature and extent of the modifications in
17 Cd speciation with or without plant were determined by electron microscopy, micro X-ray
18 fluorescence and bulk and micro X-ray absorption spectroscopy. In addition, changes in Cd
19 exchangeable and bioavailable pools were evaluated, and Cd content in leachates was
20 measured. Finally, Cd plant uptake and plant growth parameters were monitored. In the
21 original sediment, Cd was present as a mixed Zn, Cd, Fe sulfide. After five months, although
22 pots still contained reduced sulfur, Cd-bearing sulfides were totally oxidized in vegetated
23 pots, whereas a minor fraction (8%) was still present in non vegetated ones. Secondary
24 species included Cd bound to O-containing groups of organic matter and Cd phosphates. Cd
25 exchangeability and bioavailability were relatively low and did not increase during changes in
26 Cd speciation, suggesting that Cd released by sulfide oxidation was readily taken up with
27 strong interactions with organic matter and phosphate ligands. Thus, the composition of the
28 sediment, the oxic conditions and the rhizospheric activity (regardless of the plant origin)
29 created favourable conditions for Cd stabilization. However, it should be kept in mind that
30 returning to anoxic conditions may change Cd speciation, so the species formed cannot be
31 considered as stable on the long term.
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50

51 **1. Introduction**

52
53
54

55 The North of France hosts one of the oldest and largest industrial areas in Europe, with a large
56 concentration of non-ferrous metal processing activities. The Scarpe river is strongly
57
58
59
60
61
62
63
64
65

1 impacted by these activities, and sediments are contaminated by many metals including Zn
2 (about 7000 mg kg⁻¹) (Isaure et al., 2002) and Cd (about 600 mg kg⁻¹) (Alary and Demougeot-
3 Renard, 2008). The maintenance of waterways such as the Scarpe river by regular dredging
4 generates large volumes of metal-polluted sediments. Land disposal of these sediments may
5 present some risks in the environment. Sediments with contaminant levels above guidelines
6 are usually stored in landfill sites. Over the last decade, a substantial body of research has
7 been conducted on the fate of metals in the lower Scarpe river. Studies have focussed on the
8 speciation of Zn (Isaure et al., 2002; Isaure et al., 2005) and other metals (Thiry *et al.*, 2002)
9 and on their availability (Piou et al., 2009; Lions et al., 2010). Chemical extractions suggested
10 that Cd was mostly present in the oxidable fraction, likely polymetallic sulfides, but no direct
11 methods such as EXAFS spectroscopy was used to determine Cd overall speciation in this
12 sediment. Chemical extractions suggested that after land disposal of the sediment, the sulfidic
13 pool progressively decreased in favour of exchangeable forms (Piou et al., 2009). Secondary
14 Cd species formed after release of Cd²⁺ in a soil may include O-coordinated Cd adsorbed to
15 iron oxihydroxides, clay minerals, carbonates and COOH/OH groups of organic matter, and
16 S-coordinated Cd complexed by reduced organic S groups of natural organic matter or
17 bacterial cell walls or Cd adsorbed to metal sulfides (O'Day et al., 1998; Karlsson et al., 2005,
18 2007; Sajidu et al., 2008; Mishra et al., 2010; Fulda et al., 2013). To our knowledge, there is
19 no study on Cd speciation in dredged sediments after land disposal using direct methods.
20
21

22 Phytotechnologies have been proposed as alternative management methods for these
23 sediments (Bert et al. 2009; Bolan et al., 2011). In a previous work, the fate of Zn after a
24 phytostabilization treatment with graminaceous plants was studied (Panfili et al, 2005).
25 Results showed a clear impact of the rhizospheric activity on Zn speciation, regardless of the
26 plant species (*Festuca rubra* or *Agrostis tenuis*) and of the addition of amendments. Zn
27 sulfide, present as major Zn species in the original sediment, was almost completely oxidized
28 and replaced by secondary forms including Zn phosphate, Zn phyllosilicates and Zn-sorbed
29 ferrihydrite. The rhizosphere is a zone of intense and dynamic exchanges between the soil, the
30 root, and the microbial and fungal communities which colonize this zone. Exchanges in gas,
31 water, solutes, large and small organic molecules are supposed to influence the chemistry of
32 metals, although it is difficult to know exactly the role of each parameter in this complex
33 interplay (Hinsinger et al., 2006; Wenzel 2009). The rhizosphere of metal hyperaccumulating
34 plants has been the subject of many studies. Enhanced metal uptake by these species does not
35 seem to be related to specific phenomena, but to the enhancement of processes common with
36 non-accumulators. They include a highly developed root system, enhanced transport activity
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 at the soil-root interface, and possibly enhanced release (or release of different types) of
2 organic ligands (Wenzel, 2003; Li et al., 2013, Tsednee et al., 2014). *A. halleri* is a model of
3 Zn, Cd hyperaccumulating plant, and it has been intensively studied for the genetics and
4 physiology of metal tolerance and hyperaccumulation (Roosens et al., 2008; Sarret et al.,
5 2009; Huguet et al., 2012; Verbruggen et al., 2013; Isaure et al., 2015; Meyer et al., 2015). It is
6 a pseudo-metallophyte, which means that it is found both on metal-rich and normal
7 environments. Previous studies suggested some variations in metal tolerance and
8 accumulation between and within populations (Meyer et al., 2010; Meyer et al. 2015). Despite
9 these numerous studies, data concerning the impact of *A. halleri* on the speciation and
10 availability of Cd in the soil are lacking.

11 The aim of this work was to determine the speciation of Cd in a dredged sediment, to assess
12 its fate after land disposal, and to evaluate the influence of the rhizospheric activity on Cd
13 speciation. The Cd tolerant and hyperaccumulating species *A. halleri* was chosen as model
14 plant for this study because this species is naturally present in metal-contaminated soils of this
15 studied area. Moreover, we have some knowledge on Zn and Cd tolerance and accumulation
16 (Sarret et al., 2009 and Isaure et al., 2015, respectively), and on rhizospheric processes
17 (Barillot et al., 2013) for *A. halleri* from the same metallicolous origin. Thus, this species was
18 not chosen as a candidate for phytoextraction (which it is not), but as a model plant to study
19 rhizospheric processes.

20 Information on Cd solid phase speciation, on Cd extractability and leachate composition, and
21 on Cd transfer in the plant was obtained. Such combined approach provides key information
22 on metal dynamics in soil-plant system both on the short and long term. Such knowledge is
23 essential for the management and phytomanagement of dredged sediments after land disposal.
24 In this aim, a 5-month pot experiment was conducted on a Zn- and Cd-contaminated dredged
25 sediment with *A. halleri* of two origins, metallicolous (MET) and non-metallicolous (N-
26 MET). Plants originating from a contaminated site and a non contaminated site were
27 compared to examine potential differences between MET and N-MET plants in Cd uptake
28 and Cd behaviour in rhizosphere. The speciation of cadmium in the sediment before and after
29 culture and its relationships with other elements were studied by a combination of bulk and
30 microanalyses including scanning electron microscopy coupled with energy dispersive
31 spectroscopy (SEM-EDS), micro X-ray fluorescence (μ XRF) coupled with Cd L_{III}-edge and S
32 K-edge micro X-ray absorption near edge structure (μ XANES) spectroscopy, and bulk Cd K-
33 edge extended X-ray absorption fine structure (EXAFS) spectroscopy. The mobility and
34 bioavailability of cadmium in the sediment were studied by Ca(NO₃)₂ extractions and
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

diffusive gradient in thin films (DGT), and measurement of Cd content in the leachates. In addition, plant growth parameters and Cd accumulation were monitored.

2. Materials and methods

2.1 Sediment

The sediment was collected from the lower Scarpe river in the North of France (about 30 km south of Lille). In this study, 500 kg of surface sediment from an area containing 150 mg kg⁻¹ Cd (Alary, 2001) were dredged with a mechanic shovel. The sediment was then mixed, spread as a 20 cm-thick layer and dried outdoor for 7 months until the water content was 20 % in mass. The sediment was mechanically homogenized several times and sieved (< 5 mm with a Cross Beater Mill SK – RETSCH). Characteristics of the sediment at this time, “initial time” *ti* (Fig. 1), just before plant culture, are given in Table 1. Particle size distribution was analyzed following methods described in Isaure et al. (2002). Pseudo-total elements concentrations (Cd, Zn, Cu, Pb, Ni, and As) were quantified in sediment and in the different granulometric fractions. Aliquots of 0,5 g of samples were dried and sieved (100µm) and then digested by aqua regia micro-waves assisted dissolution. Metal concentrations were determined by ICP-AES. Quality control was based on the use of sediment certified standard samples (NWRI TH-2) and internal control samples.

The pH of the sediment before culture was about 7.48 ± 0.01 . The sediment was relatively rich in organic matter and had a relatively high cation exchange capacity (Table 1). As expected the metal concentrations in sediment were high with 141 ± 24 mg kg⁻¹ Cd, and other metals (Table 1). The Cd content was higher in finest fractions (e.g. 290 ± 10 mg kg⁻¹ Cd for <2µm fraction). Sediment was mainly composed by <50 µm fractions (Table 1), which concentrated 72 % Cd.

2.2 Plant material

A. halleri develops natural populations on both metal contaminated and uncontaminated soils in Europe (Bert et al., 2002). Viable seeds of *A. halleri* were collected in a smelter-impacted site (Bois des Asturies - Auby, France) and in an uncontaminated site (Hautes Fagnes, Belgium). The soil of Bois des Asturies has been characterized in several studies (Bert et al., 2000; Cuny et al., 2004; Sarret et al., 2004; Pauwels et al., 2006; Farinati et al., 2011; Gomez-

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Balderas et al. 2014). The data from Sarret et al. (2004) are given in Figure SI-1. The topsoil (0-20 cm) in which *A. halleri* developed roots was collected, and characterized as previously described for the sediment (Fig. SI-1).

2.3 Pot experiment

After vernalisation, *A. halleri* seeds were germinated on filter papers moistened with deionized water. Seedlings were transferred to pots filled with compost and grown for 4 weeks. Just before transfer on sediment (at t_i – Fig. 1), metals concentrations in aerial parts of *A. halleri* seedlings of both origins were analysed. Seedlings of *A. halleri* from metallicolous (MET) and non metallicolous (N-MET) origin were transferred to 4 L pots containing 2,8 kg of 5 mm-sieved sediment after roots had been washed carefully with deionised water. The monitoring of the culture was started after a 3-weeks period of adaptation to the new substrate (at t_0). Non vegetated pots were used as control, and each vegetated pot contained one seedling. A total of 39 pots were used, including 3 for the control and 18 for each origin of *A. halleri* (a triplicate for each sampling time, t_0 to t_5). Sediment moisture was maintained at 80% field water capacity by regular addition of deionised water. Plants were grown for five months in controlled conditions (12h photo period, 20/16°C day/night temperature, 80 % relative humidity) and pots were moved randomly each week.

2.4 Microscopic and spectroscopic analyses of the sediment before and after culture

Cd localization in the sediment was studied by SEM-EDS and μ XRF. Cd speciation was studied by Cd K-edge bulk EXAFS spectroscopy and Cd L_{III}-edge μ XANES spectroscopy, and S speciation was determined by S K-edge μ XANES spectroscopy.

2.4.1 Sample preparation

Undisturbed blocks of sediments were collected from the pots before and after culture with MET and N-MET plants. Rhizosphere blocks were then freeze-dried, impregnated with epoxy resin, and prepared as 30 μ m-thick micro-polished thin sections for electron and X-ray analyses (SEM-EDS, μ XRF and μ XANES). For bulk analyses, other blocks from pots with or without plant were collected. Roots were removed, and the substrate was freeze-dried, ground and pressed as pellets.

2.4.2 Reference compounds

The XANES and EXAFS analysis was based on a large database of reference Cd-containing compounds. They included commercial Cd minerals, Cd-containing compounds prepared at the laboratory and natural samples. Purchased chemicals used were all ACS reagent or analytical grade quality. The database included CdS, CdCl₂, CdCO₃, Cd(NO₃)₂, CdO, Cd(OH)₂, Cd-phosphate (Cd₅H₂(PO₄)₄, 4H₂O), CdSO₄, Cd-sorbed goethite and Cd-sorbed ferrihydrite containing ~8000 mg kg⁻¹ Cd kindly provided by A. Voegelin (Fulda et al., 2013), and a mixed sulfide (Zn, Cd, Fe)S extracted from a metamorphic rock was used as well. It was composed of sphalerite enriched in Cd and Fe (XRD spectrum in Figure SI-2 – Cd content: 1350 ppm). In addition, a library of Cd-organic complexes including Cd-malate, Cd-citrate, Cd-succinate, Cd-alginate, Cd-histidine, Cd-cysteine, Cd-glutathione, Cd-PC2, Cd-oxalate, Cd-cellulose, Cd-pectin, already described by Isaure et al. (2006, 2015) and Huguet et al. (2012) was used. Two more reference compounds included Cd with three organic acids in solution (Cd-OAs, 5mM Cd, 14mM citrate, 100mM malate and 400 mM succinate at pH=5.5 - concentrations were chosen according to PHREEQC calculation to have equivalent concentrations of (Cdsuc₂)²⁻, Cdsuc, (Cdcit₂)⁴⁻, (Cdcit)⁻, Cd²⁺, Cdmal complexes); and free Cd²⁺ (10mM Cd²⁺ at pH = 2.2). Solid state references were diluted in boron nitride and pressed as 5 mm diameter pellets. All solutions reference compounds were mixed with 20% glycerol to prevent ice crystal formation during cooling. Spectra for all Cd-containing references were recorded at Cd K-edge and L_{III}-edge. For S K-edge XANES analyses, the database presented in Sarret et al. (1999) was used.

