Phytoremediation of trace element-contaminated soils in Europe - option appraisal based on long-term field experiments

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Gentle remediation options - GRO
GREENLAND – Gentle remediation of trace element contaminated land*

project objectives

• Assess the efficiency tested in long-term field trials
• Test the possibilities for biomass valorisation
• Evaluation of a set of soil tests to assess the pollution level, the progress and success of GRO and the monitoring of sustainability
• Enhance the efficiency of GRO (e.g. by selection of most effective plants, microbes, and soil amendments)
• Development of a decision support system and publication of a guide for practical application

* FP7-KBBE-266124; 2011-2014
GREENLAND field trials: 17 case studies on 13 sites
<table>
<thead>
<tr>
<th>No.</th>
<th>Experimental coordinator</th>
<th>Strategy and gentle remediation technology</th>
<th>Plant species</th>
<th>Contaminants</th>
<th>Site type</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>UHASSELT</td>
<td>phytoextraction using SRC and crops</td>
<td>poplars, willows, maize, rapeseed</td>
<td>Cd, Zn</td>
<td>agricultural soils</td>
<td>8 yrs</td>
</tr>
<tr>
<td>2</td>
<td>SLU</td>
<td>phytoextraction using SRC</td>
<td>willows</td>
<td>Cd, Zn (Cu, Ni, Cr, Pb)</td>
<td>Commercial sludge-amended fields</td>
<td>19 yrs / 8 yrs</td>
</tr>
<tr>
<td>3</td>
<td>INERIS</td>
<td>phytoextraction using HA and high biomass crop</td>
<td>Arabidopsis halleri rapeseed</td>
<td>Cd, Zn, Pb</td>
<td>Marginal lands in surrounding industrial facility</td>
<td>6 yrs</td>
</tr>
<tr>
<td>4</td>
<td>CSIC</td>
<td>phytoextraction using HA and SRC</td>
<td>Thlaspi caerulescens, willows</td>
<td>Cd, Zn</td>
<td>tailings</td>
<td>3 yr</td>
</tr>
<tr>
<td>5</td>
<td>INRA</td>
<td>aided phytoextraction using high biomass crops from fast-track breeding</td>
<td>sunflower, tobacco sorghum</td>
<td>Cu and Cu/PAHs</td>
<td>industrial soils</td>
<td>6 yrs</td>
</tr>
<tr>
<td>6</td>
<td>LfULG</td>
<td>phytoextraction using SRC</td>
<td>poplars, willows</td>
<td>Cd, As, Pb</td>
<td>agricultural soils</td>
<td>8 yrs</td>
</tr>
<tr>
<td>7</td>
<td>PT-F</td>
<td>phytoextraction using high biomass crop from fast-track breeding</td>
<td>sunflower, tobacco</td>
<td>Cd, Zn (Cu, Ni, Cr, Pb)</td>
<td>sludged and agricultural soils on landfill</td>
<td>8 yrs</td>
</tr>
<tr>
<td>8</td>
<td>INRA</td>
<td>phytostabilisation and rhizodegradation (SRC and grassy cover)</td>
<td>Poplars, willows, grasses, vetiver</td>
<td>Cu and Cu/PAHs</td>
<td>industrial soils</td>
<td>8 yrs</td>
</tr>
<tr>
<td>9</td>
<td>CSIC</td>
<td>phytostabilisation</td>
<td>Tobacco, willows</td>
<td>Cu</td>
<td>tailings</td>
<td>3 yr</td>
</tr>
<tr>
<td>10</td>
<td>INERIS</td>
<td>aided phytostabilisation</td>
<td>Miscanthus, spontaneous grasses, shrubs, trees</td>
<td>Cd, Zn, Pb, As, Cu</td>
<td>dredged sediments</td>
<td>2 yr</td>
</tr>
<tr>
<td>11</td>
<td>AIT</td>
<td>in situ stabilization/phytoexclusion</td>
<td>barley, maize</td>
<td>Cd, Pb, Zn, (As, Cu)</td>
<td>agricultural soils</td>
<td>11 yrs</td>
</tr>
<tr>
<td>12</td>
<td>IUNG</td>
<td>in situ stabilization (lime, sludges)/phytoexclusion</td>
<td>grassland</td>
<td>Cd, Zn, Pb</td>
<td>Post-industrial soils</td>
<td>18 yrs</td>
</tr>
<tr>
<td>13</td>
<td>LfULG</td>
<td>in situ stabilization/phytoexclusion</td>
<td>crops, grassland</td>
<td>Cd, As, Pb</td>
<td>agricultural soils</td>
<td>8 yrs</td>
</tr>
</tbody>
</table>
Greenland success stories