2.4.3 Data acquisition

Micro-analyses were performed on thin sections of sediment samples. Cd-rich regions and geochemical associations were first investigated by environmental SEM-EDS. For the sediment before culture, we used a Quanta 200, FEI interfaced with a RONTEC single Drift detector. The chamber pressure was 0.45 Torr and the accelerating voltage 20 kV. Ten Cd-rich regions areas were identified. For the sediment after culture, we used a Hitachi S-4300 environmental scanning electron microscope with Thermo Ultradry Silicon Drift detector, using an acceleration voltage of 20 kV and pressure was 3990 Torr (30 Pa). Twelve Cd-rich regions areas were analyzed (6 for sediment with MET plants and 6 for sediment with N-MET plants). μ XRF and μ XANES analyses were performed on beamline LUCIA (SLS, Villigen, Switzerland) equipped with Si (111) crystals and a SDD fluorescence detector, with a beam size of 2.5 x 5 μ m on the sample and at room temperature. Regions of interest

1 identified by SEM were mapped by μ XRF before recording Cd L_{III}-edge (3538 eV) and S K-
2 edge (2472 eV) μ XANES spectra. For each sample, 6 to 8 XANES scans of 20 min were
3 averaged. Cd L_{III}-edge and S K-edge XANES spectra were also recorded in unfocused mode
4 on various Cd- and S-containing references (see above). For reference compounds, 2 to 3
5 spectra were averaged.
6

7
8 Cd K-edge bulk EXAFS measurements were performed on sediment samples on the beamline
9 FAME (BM30B – Proux et al., 2006) at the European Synchrotron Radiation Facility (ESRF,
10 Grenoble, France) equipped with a Si (220) double crystal monochromator. Pellets of
11 sediment samples and reference compounds (pellets and solutions) were transferred in a liquid
12 He cryostat cooled to 15 K. Spectra were recorded in fluorescence mode using a 30-element
13 solid-state Ge detector (Canberra). For each sample, 10 to 17 scans of 40 min were averaged.
14
15
16
17
18
19
20

21 2.4.4 μ XRF and XAS data treatment

22 For μ XRF elementary maps, fluorescence intensities were normalized by the incident photon
23 intensity (I_0) and counting time. XAS spectra were treated using ATHENA (Ravel, 2009)
24 software. The calibration of energy was done using a metal foil reference by setting the first
25 inflexion position of Cd-metal XANES spectrum to the tabulated value of 26711 eV; the
26 contribution of the matrix was subtracted and a normalization of signal was done using a
27 linear or a two-degree polynomial. The extracted EXAFS was then k^3 -weighted to enhance
28 the high- k region, and Fourier-transformed (FT) over the k range 3.0 to 10.5–13 \AA^{-1} ,
29 depending on the level of noise. The proportions of Cd species in sediment samples were
30 obtained by least-squares fitting of recorded spectra to linear combinations of reference
31 spectra from a library of Cd model compounds including Cd-substituted and Cd-sorbed
32 minerals and Cd-complexed organic compounds (see above). For each spectrum, LCFs using
33 one, two and three components were tested successively. The fit with $n+1$ components was
34 retained if the normalized sum-squares residual ($NSS = \sum[k^3 \chi_{\text{exp}} - k^3 \chi_{\text{fit}}]^2 / \sum[k^3 \chi_{\text{exp}}]^2 \cdot 100$)
35 was decreased by more than 10 % as compared to the fit with n components. Percentages of
36 Cd species are given as average and standard deviations presented are the average over
37 satisfactory fits, defined by NSS comprised between the value obtained for the best fit
38 (NSS_{best}) and $1.1 NSS_{\text{best}}$.
39
40
41
42
43
44
45
46
47
48
49
50
51
52

53 In parallel, from k^3 EXAFS spectra, the structural parameters for Cd reference compounds and
54 sediment samples were determined by shell simulations using ARTEMIS (Ravel & Newville,
55 2005). Phase and amplitude functions were calculated by FEFF 6.0 using the structure of
56 greenockite (CdS) and cernyite ($\text{Cu}_2(\text{Cd}_{0.37}\text{Zn}_{0.33}\text{Fe}_{0.29})\text{SnS}_4$) (Szymanski, 1978), Cd-organic
57
58
59
60
61
62
63
64
65

1 structures from the Cambridge Structural Database (CSD, Bruno et al., 2002) and the
2 structure of $\text{Cd}_5\text{H}_2(\text{PO}_4)_4 \cdot 4\text{H}_2\text{O}$. EXAFS spectra were Fourier transformed over a k range of
3 3.2–11 Å for sediment samples, and the contribution of the first shell was simulated in R
4 space, either with O atoms only, or with O and S atoms.
5

6
7 S K-edge XANES spectra were treated by LCFs as described above. S reference compounds
8 were grouped into three families: mineral sulfides (including CdS and (Zn, Cd, Fe)S), organic
9 sulfides (including R-SH, R-S-R and R-S-S-R groups) and oxidized sulfur (including
10 sulfoxides, sulfone, sulfonic acid, and sulfates).
11
12
13
14

15 16 **2.5 Monitoring of Cd in sediment, plant and leachates**

17
18
19 A monthly monitoring of the sediment, plants and leachates was performed for five months.
20 Each month, three pots per condition were removed from the experiment for the analysis of
21 the sediment and plant. The sediment was separated manually from the roots, sieved (< 2
22 mm), and total metals concentrations, pH, total carbon (TC) and metals exchangeable and
23 phytoavailable pools were measured on triplicates.
24
25
26
27
28

29
30 The $\text{Ca}(\text{NO}_3)_2$ exchangeable pool was measured according to (Bert et al. 2012). After sieving
31 (< 2 mm) and drying the sediment at 60°C, 10 g (DW) were shaken in 20 mL $\text{Ca}(\text{NO}_3)_2$ 0.01
32 N (analytical quality in ultrapure water) for 48 hours at room temperature. After
33 centrifugation (20 min at 1200 g), filtration (0.45 µm), and acidification of the supernatant
34 (0.5 mL of concentrated, supra-pure nitric acid), metal concentrations were determined by
35 ICP-AES.
36
37
38
39
40
41

42
43 Metals phytoavailability was estimated by diffusive gradient in thin film (DGT) probes
44 (Zhang *et al.*, 2001, Nolan *et al.*, 2005). DGT devices loaded with a 0.4 mm resin gel layer
45 (chelex gel), a 0.7 mm diffusive gel layer (polyacrylamide gel, restrictive pore) and a 0.13
46 mm filter (cellulose nitrate) were provided by DGT Research Ltd. 100 g of sieved sediment
47 were wet to 100 % field water capacity, manually mixed to make a smooth paste, and finally
48 shaken for 3 days. DGT were pressed gently onto the surface of the sediment and placed for
49 17h between 20°C and 24°C. Metal analyses and determination of C_{DGT} were made by ICP-
50 MS or AAS by DGT Research Ltd.
51
52
53
54
55
56

57
58 Plant aspects were examined and rosette diameters were measured on a monthly basis.
59 Besides, on monthly removed pots, three plants of each origin were harvested to analyze their
60
61
62
63
64
65

1 aboveground parts (biomass and metals concentrations). Aerial parts were washed with
2 deionised water, oven-dried at 40°C until constant weight, then biomass was weighed, ground
3 and homogenized to prepare one aliquot per pot. Total concentrations of Cd in plant tissues
4 were determined after digestion of 1 g dry matter in 10 ml of HNO₃ and 3 ml of H₂O₂, in a
5 microwave oven. Solutions were filtered, adjusted to 100 ml with Milli-Q® water and stored
6 at 4°C before analysis. Cd concentrations in the digests were determined by ICP-AES.
7 Spinach leaves samples (SRM 1570a) were used as certified standard.
8
9
10
11
12

13
14 The monitoring of leachates was performed monthly on the same three pots (cultivated or
15 not). Leachates were collected at the bottom of the pots after the substrate (cultivated and
16 non-cultivated) had been watered with 1 L of deionised water, delivered in small volumes
17 (200 mL). Leachates were collected for 2 hours after watering. Leachates were filtered (0.45
18 µm), then aliquots of 10 mL were acidified with HNO₃ (suprapur®) and stored at 4°C before
19 analysis. Metals concentrations were determined by ICP-AES for which quality control was
20 based on the use of internal control samples.
21
22
23
24
25
26
27

28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Statistic analysis was performed using two and one-way ANOVA followed by post hoc
comparison using Tukey's test for comparison of individual means (statistical program SPSS
15.0 (2007)).

3. Results

3.1 Cd speciation in the sediment before and after culture of *A. halleri*

3.1.1 Average Cd speciation by Cd K-edge bulk EXAFS spectroscopy

The speciation of Cd in the sediment before and after culture was examined by EXAFS
spectroscopy. Representative Cd K-edge EXAFS reference spectra used for the linear
combination fits are shown in Figure 2. Figure 3 shows the sediment spectra and LCFs
results. The spectrum for the sediment before culture was correctly reconstructed with 100%
(Zn, Cd, Fe)S (Fig. 3). Adding a second component did not improve significantly the fit (not
shown). Thus, Cd was mainly present as a mixed metallic sulfide. Spectra for the sediment
after culture with *A. halleri* MET and N-MET, and for the control (*i.e.* non vegetated)
sediment were similar, although the later presented slightly lower amplitude oscillations, in
particular at 11 Å⁻¹ (Fig. 3A). Cd in the non vegetated pot was present as 74 ± 2 % Cd-

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Organic acids, 22 ± 1 % Cd-phosphate and 8 ± 1 % Cd as mixed sulfide ((Zn, Cd, Fe)S - Fig. 3B). Removing this later species increased the fit residual by 11 %. Thus, although the proportion of Cd mixed sulfide is within the precision of the method as generally estimated (± 10 %), its contribution may be significant in the present case. At the opposite, spectra for vegetated sediment were correctly fitted with a combination of Cd-organic acids (64 ± 5 % and 61 ± 16 % for MET and N-MET respectively) and Cd-phosphate (34 ± 2 % and 30 ± 16 % respectively). These results evidence changes in Cd speciation during the pot experiment. Cd sulfide was almost completely oxidized in the absence of plants, and secondary phases including Cd-organic complexes and Cd phosphate were formed. The same process was observed in the presence of plants, but the removal of Cd sulfide was total and the proportion of Cd-phosphate increased. There was no influence of the origin (MET or N-MET) of *A. halleri* on Cd speciation in the substrate.

Structural parameters for Cd in the sediment and several representative Cd reference compounds were then determined by shell fitting (Fig. 4, Table 2). For CdS, Cd-phosphate and CdCO₃, structural parameters were consistent with the XRD structures (Huguet et al., 2012). For (Zn, Cd, Fe)S, the first shell of coordination was simulated by 4 S atoms at 2.52 Å, as in CdS structure, and the second shell by a mixture of Fe, Zn and Cd atoms (Table 2, Fig. SI-3). As expected, the same type of environment was obtained for the sediment before culture. Fit with Cd only as next nearest neighbour was not satisfactory (Fig. 4B). Based on the Fe, Zn, Cd coordination numbers (0.3, 4.8 and 2.2, respectively, Table 2), it can be concluded that Cd was present as a mixed sulfide containing about 2/3 Zn, 1/3 Cd and traces of Fe. The sum of Zn, Cd and Fe contributions was 7.3 atoms, *i.e.* significantly lower than the 10 atoms in CdS or ZnS structure, but like in the (Fe Zn Cd)S reference, *i.e.* about 8 neighbours in the second shell. This difference likely reflects some structural disorder, probably due to the presence of metals with very different ionic radii in the crystal lattice, and/or to the presence of non-equivalent crystallographic sites for Cd. The Fourier transformed spectra for the sediments after the pot experiment showed a first shell at a distance typical of oxygen ligands, and almost no second shell peak (Fig. 4B). For the vegetated pots, fit results gave 6-7 O atoms at 2.29-2.3 Å (Table 2). For the non vegetated pot, a minor contribution of S atoms was found, which is consistent with LCFs results. Due to the very low amplitude, no significant signal was observed for $R+\Delta R > 2.5$ Å: no second shell was needed for the simulation.

3.1.2 SEM-EDS, micro-XRF and Cd-L_{III} edge and S-K edge μ XANES analyses

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Micro-scale investigations were performed to observe geochemical associations, weathering processes of Cd sulfide grains, and to identify possible minor forms of Cd in sediment before and after culture. SEM-EDS enabled the localization of Cd-rich regions in various types of grains. A representative coarse grain of the sediment before culture is shown in Figure 5, and two representative grains for the sediment after culture are shown in Figure 6. For the sediment before culture, metal-rich areas were localized at the edge of the grain (Fig. 5A, B). The Cd richest region contained Zn and S as major elements (40 and 31 % in atomic % based on the EDS calculated composition), as well as Si (12 %), Al (6.9 %), Mg (3.1 %), Cd, Ca and Na (1.8 %), Fe (1.1 %). These results suggest the presence of Zn sulfide containing impurities of Cd and Fe, associated with aluminosilicates nanoparticles. These findings are consistent with bulk EXAFS results. Other regions contained more diffuse Cd concentrations around Cd-rich spots. Two spots were selected for μ XANES analyses, the Cd rich spot described above (P2, with S/Cd fluorescence intensity ratio = 8 and P/Cd = 0.4, Fig. 5B), and a spot with more diffuse Cd concentration (P1, with S/Cd = 21 and P/Cd = 0.8, Fig. 5B). Cd L_{III}-edge μ XANES spectra recorded on the bulk sediment, on P2 and P1 are shown in Figure 7. They show a smooth edge characteristic of S ligands (Isaure et al., 2006). They were all fitted with 100 % Cd sulfide species. (Zn, Cd, Fe)S was the only component for the bulk sediment and the Cd richest spot (P2), whereas Cd-thiols (Cd-organic sulfides) were present as additional component in P1 (Fig. 9). Figure 7 shows that the spectrum for Cd-thiol has some similarities with CdS and (Zn, Cd, Fe)S, but is smoother.

In addition, S K-edge μ XANES were recorded in the bulk sediment and on P1 and P2 spots to investigate S oxidation state (Fig. 8). They all showed a first peak at 2473 eV, characteristic of reduced S (Fig. 8). In addition, P1 shows a peak at 2482 eV (Fig. 8) characteristic of oxidized S. Three families were distinguished by LCFs, including mineral sulfides, organic sulfides and oxidized S species. Mineral sulfides dominated in the bulk and in P1 and P2 spots, organic sulfides represented minor species in P1 and P2 spots, and oxidized species represented 4 % (in the bulk) to 12 % (in P1 - Fig. 9).

Two representative grains for the sediment after culture showed reddish brown area around the grains that indicated the presence of oxidized Fe (Fig. 6A). SEM-EDS analyses showed that Cd-rich region contained also S, Fe, Zn, Si, Al and P in various proportions (Fig. 6B). Micro-XRF maps allowed to localize the Cd most concentrated spot previously identified by SEM and to visualize more precisely the chemical associations. The Cd richest spot, P3A, contained also S and P (Fig. 6B). Another Cd-rich spot, P3B, was less rich in S and P than

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

P3A (Fig. 6B). The spot P3C contained less Cd (Fig. 6B). The second representative grain shows a zone with diffuse Cd co-localized with P, and to a lesser extent with S (spot P4, Fig. 6C). The Cd L_{III} μ XANES spectra for P3A and P3B were similar to P1 and P2, whereas P3C and P4 spectra presented a pre-peak at 3538 eV characteristic of Cd-O bond (Fig. 7). Based on LCFs, the Cd richest spots (P3A and P3B) contained a majority of Cd sulfides and 15 to 25 % Cd Cd-organic acids, whereas the more diffuse zones (P3C and P4) contained Cd-organic acids and Cd-phosphate as major species (80 and 100 %, respectively – Fig. 9). Thus, Cd speciation drastically changes from P3B to P3C which are distant of about 50 μ m. The presence of Cd phosphate is consistent with the high P signal in spot P4. The chemical state of S as determined by S K-edge XANES showed an increase in oxidized S species following the increase in Cd-O species. The spot containing the higher amount of oxidized S is P4, with 34 % (Fig. 9). In this spot, Cd-S species were completely replaced by Cd-O species. Thus, other sulfide species, more resistant to oxidation than the one hosting Cd, are still present. Again, spots distant of 50 μ m only showed very different S speciation. These results were obtained on the sediment vegetated with MET plants. Very similar results were obtained with N-MET plants, therefore these results are not presented here.

To conclude, the persistence of Cd sulfide species in some Cd rich spots was observed in the sediment after culture. These species represent less than 10 % of total Cd since they were not detected by bulk XAS. In addition, a large variety of S oxidation states was observed, but reduced S dominated, even in spots where Cd sulfides species had been oxidized.

3.2 Cd exchangeability and leaching

XAS is not very sensitive to weakly sorbed species, and it is useful to evaluate in parallel the exchangeable and bioavailable pool at the macroscopic scale by physico-chemical approaches. Cd pseudo-total concentration in sediment before culture was about 140 mg kg⁻¹ (Tab.1) and was not significantly different than those measured in sediment during and after culture with MET or N-MET plants and in control pots, *i.e.* without plant (not shown). However, after culture, a decrease of approximately 0.6 pH unit was observed in pots with plants (regardless their origin) and in control pots (ANOVA 1 factor $P > 0.05$ - not shown). Indeed the pH measured before culture in sediment at 7.48 ± 0.01 (Tab.1) was then measured at 6.86 ± 0.22 , 6.95 ± 0.03 and 6.81 ± 0.02 for MET, N-MET and control pot respectively. Decrease in pH measurement was not a plant effect. It was probably correlated with oxidation of metallic sulfides in sediment.

1 For the sediment before culture, $\text{Ca}(\text{NO}_3)_2$ -extractable Cd concentration was $1.02 \pm 0.1 \text{ mg}$
2 $\text{kg}^{-1} \text{ DW}$ (Fig. 10A). At the end of the monitoring, this parameter decreased significantly in
3 the control pot ($P < 0.05$, $0.71 \pm 0.03 \text{ mg kg}^{-1} \text{ DW}$ at t_6 for control pot, Fig. 10A). For
4 vegetated pots, extractable Cd concentrations measured monthly were significantly different
5 from the sediment before culture, even after only one month ($P < 0.05$, Fig. 10A). However,
6 they were not significantly different from those measured in the control pot at t_6 ($P > 0.05$, Fig.
7 10A). Thus, there was no plant effect on Cd extractable concentrations during culture
8 regardless of *A. halleri* origin.

9 DGT was used to quantify Cd phytoavailable pool in sediment for some samples (Fig. 10B).
10 Cd bioavailable concentrations were lower than Cd extractable concentrations. By
11 comparison with Cd extractable concentrations, there was no significant difference between
12 bioavailable Cd in the sediment before culture and in vegetated pots (Fig. 10B). Bioavailable
13 Cd was not measured on pots without plant at the end of the assay.

14 Thus, the major changes in Cd speciation observed between the sediment before and after
15 culture did not induce marked changes in Cd exchangeability and bioavailability.

16 The evolution of Cd concentrations in leachates was monitored monthly (Fig. 11A). For
17 control pots, Cd concentrations were not significantly different over time ($P > 0.05$ – Fig. 11A):
18 about $0.30 \pm 0.07 \text{ mg L}^{-1}$. By contrast, in vegetated pots Cd concentrations were lower from t_2
19 and then did not vary significantly (Fig. 11A). Thus, the presence of plants seems to decrease
20 Cd concentrations in leachates.

21 **3.3 Cd transfer in the plant**

22 The plant biomass was measured monthly. At t_i , when plants were transferred on sediment,
23 plants of both origins presented similar biomasses, *i.e.* $3.0 \pm 1.1 \text{ g}$ for MET plants and $3.2 \pm$
24 1.7 g for N-MET (average for $n=3 \pm \text{SD}$, ($P > 0.05$, test of Student - Fig.11B). Biomasses
25 measured after one month of growth, *i.e.* at t_1 , were higher than those measured at t_i (Fig.
26 11B). This shows that plants were able to develop on contaminated sediment. No significant
27 increase of biomass was observed for N-MET plants between t_1 and t_5 ($P > 0.05$, Fig. 11B), but
28 standard deviations were important. MET plants biomass increased from t_1 to t_3 and then
29 decreased ($P < 0.05$, Fig. 11B). The maximum difference in biomass was observed the third
30 month ($33.1 \pm 4.6 \text{ g}$ for MET), and could be related to a better tolerance of metallicollous
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 plants compared to non metallicolous ones (Meyer et al. 2015) as shown for Zn (Meyer et al.,
2 2010). During the fourth month of culture, one part of MET plant leaves began to show
3 drought signs. The decrease in biomass observed at t_4 and t_5 could be a response to sediment
4 toxicity.
5
6

7
8
9 Cd concentrations were measured in aerial parts of *A. halleri* at t_i as follow: 3.7 ± 2.4 and 4.7
10 ± 1.0 mg kg⁻¹ DW for MET and N-MET plants respectively (Fig. 11C). There was no
11 significant difference between plant origins (Student test: $P>0.05$). From t_1 to the end of
12 growth, Cd concentrations were higher than those measured at t_i . For instance, between t_i and
13 t_1 Cd concentrations in aerial parts were respectively increased by 30 and 39 times for MET
14 and N-MET. All measured concentrations, except for N-Met at t_2 , reached the
15 hyperaccumulating threshold set to 100 mg Cd kg⁻¹ DW (Baker and Brooks, 1989, Wenzel
16 and Jockwer, 1999). For each origin tested separately, no significant variation of Cd
17 concentrations in aerial parts was observed with time ($P>0.05$, Fig. 11C). Maximal Cd
18 concentrations were 204 ± 96 and 185 ± 18 mg kg⁻¹ ($n=3 \pm$ SD) for, respectively, MET plant
19 at t_4 and N-MET plant at t_1 (Fig. 11C). Standard deviations were important, suggesting a high
20 inter-individual variability in Cd accumulation.
21
22
23
24
25
26
27
28
29
30

31 32 33 **4. Discussion**

34 35 36 **4.1 Cd speciation in sediment before and after culture of *A. halleri***

37
38
39 Before culture, Cd in the sediment was present as a mixed Cd,Zn,Fe-sulfide containing about
40 2/3 Zn, 1/3 Cd and traces of Fe. Cd-containing mixed sulfides were also observed in metal-
41 contaminated marine sediments (O'Day et al.; 1998; Carroll et al., 2002). A previous study on
42 Zn speciation in the Scarpe sediment showed that Zn was mostly present as sphalerite (Isaure
43 et al, 2002). Considering that Zn is 25 to 30 times more concentrated than Cd in this sediment
44 (Table 1), it is clear that the sediment contains both some mixed Cd,Zn,Fe-sulfides and pure
45 Zn sulfide. This was confirmed by SEM-EDS. Likewise, pure pyrite grains were observed by
46 SEM-EDS (not shown), so Fe is present both in mixed metallic and pure Fe sulfide.
47 Polymetallic sulfides may come from the ore which was transported by boat on the river, from
48 atmospheric emissions of the smelters and dissemination of smelter slag (Isaure et al, 2002).
49 They may also be formed during early diagenesis of sediments (Audry et al., 2005). The
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2 presence of both reduced and oxidized forms of sulfur in the sediment shows that it has been
3 partially oxidized during the drying and preparation procedure.

4 After 5 months of pot experiment, Cd sulfides were totally (for vegetated pots) and almost
5 totally (8 % remaining Cd sulfides in non vegetated ones) oxidized, and secondary species
6 included Cd-organic acids and Cd phosphates. Micro analyses confirmed the persistence of
7 Cd sulfides in some regions of the sediment thin sections. The study of Zn speciation in
8 dredged sediment from the Scarpe vegetated or not with two *Poaceae* (*Agrostis tenuis* and
9 *Festuca rubra*) showed that after 18 months of culture, ZnS was almost completely oxidized,
10 whereas half of Zn was still present as ZnS in the pot without plant (Panfili et al., 2005).
11 Although plants and conditions differed between the two studies, the comparison of the
12 results suggested a higher sensitivity to oxidation for Cd than for Zn in this sediment.
13 Previous studies on mixed metallic sulfides suggested different sensitivities of metals towards
14 oxidation, with preferential release of Zn relative to Cd (O'Day et al., 1998; Barret and
15 McBride, 2007). The same tendency was observed in Zn, Cd-containing soils rich in sulfur
16 (McBride et al., 2006; de Livera et al., 2011). These results are not in contradiction with our
17 results because in the Scarpe sediment, Cd was mostly present in a mixed (Zn, Cd, Fe)sulfide,
18 whereas Zn was mostly present as pure ZnS. Thus, the change in Zn speciation in this
19 sediment is controlled by ZnS much more than by the mixed sulfide. The persistence of
20 reduced S species in regions of the thin sections where Cd was bound to O ligands (see
21 Results) suggests that other metallic sulfides are still present in regions where Cd has been
22 oxidized.

23 In the sediment without plant, the oxidation of metallic sulfides may be ascribed to the
24 alternating dry and wet conditions due to watering, which brings oxygen to the system.
25 Barrett and McBride (2007) demonstrated that oxidation of inorganic sulfides to SO_4^{2-} in
26 aerated soil environments proceeded within hours. In a study on Cd speciation in a paddy soil,
27 Fulda et al. (2013) showed the formation of Cd sulfides under flooded (anoxic) conditions.
28 The CdS crystallites, estimated to be nanometer-sized, were oxidized upon aeration of the
29 system, and the original Cd speciation, dominated by Cd-carboxyl species, was restored. Like
30 in acid mine drainage environments, the oxidation of metallic sulfides may be catalyzed by
31 microorganisms. Bacteria present in sediments of the Scarpe River have been shown to play
32 an important role in increasing or decreasing metal availability (Lors et al. 2004; Bert et al
33 2009, 2012). Bert al. (2012) suggested that bioleaching of metals was caused by sulfur-
34 oxidizing bacteria whereas anaerobic sulfate-reducing bacteria could precipitate metals.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

In the planted sediment, the oxidation process was slightly higher, although the difference is close to the uncertainty of the method. Several processes taking place in the rhizosphere might explain this oxidation: Plant rooting may increase the penetration of oxygen in the sediment. This effect counterbalances the effect of root respiration which, conversely, causes O₂-impoverishment and CO₂-enrichment of the rhizosphere (Marschner 1995; Hinsinger et al, 2003). The uptake of water, ions and nutrients and the release of ions and organic ligands by the root and associated organisms (fungi, bacteria) are supposed to affect the chemical equilibria and induce dissolution-reprecipitation and sorption-desorption processes.

In vegetated and non vegetated pots, Cd was mainly associated with phosphates (30-34 and 22 %, respectively) and with COOH/OH groups of organic matter (61-64 and 74 %, respectively). Cd phosphate can be considered as a stable species on the long term (Hamon et al., 1998). The role of organic matter in Cd binding in the Scarpe sediment after land disposal was highlighted by Vansimaey et al. (2009), who evaluated by chemical extractions an increase from 10 to 65 % of organically bound Cd from the fresh to land deposited, drained sediment. Piou et al. (2009) also suggested an important role of organic matter in the control of the seasonal dynamics of Cd. The binding of Cd to COOH/OH groups of organic matter is consistent with previous findings by Liu et al. (2001) and Fulda et al (2013). Karlsson et al. (2007) identified a mixture of O- and S-containing ligands for Cd in a peat soil. The association of Cd with phosphate is not surprising because of the high P content of the sediment, and high affinity of Cd for phosphate minerals. The proportion of Cd phosphate was slightly higher in the vegetated than in the non vegetated pots. This can be related to the rhizosphere activity favouring the mobilization and increasing its availability (Hinsinger et al., 1998). The present EXAFS data do not allow to distinguish Cd-sorbed or coprecipitated phosphate, but both phenomena are likely (Brown et al. (2004).

4.2 Impact of *A. halleri* culture on Cd exchangeable pool and leachates

Although the presence of plants had an impact on Cd speciation in the sediment, they did not influence Cd exchangeable and phytoavailable pools. Both the Cd exchangeable and phytoavailable pools did not vary significantly with time for MET and N-MET plants. Low standard deviations indicated low variability between pots for these pools. The relative stability in the exchangeable and phytoavailable pools suggests that Cd sulfides on one hand, and the mixture of Cd phosphate and Cd-organic acids on the other hand, display similar exchangeabilities. This result suggest that the Cd-organic acid complexes are weakly

1 exchangeable. At the opposite, Zn-organic complexes found in Zn-contaminated organic soil
2 were highly exchangeable (Sarret et al., 2004). The stability of Cd exchangeability during the
3 experiment also suggests that Cd released by oxidation of sulfides was readily taken up by the
4 secondary phases, with no transient phase with high Cd availability. The Cd content in the
5 leachates was very low and the presence of the plant induced a decrease in Cd concentrations
6 from the second month of culture. This phenomenon can be related to the colonization of the
7 pot by roots and the development of a stable rhizosphere, decreasing the transfer of dissolved
8 and particulate Cd. Plants grown on the sediment contained between 100 to 200 mg kg⁻¹ Cd
9 DW in their aerial parts. This relatively low Cd accumulation is consistent with the low Cd
10 availability and with the fact that *A. halleri* is not a strong Cd hyperaccumulator (Huguet et
11 al., 2012). The lack of difference in Cd solid state speciation, availability and leachability
12 suggests that the rhizospheric activity of both plants have a similar impact on the soil
13 chemistry. Additional data on root exudates, microbial activity and redox potential would be
14 necessary to elaborate more on this point.
15
16
17
18
19
20
21
22
23
24
25
26
27
28