Field Demonstrations of Phytoremediation Options in the EU FP7 GREENLAND Network of Trace Element-Contaminated Sites. Michel Mench, 14:30

Touro, ES

Bettwiesen, CH

Lommel, BE

Piekary, PL

Site 1 – smelter slag 400m from gardens and houses; 2 slag types – Doerchel more acidic, high salinity, both Zn 1-12%, Pb 0.3-4.0%, Cd up to 0.35%; revegetated 1994-1995; 300tha biosolids + lime 30tha; grass mixture
In situ Immobilisation: Arnoldstein, AT

- **ARN-B soil (moderate contamination)**
  - Cd (5), Pb (950), Zn (500), (As)

- **ARN-D soil (high contamination)**
  - Cd (15), Pb (1600), Zn (1800), (As)
Aided phytostabilisation: IUNG (Poland)

Site 1 – smelter slag 400m from gardens and houses; 2 slag types – Doerschel more acidic, high salinity; both Zn 1-12%, Pb 0.3-4.0%, Cd up to 0.35%; revegetated 1994-1995; 300t/ha biosolids + lime 30t/ha; grass mixture

Table 3. Chemical properties of waste materials sampled before (1994) and after remediation amendment with biosolids and lime.

<table>
<thead>
<tr>
<th>Waste material</th>
<th>Sampling time</th>
<th>Soluble Zn [mg kg⁻¹]</th>
<th>Soluble Cd [mg kg⁻¹]</th>
<th>Soluble Pb [mg kg⁻¹]</th>
<th>pH</th>
<th>EC [dS m⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welz</td>
<td>Before</td>
<td>343</td>
<td>17.6</td>
<td>1.80</td>
<td>7.00</td>
<td>7.30</td>
</tr>
<tr>
<td></td>
<td>1995</td>
<td>279</td>
<td>17.7</td>
<td>1.10</td>
<td>7.20</td>
<td>3.50</td>
</tr>
<tr>
<td></td>
<td>1996</td>
<td>10.4</td>
<td>0.41</td>
<td>0.34</td>
<td>7.47</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>11.4</td>
<td>0.55</td>
<td>0.41</td>
<td>7.70</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>33.3</td>
<td>0.62</td>
<td>0.02</td>
<td>7.22</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>1999</td>
<td>31.7</td>
<td>1.22</td>
<td>0.03</td>
<td>7.39</td>
<td>1.15</td>
</tr>
<tr>
<td>Doerschel</td>
<td>Before</td>
<td>1670</td>
<td>108</td>
<td>5.40</td>
<td>5.80</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>1995†</td>
<td>983</td>
<td>57.4</td>
<td>2.90</td>
<td>6.00</td>
<td>9.00</td>
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<tr>
<td></td>
<td>1996</td>
<td>12.4</td>
<td>0.66</td>
<td>0.42</td>
<td>7.44</td>
<td>2.98</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>17.9</td>
<td>0.80</td>
<td>0.40</td>
<td>7.74</td>
<td>2.06</td>
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<tr>
<td></td>
<td>1998</td>
<td>24.1</td>
<td>0.48</td>
<td>0.01</td>
<td>7.28</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>1999</td>
<td>104</td>
<td>0.99</td>
<td>0.02</td>
<td>7.36</td>
<td>2.08</td>
</tr>
</tbody>
</table>