29 **5. Conclusion**

30
31
32 This study assessed the fate of Cd present in a contaminated dredged sediment during a pot
33 experiment. The combination of chemical analyses and EXAFS spectroscopy allowed to
34 elucidate chemical forms of Cd in the sediment before and after plant culture. Before culture,
35 Cd was present as a mixed Zn, Cd, Fe sulfide. This mixed sulfide was relatively sensitive to
36 oxidation since after 5 months of pot experiment, Cd-bearing sulfides were mostly oxidized in
37 control pots without plants. The presence of *Arabidopsis halleri* seemed to enhance this
38 process since Cd sulfides were totally oxidized in vegetated pots. Secondary species including
39 Cd bound to O-containing groups of organic matter and Cd phosphates were formed both in
40 vegetated and non vegetated pots. These changes probably occurred via both abiotic and
41 biotic processes, and were enhanced by the plant activity. Despite these changes in speciation,
42 there was no change in Cd exchangeability or phytoavailability. Cd phosphate can be
43 considered as stable on the long term. Cd–organic matter complexes may not be stable on the
44 long term, but their presence did not increase Cd phytoavailability during the experiment.
45 This low availability and low transfer of Cd to leachates and plants are positive signals in
46 terms of environmental management. A low Cd availability was also observed in the field
47 after land application of the Scarpe sediment (Piou et al., 2009). The presence of plants is
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 supposed to give an added value to land disposal because of their role in the limitation of
2 aerial dispersion of contaminants. This study shows that it also has a positive effect on Cd
3 speciation. However, it is important to consider that Cd speciation may fluctuate depending
4 on flooding and redox conditions (Piou et al., 2009; Fulda et al., 2013), and that Cd sulfide
5 species may form again under flooded or saturated conditions. Thus, land application and
6 vegetation of the sediment may be an interesting option, provided that the substrate remains
7 unsaturated. .
8
9
10
11
12

13 **Acknowledgements**

14
15
16
17
18 This work was supported by the Nord-Pas de Calais Region and Voies Navigables de France,
19 FEDER funds through French research program: Programme de Recherche Concertées (PRC
20 “Sites et Sols Pollués, Environnement et Activité Humaines”). ISTERre is part of Labex
21 OSUG@2020 (ANR10 LABX56). Martine Lanson and Vasilica Hammade are acknowledged
22 for their help during chemical analyses. Patrick Degrugilliers is thanked for the preparation of
23 thin sections and Philippe Recourt for his assistance during SEM analyzes. Pierre Lagarde and
24 Nicolas Geoffroy are acknowledged for their assistance during synchrotron experiments. We
25 also thank the ESRF (Grenoble, France), SOLEIL (Saclay, France) and the French CRG
26 committees for the provision of beamtime.
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

References

1
2
3 Alary C. (2001) Technical report Douai - Fr., CNRSSP: 72.
4
5

6
7 Alary C. and Demougeot-Renard H. (2008) Fate of pollutant load in a small canalised river
8 (Scarpe, North of France): understanding the spatial distribution of heavy metals in sediments
9 using factorial kriging analysis. International Symposium on Sediment Management (I2SM),
10 Lille, France.
11
12
13

14
15
16 Audry S., Blanc G. and Schäfer J. (2005) The impact of sulphide oxidation on dissolved metal
17 (Cd, Zn, Cu, Cr, Co, Ni, U) inputs into the Lot-Garonne fluvial system (France). *Applied*
18 *Geochemistry*, **20**, 919-931.
19
20
21

22
23 Baker A.J.M. and Brooks R.R. (1989). Terrestrial higher plants which hyperaccumulate
24 metallic elements – a review of their distribution, ecology and phytochemistry. *Biorecovery* **1**,
25 81–126.
26
27
28

29
30 Barillot C.D.C., Sarde C.O., Bert V., Tarnaud E. and Cochet N. (2013). A standardized
31 method for the sampling of rhizosphere and rhizoplan soil bacteria associated to a herbaceous
32 root system. *Annals of Microbiology* **63** (2), 471-476
33
34
35
36

37
38 Barrett K.A. and McBride M.B. (2007) Dissolution of zinc-cadmium sulfide solid solutions in
39 aerated aqueous suspension. *Soil Science Society of America Journal* **71**, 322-328.
40
41
42

43 Bert V., Macnair M.R., De Laguerie P., Saumitou-Laprade P. and Petit D. (2000) Zinc
44 tolerance and accumulation in metalicolous populations of *Arabidopsis halleri*
45 (Brassicaceae). *New Phytologist* **146**, 225–233.
46
47
48

49
50 Bert V., Bonnin I., Saumitou Laprade P., de Laguerie P. and Petit D. (2002) Do *Arabidopsis*
51 *halleri* from nonmetallicolous populations accumulate zinc and cadmium more effectively
52 than those from metalicolous populations? *New Phytologist*, **155**, 47-57.
53
54
55
56

57
58 Bert V., Seuntjens P., Dejonghe W., Lacherez S., Thuy H.T.T., Vandecasteele B. (2009)
59 Phytoremediation as a management option for contaminated sediments in tidal marshes, flood
60
61
62
63
64
65

1 control areas and dredged sediment landfill sites. *Environmental Science and Pollution*
2 *Research* **16**: 745-764.

3
4
5 Bert V., Lors C., Ponge J.-F., Caron L., Biaz A., Dazy M. and Masfaraud J.-F. (2012) Metal
6 immobilization and soil amendment efficiency at a contaminated sediment landfill site: A
7 field study focusing on plants, springtails, and bacteria. *Environmental Pollution* **169**, 1-11.

8
9
10
11
12 Bolan N.S., Park J.H., Robinson B., Naidu R., and Huh K.Y. (2011) Chapter four -
13 Phytostabilization: A Green Approach to Contaminant Containment. *Advances in Agronomy*,
14 **112**, 145-204.

15
16
17
18
19
20 Brown S., Chaney R., Hallfrisch J., Ryan J.A. and Berti W.R. (2004) In situ soil treatments to
21 reduce the phyto- and bioavailability of lead, zinc, and cadmium. *Journal of Environmental*
22 *Quality*, **33**, 522–531.

23
24
25
26
27 Bruno I., Cole J., Edgington P., Kessler M., Macrae C., McCabe P., Pearson J. and Taylor R.
28 (2002) New software for searching the Cambridge Structural Database and visualising crystal
29 structures. *Acta Crystallographica B* **58**, 389–397.

30
31
32
33
34
35 Carroll S. A., O'Day P. A., Esser B. and Randall, S. (2002) Speciation and fate of trace metals
36 in estuarine sediments under reduced and oxidized conditions, Seaplane Lagoon, Alameda
37 Naval Air Station (USA). *Geochemical Transactions* **3**, 81-101.

38
39
40
41
42 Cuny D., Denayer F.O., de Foucault B., Schumacker R., Colein P. and Van Haluwyn C.
43 (2004) Patterns of metal soil contamination and changes in terrestrial cryptogamic
44 communities. *Environmental Pollution*, **129**, 289-297.

45
46
47
48
49 de Livera J., McLaughlin M.J., Hettiarachchi G.M., Kirby J.K. and Beak, D.G. (2011)
50 Cadmium solubility in paddy soils: Effects of soil oxidation, metal sulfides and competitive
51 ions. *Science of the Total Environment*, **409** (8), 1489–1497.

52
53
54
55
56 Farinati S., DalCorso G., Panigati M. and Furini A. (2011) Interaction between selected
57 bacterial strains and *Arabidopsis halleri* modulates shoot proteome and cadmium and zinc
58 accumulation. *Journal of Experimental Botany*, **62**, 3433–3447.

1 Fulda B., Voegelin A., Ehlert K. and Kretzschmar R. (2013) Redox transformation, solid
2 phase speciation and solution dynamics of copper during soil reduction and reoxidation as
3 affected by sulfate availability. *Geochimica et Cosmochimica Acta* **123**, 385-402.
4
5
6

7
8
9 Gomez-Balderas C.D.C., Cochet N., Bert V., Tarnaud E. and Sarde C.-O. (2014) 16S rDNA
10 analysis of bacterial communities associated with the hyper accumulator *Arabidopsis halleri*
11 grown on a Zn and Cd polluted soil. *European Journal of Soil Biology* **60**, 16-23.
12
13
14

15
16 Hamon, R.E., McLaughlin, M.J., Naidu, R., Correll, R. (1998) Long-term changes in
17 cadmium bioavailability in soil. *Environmental Science and Technology* **32**, 3699-3703.
18
19
20

21
22 Hinsinger P. (1998) How do plant roots acquire mineral nutrients? Chemical processes
23 involved in the rhizosphere. *Advances in Agronomy*, **64**, 225-265.
24
25
26

27
28 Hinsinger P., Plassard C., Tang C. and Jaillard B. (2003) Origins of root-mediated pH
29 changes in the rhizosphere and their responses to environmental constraints: A review. *Plant*
30 *and Soil*, **248**, 43-59.
31
32
33

34
35 Hinsinger P., Plassard C. and Jaillard B. (2006) Rhizosphere: A new frontier for soil
36 biogeochemistry. *Journal of Geochemical Exploration* **88**, 210-213.
37
38
39

40
41 Huguet S., Bert V., Laboudigue A., Barthès V., Isaure M.P., Llorens I., Schat H. and Sarret G.
42 (2012) Cd speciation and localization in the hyperaccumulator *Arabidopsis halleri*.
43 *Environmental and Experimental Botany*, **82**, 54-65.
44
45
46

47
48 Isaure M.P., Laboudigue A., Manceau A., Sarret G., Tiffreau C., Trocellier P., Lamble G.,
49 Hazemann J.L. and Chateigner D. (2002) Quantitative Zn speciation in a contaminated
50 dredged sediment by μ -PIXE, μ -SXRF, EXAFS spectroscopy and principal component
51 analysis. *Geochimica et Cosmochimica Acta*, **66**, 1549-1567.
52
53
54
55

56
57 Isaure M.P., Manceau A., Geoffroy N., Laboudigue A., Tamura N. and Marcus M.A. (2005)
58 Zinc mobility and speciation in soil covered by contaminated dredged sediment using
59
60
61
62
63
64
65

1 micrometer-scale and bulk-averaging X-ray fluorescence, absorption and diffraction
2 techniques. *Geochimica et Cosmochimica Acta*, **69**, 1173-1198.

3
4
5 Isaure M.P., Fayard B., Sarret G., Pairis S. and Bourguignon J. (2006) Localization and
6 chemical forms of cadmium in *Arabidopsis thaliana*. *Spectrochimica Acta B*, **61**, 1242–1252.

7
8
9
10
11 Isaure M.P., Huguet S., Meyer, C.L., Castillo-Michel H., Testemale D., Vantelon D.,
12 Saumitou-Laprade P., Verbruggen N. and Sarret G. (2015) Evidence of various mechanisms
13 of Cd sequestration in the hyperaccumulator *Arabidopsis halleri*, the non-accumulator
14 *Arabidopsis lyrata*, and their progenies by combined synchrotron-based techniques. *Journal*
15 *of Experimental Botany*. **66**, 3201-3214.

16
17
18
19
20
21 Karlsson T., Persson P. and Skyllberg U. (2005) Extended X-ray absorption fine structure
22 spectroscopy evidence for the complexation of cadmium by reduced sulfur groups in natural
23 organic matter. *Environmental Science and Technology*, **39**, 3048-3055.

24
25
26
27
28
29 Karlsson T. and Skyllberg U. (2007) Complexation of zinc in organic soils - EXAFS evidence
30 for sulfur associations. *Environmental Science and Technology*, **41**, 119-124.

31
32
33
34
35 Li T., Liang C., Han X. and Yang X. (2013) Mobilization of cadmium by dissolved organic
36 matter in the rhizosphere of hyperaccumulator *Sedum alfredii*. *Chemosphere* **91**, 970-976.

37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000

Lions J., Guérin V., Bataillard P., Van der Lee J. and Laboudigue A. (2010) Metal availability
in a highly contaminated, dredged-sediment disposal site: Field measurements and
geochemical modelling. *Environmental Pollution*, **158**, 2857-2864.

Liu C., Frenkel A.I., Vairavamurthy A. and Huang P.M. (2001) Sorption of cadmium on
humic acid: Mechanistic and kinetic studies with atomic force microscopy and X-ray
absorption fine structure spectroscopy. *Canadian Journal of Soil Science*, **81** (3) Special Iss.
SI, 337-348.

Lors C., Tiffreau C. and Laboudigue A. (2004) Effects of bacterial activities on the release of
heavy metals from contaminated dredged sediments. *Chemosphere*, **56**, 619-630.

1 Marschner H. (1995) *Mineral nutrition of higher plants, second edition* Academic Press,
2 London.

3
4
5 McBride M.B., Barrett K.A. and Martinez C.E. (2006) Zinc and cadmium distribution and
6 leaching in a metalliferous peat. *Water Air and Soil Pollution*, **171**, 67-80.

7
8
9
10 Meyer C.L., Kostecka A.A., Saumitou-Laprade P., Créach A., Castric V., Pauwels M. and
11 Frérot H. (2010) Variability of zinc tolerance among and within populations of the
12 pseudometallophyte species *Arabidopsis halleri* and possible role of directional selection.
13 *New Phytologist* **185**, 130–142

14
15
16 Meyer C.L., Juraniec M., Huguet S., Chaves-Rodriguez E., Salis P., Isaure M.P.,
17 Goormaghtigh E. and Verbruggen N. (2015). Intraspecific variability of cadmium tolerance
18 and accumulation, and cadmium-induced cell wall modifications in the metal
19 hyperaccumulator *Arabidopsis halleri*. *Journal of Experimental Botany*, **66**, 3215-3227.

20
21
22 Mishra B., Boyanov M., Bunker B.A., Kelly S.D., Kemner K.M. and Fein J.B. (2010) High-
23 and low-affinity binding sites for Cd on the bacterial cell walls of *Bacillus subtilis* and
24 *Shewanella oneidensis*. *Geochimica et Cosmochimica Acta*, **74**, 4219–4233.

25
26
27 Nolan A.L., Zhang H. and McLaughlin M.J. (2005) Prediction of zinc, cadmium, lead, and
28 copper availability to wheat in contaminated soils using chemical speciation, diffusive
29 gradients in thin films, extraction, and isotopic dilution techniques. *Journal of Environmental*
30 *Quality*, **34**, 496-507.

31
32
33 O'Day P., Carrol S.A. and Waychunas G.A. (1998) Rock-Water interactions controlling zinc,
34 cadmium, and lead concentrations in surface waters and sediments, US tri-state mining
35 district. 1. Molecular identification using X-ray absorption spectroscopy. *Environmental*
36 *Science and Technology*, **32**, 943-955.

37
38
39 Panfili F., Manceau A., Sarret G., Spadini L., Kirpichtchikova T., Bert V., Laboudigue A.,
40 Marcus M., Ahamdach N. and Libert M. (2005) The effect of phytostabilization on Zn
41 speciation in a dredged contaminated sediment using scanning electron microscopy, X-ray
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

fluorescence, EXAFS spectroscopy and principal components analysis. *Geochimica et Cosmochimica Acta*, **69**, 2265-2284.

Pauwels M., Frérot H., Bonnin I. and Saumitou-Laprade P. (2006) A broad-scale analysis of population differentiation for Zn tolerance in an emerging model species for tolerance study: *Arabidopsis halleri* (Brassicaceae). *Journal of Evolutionary Biology*, **19**, 1838-1850.

Piou S., Bataillard P., Laboudigue A., Féraud J.F. and Masfaraud J.F. (2009) Changes in the geochemistry and ecotoxicity of a Zn and Cd contaminated dredged sediment over time after land disposal. *Environmental Research*, **109**, 712-720.

Proux O., Nassif V., Prat A., Ulrich O., Lahera E., Biquard X., Menthonnex J.J. and Hazemann, J.L. (2006). Feedback system of a liquid-nitrogen-cooled double-crystal monochromator: design and performances. *Journal of Synchrotron Radiation* **13**, 59–69.

Ravel B. (2009). ATHENA Users' Guide, version 1.5
<http://cars9.uchicago.edu/~ravel/software/doc/Athena/html/athena.pdf>

Ravel B. and Newville M. (2005). ATHENA and ARTEMIS: interactive graphical data analysis using IFEFFIT. *Journal of Synchrotron Radiation*, **12**, 537–541.

Roosens N., Willems G. and Saumitou-Laprade P. (2008) Using *Arabidopsis* to explore zinc tolerance and hyperaccumulation. *Trends in Plant Science* **13**, 208-215.

Sajidu S.M.I., Masamba W.R.L., Thole B. and Mwatseteza J.F. (2008) Groundwater fluoride levels in villages of Southern Malawi and removal studies using bauxite, *International Journal of Physical Sciences*, **3**, pp. 001–011.

Sarret G., Connan J., Kasrai M., Eybert-Bérard L., Bancroft G.M. (1999). Characterization of sulfur in asphaltenes by sulfur K- and L-edge XANES spectroscopy. *Journal of Synchrotron Radiation*, **6**, 670-672.

Sarret G., Balesdent J., Bouziri L., Garnier J.M., Marcus M.A., Geoffroy N., Panfili F. and Manceau A. (2004) Zn speciation in the organic horizon of a contaminated soil by micro X-

1 ray fluorescence, micro and powder EXAFS spectroscopy and isotopic dilution.
2 *Environmental Science and Technology*, **38**, 2792-2801.
3

4
5 Sarret G., Willems G., Isaure MP., Marcus M.A., Fakra S., Frérot H., Pairis S., Geoffroy N.,
6 Manceau A. and Saumitou-Laprade P. (2009) Zn distribution and speciation in *Arabidopsis*
7 *halleri* x *Arabidopsis lyrata* progenies presenting various Zn accumulation capacities. *New*
8 *Phytologist*, **184**, 581–595.
9
10
11

12
13
14 Szymanski J.T. (1978) The crystal structure of cernýite, Cu₂CdSnS₄, a cadmium analogue of
15 stannite. *The Canadian Mineralogist*, **16**, 147-151
16
17

18
19
20 Thiry M., Huet-Taillanter S. and Schmitt J.M. (2002) The industrial waste land of Mortagne-
21 du-Nord (59) - I - Assesment, composition of the slags, hydrochemistry, hydrology and
22 estimate of the outfluxes. *Bulletin De La Societe Geologique De France*, **173**, 369-381.
23
24
25

26
27 Tsednee M., Yang S.-C., Lee D.-C., Yeh K.-C. (2014) Root-secreted nicotianamine from
28 *Arabidopsis halleri* facilitates zinc hypertolerance by regulating zinc bioavailability. *Plant*
29 *Physiology*, **166**, 839-852.
30
31
32

33
34
35 Vansimaey C., Alary C., Bataillard P., Zentar R. and Laboudigue A. (2009) Ripening of
36 contaminated sediments: effect on organic matter-bound and iron oxides-bound metals.
37 International Conference on the Biogeochemistry of Trace Element (ICOBTE), Chihuahua,
38 Mexico.
39
40
41

42
43
44 Verbruggen N., Juraniec M., Baliardini C. and Meyer C.-L. (2013) Tolerance to cadmium in
45 plants: the special case of hyperaccumulators. *Biometals* **26**, 633–638.
46
47
48

49
50 Wenzel W.W. and Jockwer F. (1999) Accumulation of heavy metals in plants grown on
51 mineralised soils of the Austrian Alps. *Environmental Pollution*, **104**, 145–155.
52
53
54

55 Wenzel W.W., Bunkowski M., Puschenreiter M. And Horak O. (2003) Rhizosphere
56 characteristics of indigenously growing nickel hyperaccumulator and excluder plants on
57 serpentine soil. *Environmental Pollution*, **123**, 131-138.
58
59
60
61
62
63
64
65

1 Wenzel W.W. (2009) Rhizosphere processes and management in plant-assisted
2 bioremediation (phytoremediation) of soils. *Plant and Soil*, **321**, 385-408.
3
4
5

6
7 Zhang H., Zhao F.J., Sun B., Davison W. and McGrath S.P. (2001) A new method to measure
8 effective soil solution concentration predicts copper availability to plants. *Environmental*
9 *Science and Technology*, **35**, 2602-2607.
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table captions

Table 1: General properties of studied sediment. Averages and standard deviations over 3 samples.

Table 2: First shell structural parameters by shell fittings of the EXAFS spectra for sediment samples before and after culture, with or without plant, and for references.

Figure captions

Figure 1: Schema summarizing the design of culture experiment. t_i means « initial time » that corresponds to the time of *A. halleri* seedlings transfer in sediment. The monitoring was done every month from the time t_0 .

Figure 2: Cd K-edge EXAFS spectra for reference compounds including CdCO₃ (powder); Cd(OH)₂ (powder); CdCl₂ (powder); CdSO₄ (powder); Cd-goethite : 0.8% Cd (powder); Cd-phosphate : Cd₅H₂(PO₄)₄.4H₂O (powder); Cd(NO₃)₂ (powder); Cd²⁺ : 10 mM Cd²⁺ at pH=2.2 (Cd dissolved form); Cd-cellulose : described in Isaure et al., 2006; Cd-OAs : 5 mM Cd, 14 mM citrate, 100 mM malate and 400 mM succinate at pH 5.5; Cd-cysteine : (Zn, Cd, Fe)S as mixed sulfide (powder) characterized by XRD; CdS (powder).

Figure 3: (A) Cd K-edge EXAFS spectra for sediment before and after culture, with or without plant. Each spectrum (plain lines) is shown with its linear combination fit (dotted lines). (B) Distribution of Cd species for samples after normalization of the percentage to 100%.

Figure 4: Cd K-edge EXAFS spectra (A) and Fourier transforms (B) for sediment before and after culture, with or without plant, and for references: CdCO₃ and Cd-phosphate as representative of Cd-O bonds and CdS and (Zn, Cd, Fe)S as representative of Cd-S ligands. Each spectrum (plain lines) is shown with their shell fittings (dotted lines).

Figure 5: SEM EDS images and EDS spectrum recorded in Cd-rich spot of a coarse fraction grain of sediment before culture (A) and elemental maps for Cd, S and P of this region

1 recorded by μ XRF (B), with a step-size of $3\mu\text{m}$ and 1s/pixel of counting time. Spots were
2 called “P1-before culture” and “P2-before culture”.
3
4

5 Figure 6: Light microscope and SEM EDS images of a coarse grain of sediment after culture
6 with MET plant and EDS spectrum recorded in Cd-rich spot (A), and elemental maps for Cd,
7 S, P, Si and Al of this region recorded by μ XRF (B), with a step-size of $3\mu\text{m}$ and 1s/pixel of
8 counting time. Spots were called “P3A-after culture”, “P3B-after culture” and “P3C-after
9 culture”. Another Cd-rich grain was investigated: elemental maps for Cd, S, P, Si and Al of
10 this other region recorded by μ XRF (C), with a step-size of $3\mu\text{m}$ and 1s/pixel of counting
11 time. Spot was called “P4-after culture”.
12
13
14
15
16
17
18
19

20 Figure 7: Cd L_{III} -edge XANES spectra of bulk sediment before culture and reference
21 compounds (XANES spectra) and μ XANES spectra recorded on Cd-rich spots of sediment
22 before culture and after culture with MET plant. Experimental spectra are in plain lines and
23 best linear combination fits are in dotted lines. Reference compounds representative of Cd-O
24 ligands are CdCO_3 , Cd-organic acid (Cd-malate), and representative references of Cd-S
25 ligands are Cd-thiol (Cd-cysteine), and sulfides: CdS and (Zn, Cd, Fe)S.
26
27
28
29
30
31

32 Figure 8: S K-edge XANES spectra of bulk sediment before culture and reference compounds
33 (XANES spectra) and μ XANES spectra recorded on Cd-rich spots of sediment before culture
34 and after culture with MET plant. Experimental spectra are in plain lines and best linear
35 combination fits are in dotted lines. Reference compounds are oxidized sulfur (Cd-sulfate),
36 sulfoxide (DL-methionine sulfoxide, from Sarret et al., 1999), organic sulfide (DL-cysteine,
37 from Sarret et al., 1999) and mineral sulfides (CdS and (Zn, Cd, Fe)S).
38
39
40
41
42
43
44

45 Figure 9: Distribution of Cd (A) and S (B) species for samples after normalization of the
46 percentage to 100%. Percentages presented are the average over satisfactory fits, defined by
47 NSS comprised between the value obtained for the best fit (NSS_{best}) and $1.1 \text{NSS}_{\text{best}}$.
48
49
50
51

52 Figure 10: Comparison between concentrations of Cd extractable measured by $\text{Ca}(\text{NO}_3)_2$
53 extraction (A) and Cd phytoavailability estimated by DGT (B), in the sediment cultivated
54 with MET and N-MET plants (grey and white respectively), and in the control (without plant
55 - hatched). All data are averages \pm SD over 3 samples. “PA” means “plant adaptation”. On
56 each graph, results of statistical tests are indicated by Latin and Greek letters for MET plant
57
58
59
60
61
62
63
64
65

1 culture and N-Met plant culture respectively. A different letter indicates a significant
2 difference at the $P=0.05$ level.
3
4

5 Figure 11: (A) Cd concentrations [mg.L⁻¹] measured in leachates collected from cultivated
6 pots with MET plant (grey) and N-MET plant (white) origins and non cultivated pot as a
7 control (hatched), (B) biomass and (C) Cd concentrations measured in aerial parts of *A.*
8 *halleri* from MET and N-MET origins. Averages and standard deviations are over 3 samples.
9 For each graph, results of statistical tests are indicated by Greek and Latin letters for pots with
10 MET plant and N-MET plant respectively. A different number or letter indicates a significant
11 difference at the $P=0.05$ level. There is no significant difference of Cd concentration in
12 leachates measured in control pots without plant.
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table 1

Clay	< 2 μm	%	18 \pm 0.5	(3)
Silt	2 μm - 50 μm	%	45 \pm 1	(3)
Sand	50 μm - 2 mm	%	36 \pm 1	(3)
CaCO ₃ (total)		%	7.2 \pm 0.2	(3)
TOC		%	10.5 \pm 0.2	(3)
pH, H ₂ O			7.48 \pm 0.01	(3)
OM		g kg ⁻¹	225 \pm 1.3	(3)
CEC Metson		cmol(+) kg ⁻¹	25.4 \pm 0.5	(3)
K (K ₂ O) exchangeable		g kg ⁻¹	0.24 \pm 0.02	(3)
Mg (MgO) exchangeable		g kg ⁻¹	0.599 \pm 0.003	(3)
Ca (CaO) exchangeable		g kg ⁻¹	15.47 \pm 0.06	(3)
Na (Na ₂ O) exchangeable		g kg ⁻¹	0.205 \pm 0.003	(3)
P (P ₂ O ₅) Olsen		g kg ⁻¹	0.227 \pm 0.003	(3)
Cd concentration		mg kg ⁻¹	141 \pm 24	(3)
Zn concentration		mg kg ⁻¹	4074 \pm 280	(3)
Cu concentration		mg kg ⁻¹	233 \pm 9	(3)
Pb concentration		mg kg ⁻¹	600 \pm 20	(3)
Ni concentration		mg kg ⁻¹	48 \pm 2	(3)
As concentration		mg kg ⁻¹	57 \pm 4	(3)

Table 2

References and Samples	K range (\AA^{-1})	R range (\AA)	Atom	N	R (\AA)	σ^2 (\AA^2)	NSS
CdCO ₃	[3.2 - 14.7]	[1.35 - 4.1]	O	6.2	2.28	0.004	0.0090
			C	6.1	3.18	0.005	
			O	5.8	3.40	0.005	
			Cd	6,0	3.93	0.004	
Cd-phosphate	[3.2 - 14.3]	[0.88 - 4.5]	O	6.1	2.27	0.008	0.0110
			P	2.9	3.44	0.009	
			Cd	1.7	3.50	0.009	
CdS	[3.5 - 13.9]	[1.37 - 4.7]	S	4,0	2.52	0.003	0.0150
			Cd	10.4	4.14	0.007	
(Zn, Cd, Fe)S mixed sulfide	[3.6 - 13.4]	[1.32 - 4.6]	S	4,0	2.52	0.004	0.0190
			Fe	0.4	3.69	0.009	
			Zn	5,0	3.89	0.009	
			Cd	2.5	4.18	0.009	
Sediment - before culture Adjustment with (Zn, Cd, Fe)S structure	[3.6 - 13.4]	[1.35 - 4.3]	S	4,0	2.51	0.004	0.0024
			Fe	0.3	3.69	0.009	
			Zn	4.8	3.89	0.009	
			Cd	2.2	4.17	0.009	
Sediment - before culture Adjustment with (Zn, Cd, Fe)S Structure without Fe atoms	[3.6 - 13.4]	[1.35 - 4.3]	S	4.2	2.51	0.004	0.0037
			Zn	4.3	3.89	0.009	
			Cd	3.1	4.17	0.009	
Sediment without plant after culture	[3.2 - 10.8]	[1.2 - 2.9]	O	5.5	2.29	0.010	0.0026
			S	0.6	2.47	0.010	
Sediment with MET plant after culture	[3.2 - 10.8]	[1.2- 2.3]	O	6.7	2.29	0.009	0.0039
Sediment with N-MET plant after culture	[3.2 - 10.8]	[1.2 - 2.3]	O	6.2	2.30	0.009	0.0057

N: number of atoms, R: interatomic distance, σ^2 : Debye Waller factor, NSS: residual between fit and experiment. Experimental errors on N and R are $\pm 10\%$ and 0.01 \AA as estimated from the fit of reference compounds.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Figure

[Click here to download Figure: s-huguet_STotEn_figures.doc](#)

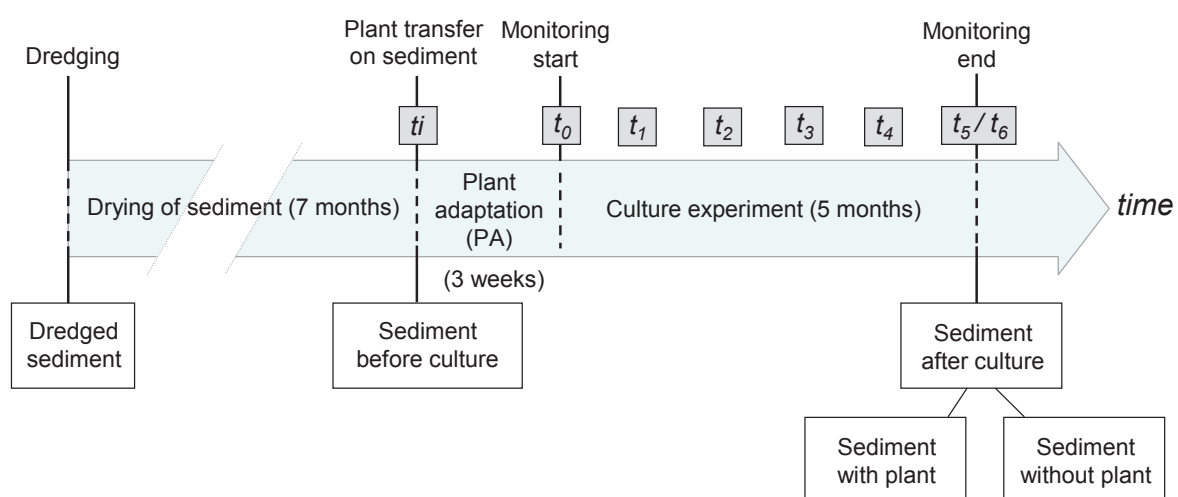


Figure 1.