† Sampled before retreatment of Doerschel waste.
Aided phytostabilisation:

CSIC (Touro, Spain)
Lommel (BE): Phytoextraction of Cd (removal of total pool) 

based on base case values (Nele Witters, 2011) and Vangronsveld et al. (2009)

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Base case</th>
<th>Vangronsveld et al. (2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cd</td>
<td>Cd removal</td>
</tr>
<tr>
<td></td>
<td>(mg kg(^{-1}) dm)</td>
<td>(kg ha(^{-1}) y(^{-1}))</td>
</tr>
<tr>
<td>EM</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>RS</td>
<td>5.2</td>
<td>2.68</td>
</tr>
<tr>
<td>SRC-stem</td>
<td>4.8</td>
<td>25</td>
</tr>
<tr>
<td>SRC-leaves</td>
<td>1.2</td>
<td>40</td>
</tr>
<tr>
<td>Tobacco</td>
<td>8</td>
<td>24</td>
</tr>
</tbody>
</table>

EM= energy maize, RS= rapeseed, SRC = SRC of willow

<table>
<thead>
<tr>
<th>From 5 to 2 mg Cd/kg soil</th>
<th>Clean up time (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRC willow (stem+leaves, 0.34 kg/ha/yr)</td>
<td>17</td>
</tr>
<tr>
<td>Tobacco (0.19 kg/ha/yr)</td>
<td>19</td>
</tr>
<tr>
<td>Sunflower</td>
<td>39</td>
</tr>
<tr>
<td>Maize</td>
<td>62</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>78</td>
</tr>
<tr>
<td>SRC poplar twigs</td>
<td>239</td>
</tr>
</tbody>
</table>
Phytoextraction of the labile metal pool

“Bioavailable contaminant striping”

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FEASIBILITY OF LABILE ZN PHYTOEXTRACTION USING ENHANCED TOBACCO AND SUNFLOWER: RESULTS OF FIVE- AND ONE-YEAR FIELD-SCALE EXPERIMENTS IN SWITZERLAND

Rolf Herzig,1 Erika Nehnevajova,1,2,3 Charlotte Pfistner,1,2 Jean-Paul Schwitzguebel,1,2 Arturo Ricci,1 and Charles Keller4
1Phytotech Foundation, Quartiergasse, Berne, Switzerland
2EPFL Swiss Federal Institute of Technology, (LBE), Lausanne, Switzerland
3Genetic Institute of Biology/Applied Genetics, Free University of Berlin, Berlin, Germany
4INCHEMA-Consulting AG, Zuerich, Switzerland
Phytotech Foundation (CH): Treatment effect over 5 Years - Reduction of labile Zinc in topsoil, site Bettwiesen on landfill Grüenau-Buech-Alpenblick 2007 – 2011/12

Long-term soil measurement sites - with and without phytoremediation

Option appraisal and success stories

Best practice guidance document

Outline structure:
1. Definitions and context – what is GRO and how does it work?
2. Overview of current state of development and risk management capability
3. Case / success stories
4. Potential economic, environmental and social benefits
5. Operating windows for GRO
6. Further information sources

Appendices:
Appendix 1: Design and implementation (WP1)
Appendix 2: Cultivars and amendments (WP4)
Appendix 3: Safe biomass usage (WP2)
Appendix 4: Indicators of success and methods (WP3)
Appendix 5: DST and cost-calculator (WP5)
Appendix 6: Stakeholder engagement guidelines (WP5)

Developing a practical decision support tool (DST) for the application of phytotechnologies. Andrew Cundy, 16:30
Harmonisation of methods to assess the bioavailability of TE and development of tool set to monitor the sustainability of GRO

- To achieve a convincing argument towards the decision makers, we need a harmonisation of methods to assess the initial and residual risks and the success of GRO on a comparable (and pan-European) basis.

- To select/harmonise methods describing the bioavailable/bioaccessible TE fractions among European case studies

- To select methods which can be used as indicators for GRO success and as sustainability monitoring tools.
Plant-microbial-soil system

Characterisation of soils

- General physicochemical properties (pH, CEC, C, N, available P (olsens), total [metal], etc.)
- Intensity of contaminant exposures (H$_2$O$^-$, NaNO$_3^-$, NH$_4$NO$_3^-$, EDTA-extractable [metal], soil pore water, DGT)
- Biochemical properties (Ecotoxicity tests: plants, bioaccessibility (DIN 19738), earthworms, nematodes, etc., Oxidoreductase & hydrolase (C, N, P, S cycles) enzyme activities)

Plant growth and establishment

- Survival, growth & coverage
- Plant ionome; contaminant accumulation

Bacterial community structure

Ecosystem services: water filtration, C sequestration, biodiversity, etc.
Selecting chemical and ecotoxicological test batteries for risk assessment of trace element-contaminated soils (phyto) managed by gentle remediation options (GRO)

Jurate Kumpiene a, Valérie Bert b, Ioannis Dimitriou c, Jan Eriksson d, Wolfgang Friesl-Hanl e, Rafal Galazka f, Rolf Herzig g, Jolien Janssen h, Petra Kidd i, Michel Mench j, Ingo Müller k, Silke Neu k, Nadège Oustriere j, Markus Puschenreiter l, Giancarlo Renella m, Pierre-Hervé Roumier j, Grzegorz Siebielec f, Jaco Vangronsveld h, Nicolas Manier n
Significant correlations between extractable Cd and biological responses for treated and untreated sites

<table>
<thead>
<tr>
<th>Cd Extractions</th>
<th>AqReg EDTA NH₄NO₃ NaNO₃ H₂O CdGT C_dln R_DGT</th>
<th>+*</th>
<th>-*</th>
</tr>
</thead>
</table>

**Plantox**

* **Lettuce**
  - shoot DW mass: x
  - shoot FW mass: -X -2

* **Turnip**
  - seed germination: x +1
  - shoot DW mass: -X -12

* **Dwarf beans**
  - shoot mass DW: -X -X -X -X -8
  - primary leaf FW mass: X -X -X -X +3 -6
  - root FW mass: -X -X -X -X -X -X -X X +2 -23
  - shoot length: x -X -X -X -X -X -X -X +1 -12

**Soil invertebrates**

* Earthworm avoidance: -X -X x x -x -X +2 -8
* Nematode growth: X x -X +3 -3
* Nematode reproduction: -X -2

**Dwarf bean stress enzymes**

* **Leaves**
  - ME: X XX XX-X XX X X -X +21 -5
  - ICDH: XX XX XX-X XX XX X X -X +26 -4
  - GPOD: X XXX XX-x XX X X -x +22 -2

* **Roots**
  - ME: X -X XX XX x X X -X +22 -3
  - GIDH: X XX XX XX x X +21
  - GPOD: X XX XX XX X X -X +23 -1

<table>
<thead>
<tr>
<th>Sum of positive and negative correlations*</th>
<th>+8</th>
<th>+15</th>
<th>+35</th>
<th>+32</th>
<th>+27</th>
<th>+16</th>
<th>+14</th>
<th>+2</th>
<th>+149</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-3</td>
<td>-9</td>
<td>-21</td>
<td>-20</td>
<td>-13</td>
<td>-5</td>
<td>-5</td>
<td>-15</td>
<td>-91</td>
</tr>
</tbody>
</table>

Significance level: x- 90%; X- 95%, X- 99%; “-“ indicates negative correlation.