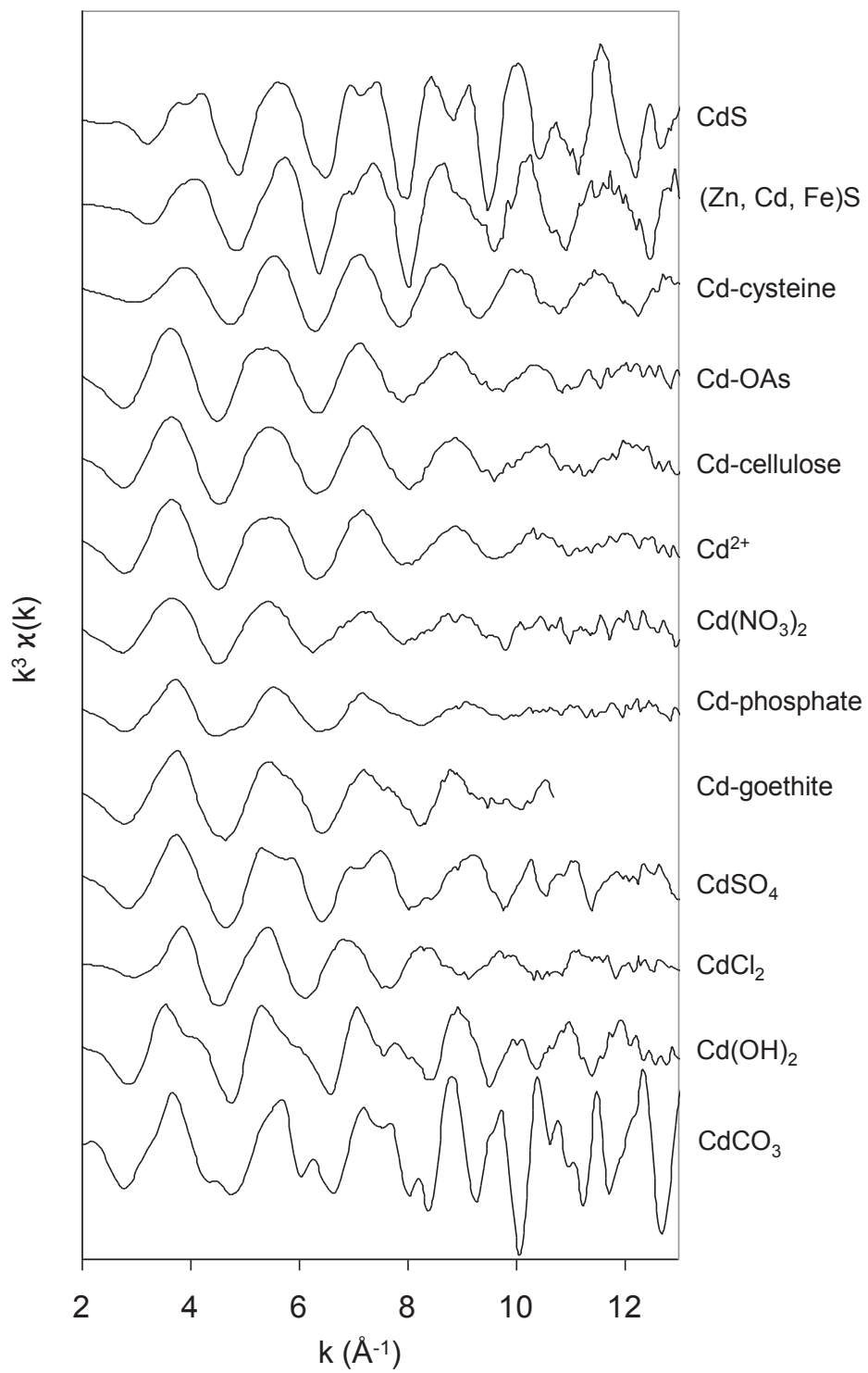


Figure 2.

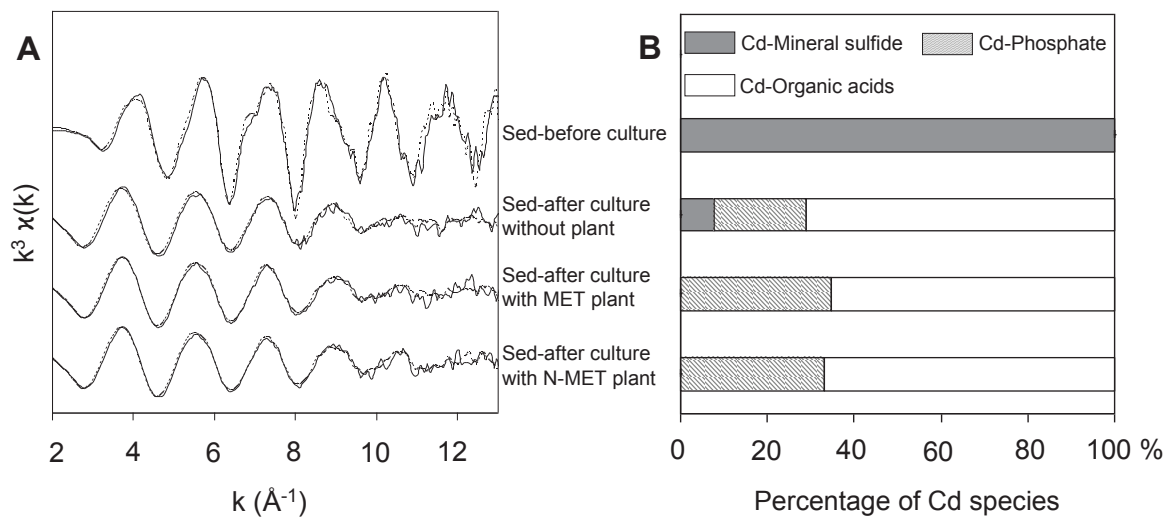


Figure 3.

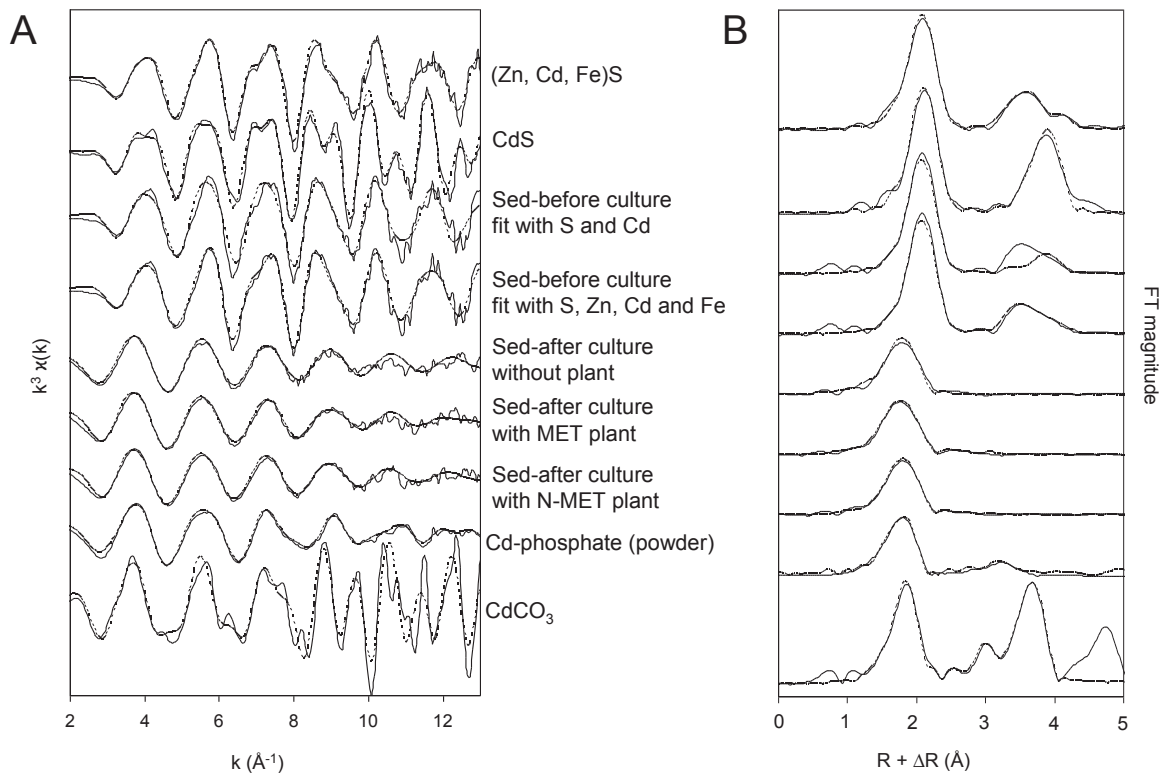


Figure 4.

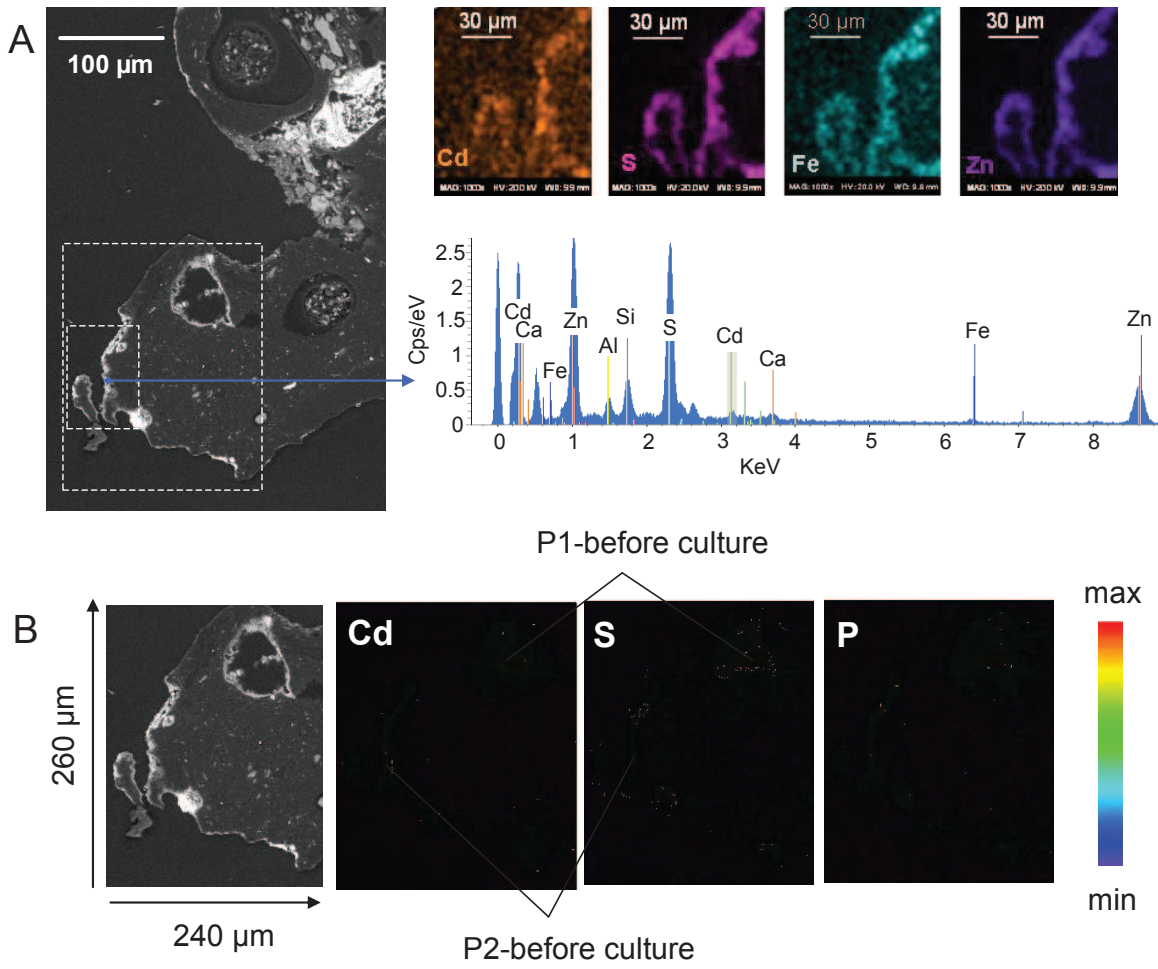


Figure 5.

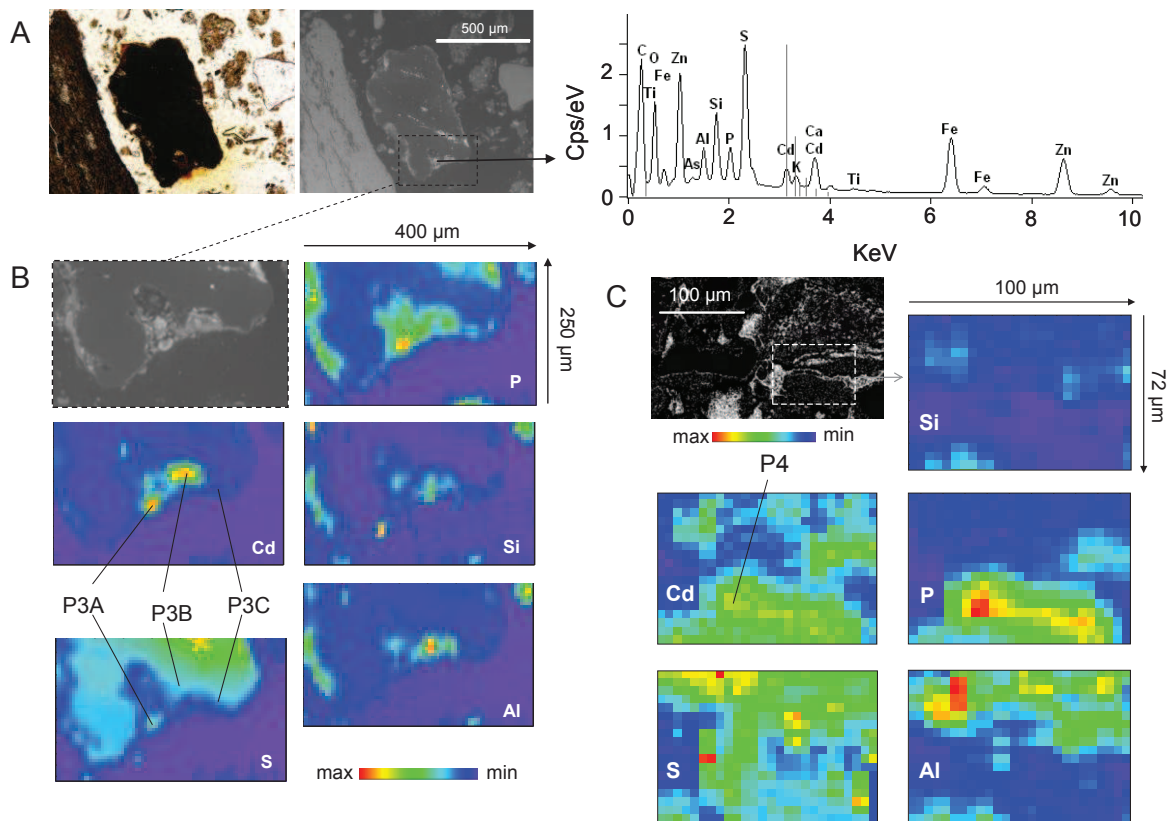


Figure 6.

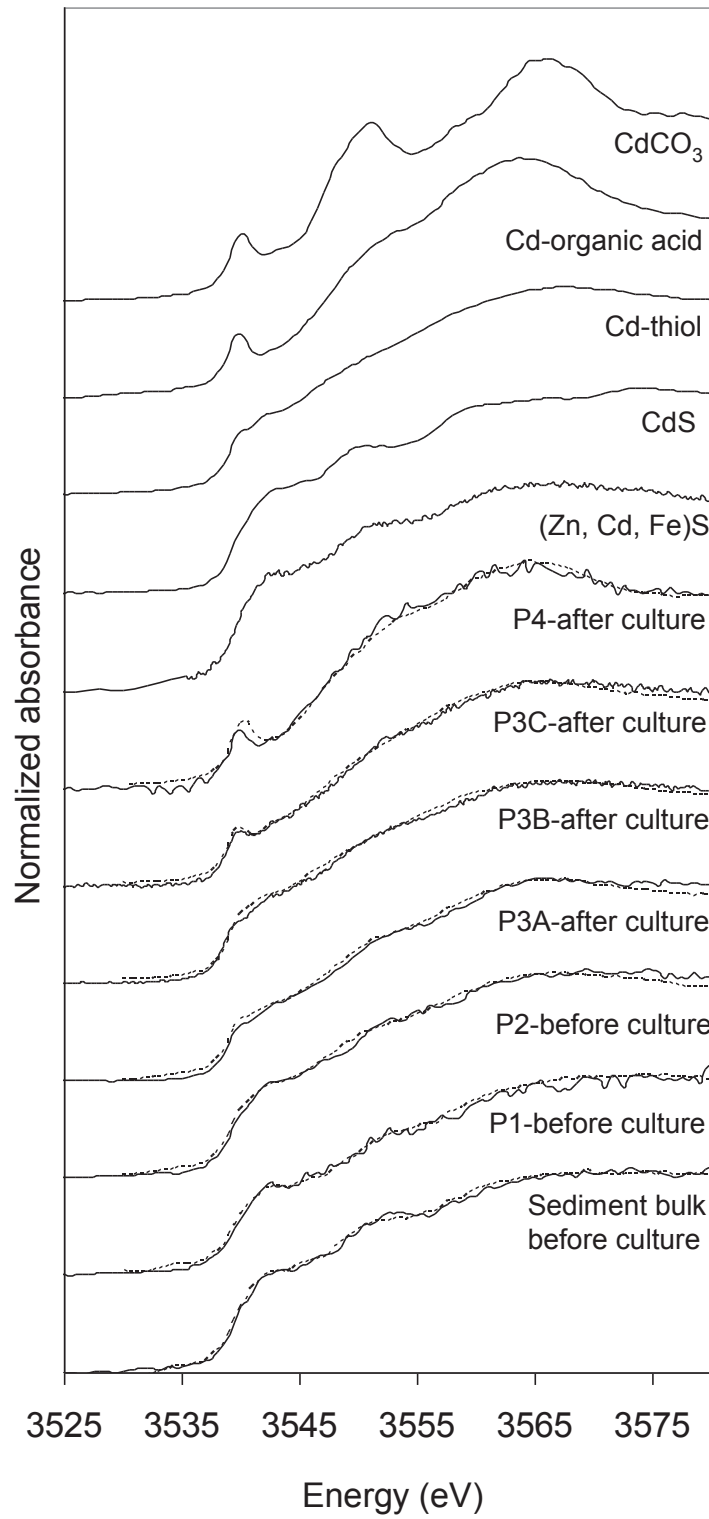


Figure 7.

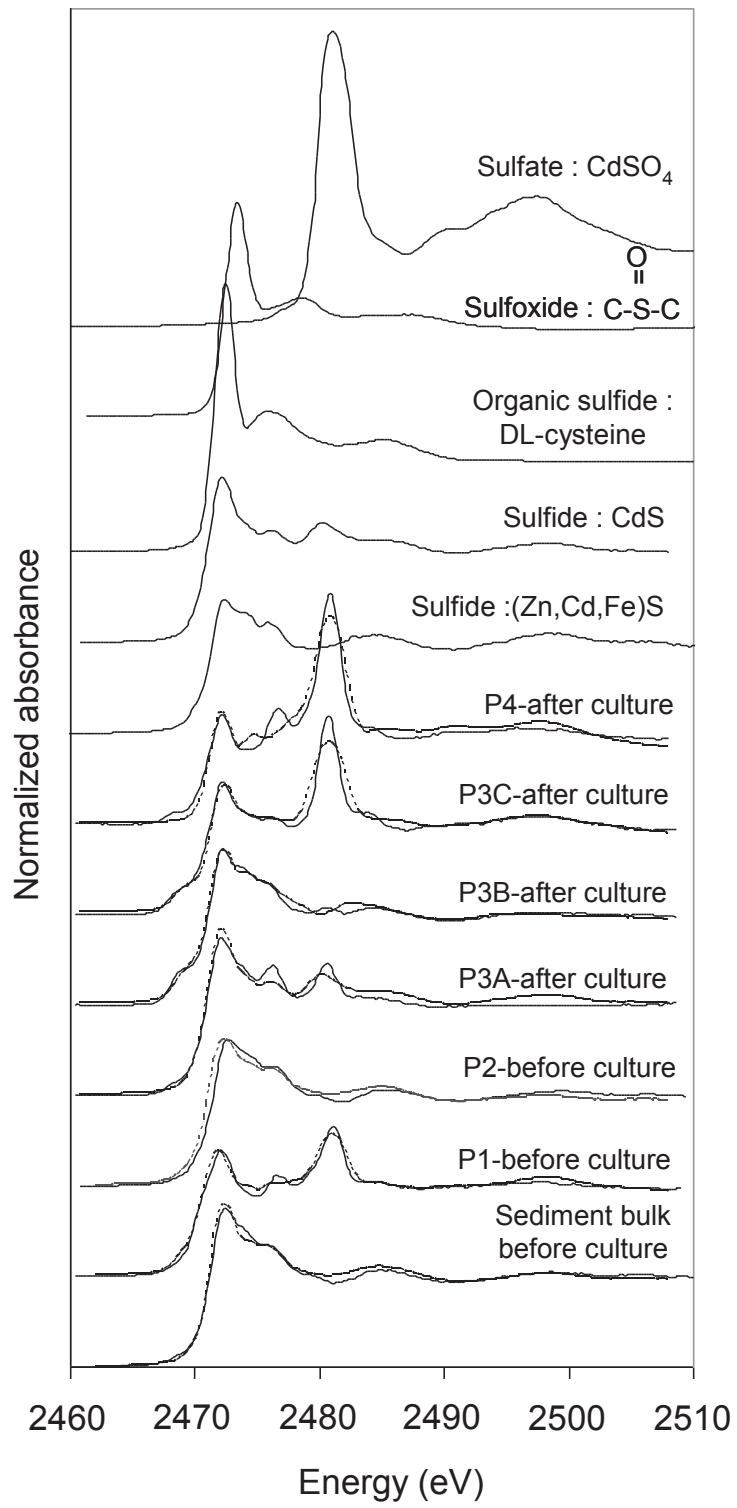
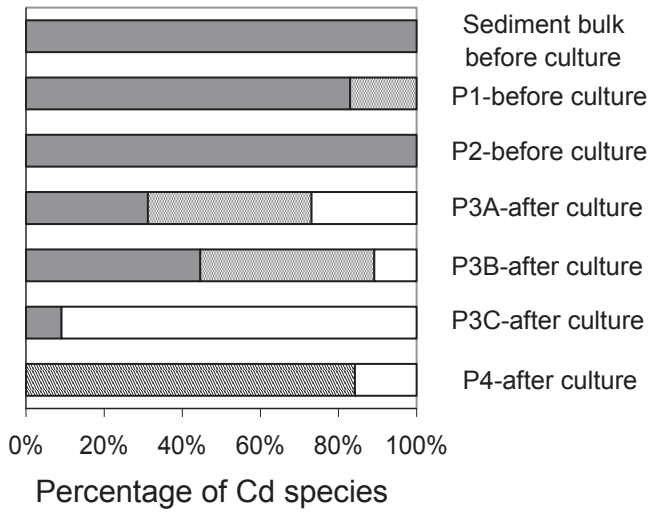


Figure 8.

A Cd species (Cd L_{III}-edge)

Cd-Mineral sulfide Cd-phosphate
Cd-Organic sulfide Cd-Organic acid



B S species (S K-edge)

Mineral sulfide Organic sulfide
Oxidized sulfur

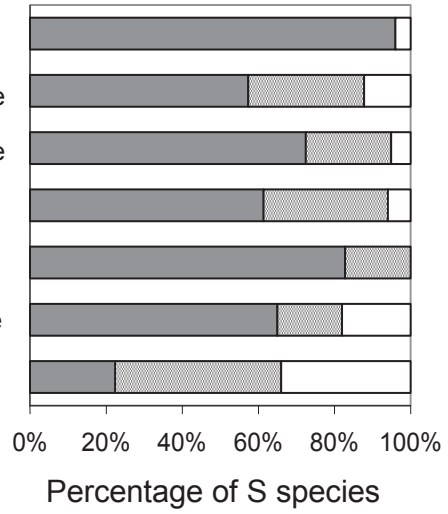


Figure 9.

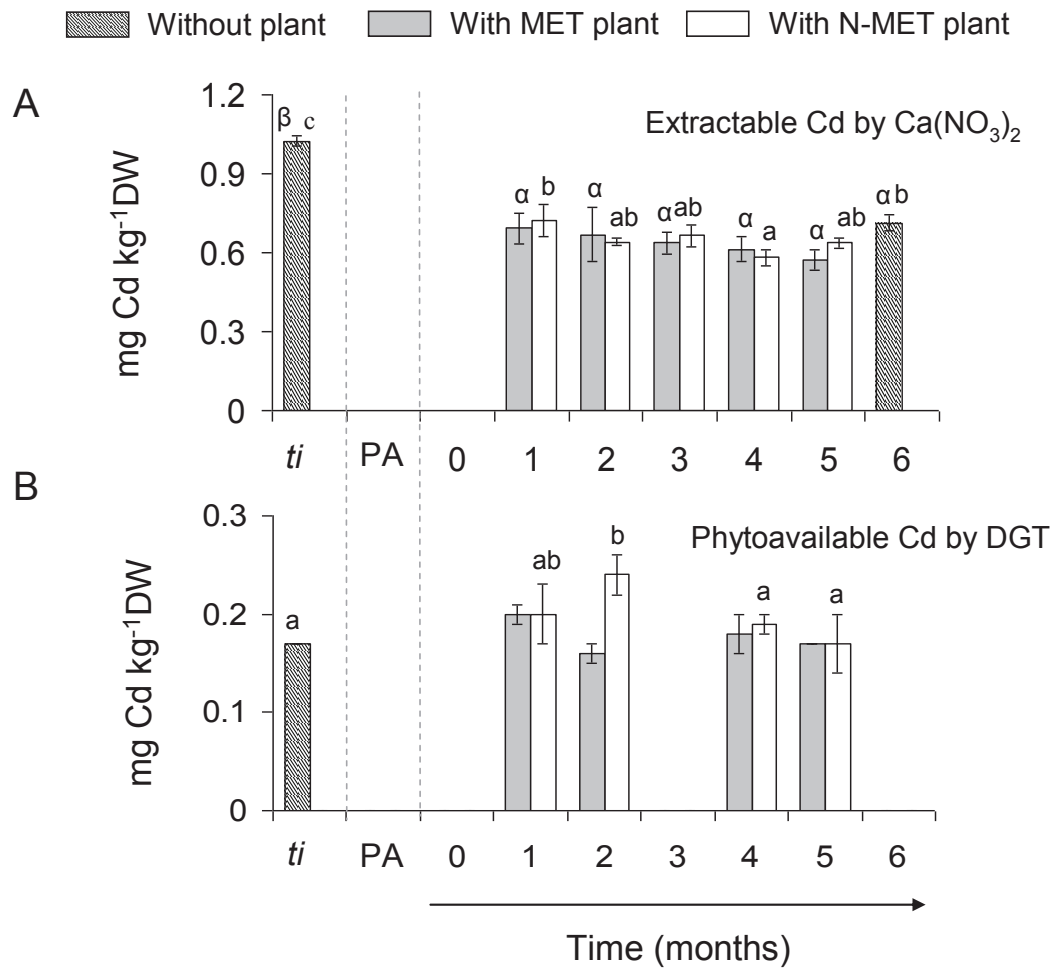


Figure 10.

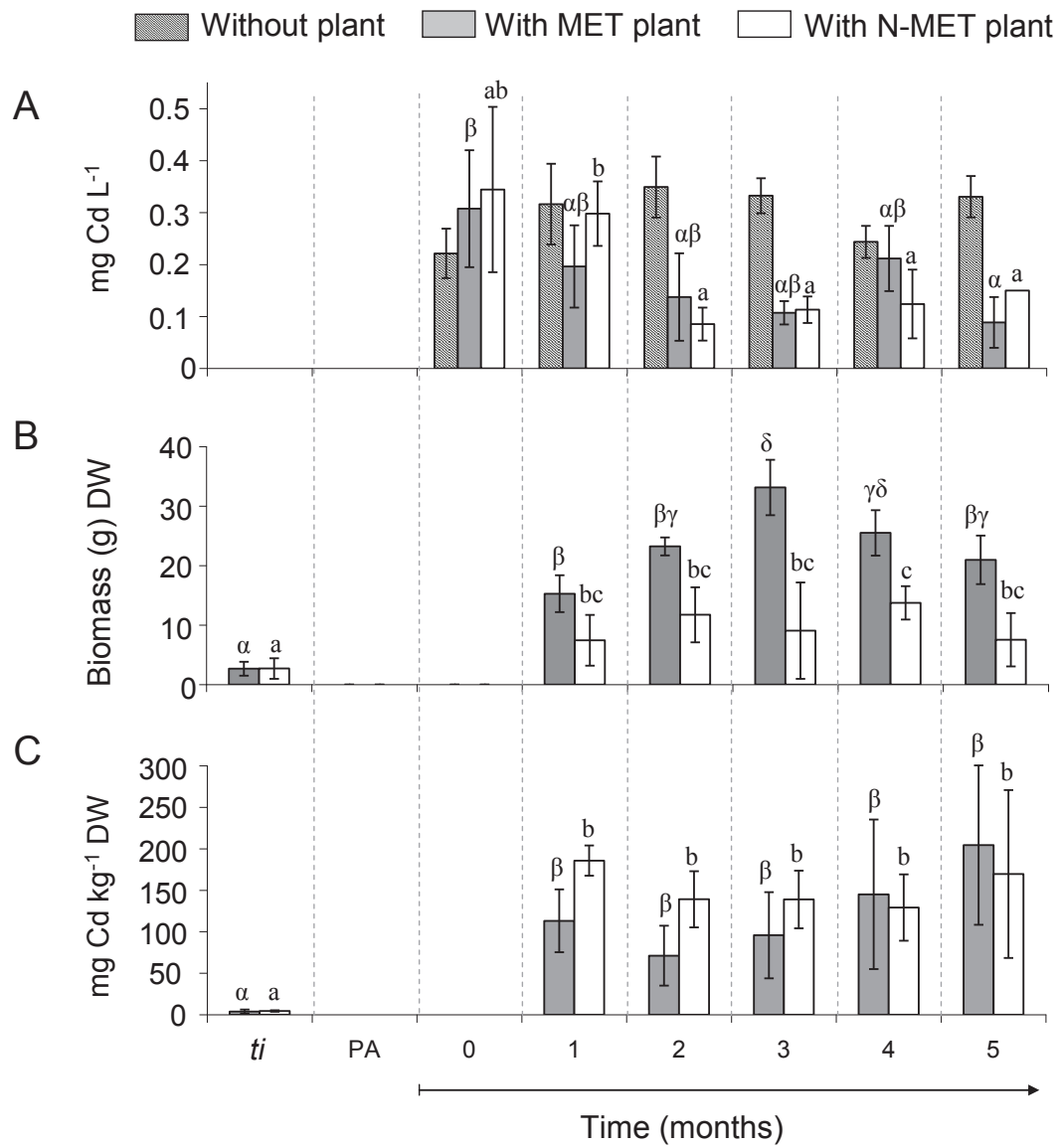


Figure 11.

Supplementary material for on-line publication only

[Click here to download Supplementary material for on-line publication only: SI_S-Huguet_STotEn.pdf](#)

Supporting informations_Science of Total Environment

Article : “Fate of cadmium in the rhizosphere of *Arabidopsis halleri* grown in a contaminated dredged sediment”.

Huguet Stéphanie, Isaure Marie-Pierre, Bert Valérie, Laboudigue Agnès, Proux Olivier, Flank Anne-Marie, Vantelon Delphine and Sarret Géraldine

		Hautes Fagnes soil		Auby soil (Sarret et al., 2004)
Clay	< 2 μm	%	19 (1)	[54]*
Silt	2 μm - 50 μm	%	64 (1)	
Sand	50 μm - 2 mm	%	17 (1)	
CaCO ₃	(total)	%	0.3 (1)	
TOC		%	9.16 \pm 0.9 (3)	
pH, H ₂ O			6.94 \pm 0.05 (3)	6.2
OM		g kg ⁻¹	278 (1)	403
CEC Metson		cmol(+) kg ⁻¹	29.5 (1)	52.7 \pm 1.6*
K (K ₂ O) exchangeable		g kg ⁻¹	0.18 (1)	0.985 \pm 0.004*
Mg (MgO) exchangeable		g kg ⁻¹	0.15 (1)	1.123 \pm 0.011*
Ca (CaO) exchangeable		g kg ⁻¹	3.23 (1)	13.06 \pm 0.03*
Na (Na ₂ O) exchangeable		g kg ⁻¹	1.86 (1)	0.0352 \pm 0.0003*
P (P ₂ O ₅) Olsen		g kg ⁻¹	0.04 (1)	2.0
Cd concentration		mg kg ⁻¹	0.90 \pm 0.21 (15)	270
Zn concentration		mg kg ⁻¹	88 \pm 20 (15)	21078
Cu concentration		mg kg ⁻¹	24.8 \pm 4.3 (15)	406
Pb concentration		mg kg ⁻¹	109 \pm 15 (15)	9135
Ni concentration		mg kg ⁻¹	18.5 \pm 2.9 (15)	
As concentration		mg kg ⁻¹	17.7 \pm 2.8 (15)	

* Value including clays and silts

Figure SI-1: General properties of two different soils where *A. halleri* seeds were collected : Grain size distribution, sediment carbonate content (CaCO₃), Organic total carbonate (TOC), pH, organic matter content (OM), cation exchange capacity (CEC), exchangeable cations and heavy metal concentrations. Averages and standard deviations over (n) samples.

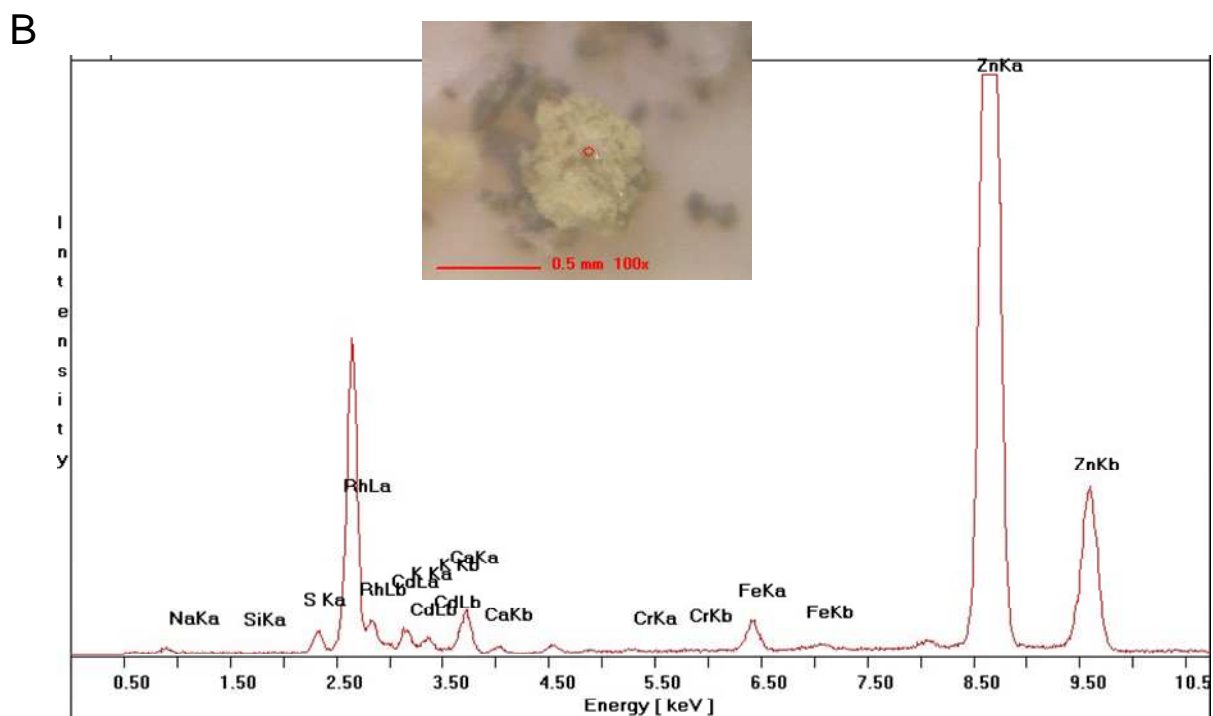
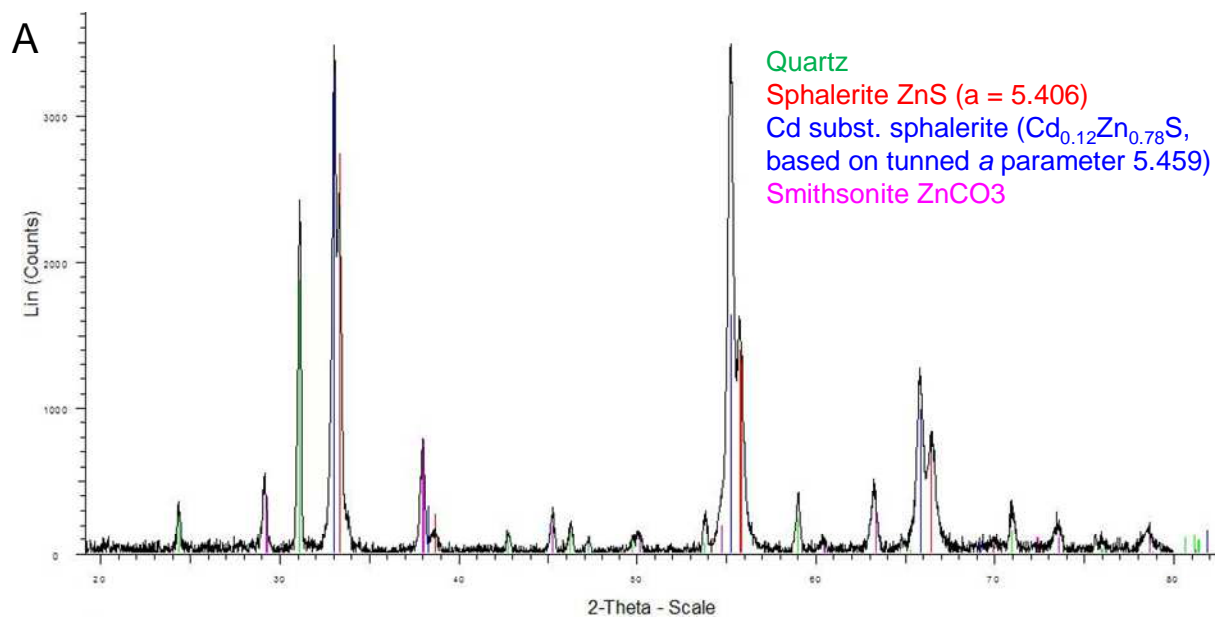


Figure SI-2: Characterization of the natural mixed sulfide reference: A: X-ray diffractogram. B: μ XRF spectrum (incident beam: 40 kV, 200 μ A)

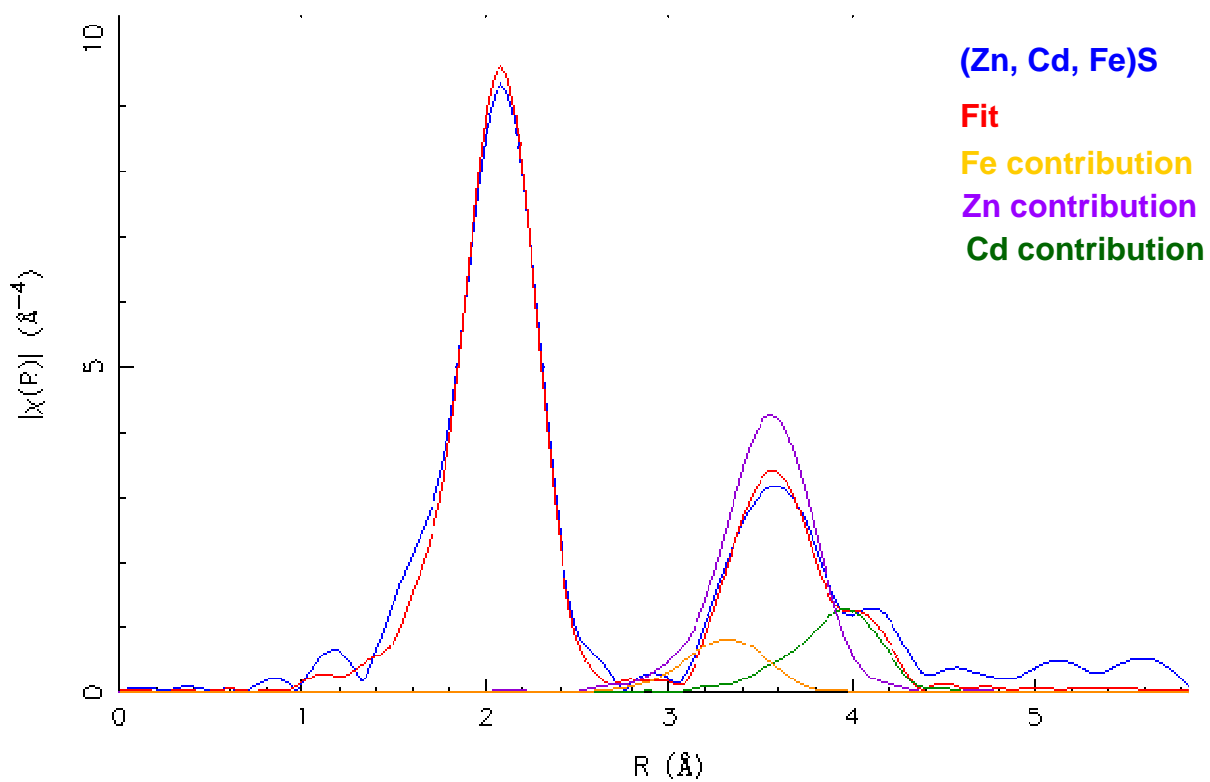


Figure SI-3: Fourier transform modulus of the $k^3 \cdot \chi(k)$ spectrum for the mixed sulfide (Zn, Cd, Fe)S reference compound (blue) and shell fitting (red). Fe, Zn and Cd individual contributions for the second shell are shown.