* The correlations were weighted by allocating 1 point for those having 90% significance level, 2 points for correlations with 95% significance level, and 3 points for correlations with 99% significance level separately for positive (+) and negative (-) correlations.
Plantox responses: site Arnoldstein

Fig. 2. Plantox responses. The biomass of above ground plant parts expressed in dry weight and per pot and root biomass in fresh weight. The dashed line represents the mean value obtained in uncontaminated control soil. Gray bar = untreated soils; hatched or dotted bar = treated soils. For Biogeoce and Piekary II, hatched bar = OMDL and LB-L treatments, respectively; dotted bar = OMZ and LB-H treatments, respectively. The stars represent statistical differences at 95% confidence level between untreated and treated soils.
Earthworm behaviour

Fig. 4. Behavior of worms *Eisenia fetida* in tested soils. (a) Behavior of worms in studied soils and the ISO control soil. The dashed lines represent the threshold for significance (± 60%); (b) behavior of worms in the treated soils as compared with the untreated ones. *OMDL treated Biogeoco soil.
Assessment of biomass valorisation options

- to review existing processes and types of biomass; to compile information on current and under development processes
- to test various types of plant biomass collected on case study sites
- to assess advantages and limitations regarding technical aspects, regulations, acceptance and costs
- Treatment options:
  - Incineration
  - Gasification
  - Anaerobic digestion
  - Solvolysis
  - Pyrolysis

Processing of Plant Biomass Harvested at Trace Element-Contaminated Sites Managed by Gentle (Phyto) Remediation Options. Valerie Bert, 15:30
Improvement of GRO efficiency

- Selection and testing of more efficient plant species, varieties, clones
- Selection and testing of more efficient soil amendments
- Selection and testing of more efficient microbial strains (rhizobacteria, endophytes)
- Application of agronomic practices for improving GRO efficiency
Selecting TE-excluding crops for phytoexclusion

Testing novel combinations of amendments for stabilization of metals in heavily contaminated soils. Grzegorz Siebielec, 17:00
Development of a decision support tool and a best-practice guidance document

- Draw together data from other WPs, and develop and test best-practice guidance documentation and tools to allow stakeholders, problem-holders and end-users to appraise the various options available, examine the potential for use of the biomass produced, and refer to a harmonised methods protocol.
  - best-practice guidance document for the application of GRO at field-scale
  - Guidelines for stakeholder participation, engagement and empowerment when implementing GRO

- To develop and trial / evaluate a decision support tool (based on Greenland and other case studies), focused on GRO, which can be integrated into existing, well-established and utilised (national) DSTs / decision-frameworks.

Developing a practical decision support tool (DST) for the application of phytotechnologies. Andrew Cundy, 16:30
GREENLAND: consortium

- 1 Markus Puschenreiter, University of Natural Resources and Life Sciences, Vienna (Coordinator)
- 2 Jaco Vangronsveld, Universiteit Hasselt
- 3 Jurate Kumpiene, Luleå tekniska universitet
- 4 Michel Mench, Institut National de la Recherche Agronomique
- 5 Valerie Bert, Institut National de l'Environnement industriel et des Risques
- 6 Andrew Cundy, University of Brighton
- 7 Petra Kidd, Consejo Superior de Investigaciones Científicas
- 8 Giancarlo Renella, University of Florence
- 9 Wolfgang Friesl-Hanl, Austrian Institute of Technology
- 10 Grzegorz Siebielec, Instytut Uprawy Nawożenia i Gleboznawstwa - Państwowy
- 11 Rolf Herzig, Phytotech-Foundation
- 12 Ingo Müller, Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie
- 13 Jannis Dimitriou, Sveriges lantbruksuniversitet
- 14 Xose Quiroga Troncoso, Tratamientos Ecológicos del Noroeste SL
- 15 Ryszard Bajorek, ATON
- 16 Patrick Lemaitre, Innoveox
- 17 Cyril Aymonier, CNRS-ICMCB
Thanks for your attention!
Stakeholder engagement/empowerment in all steps of GRO implementation

Developing principles of sustainability and stakeholder engagement for “gentle” remediation approaches: The European context

A.B. Cundy a,*, R.P. Bardos a,b, A. Church a, M. Puschenreiter c, W. Friesl-Hanl d, I. Müller e, S. Neu e, M. Mench f, N. Witter g, J. Vangronsveld g

Inform Consult Involve Collaborate Empower

Increasing stakeholder interaction and engagement

Fig. 3. Spectrum of stakeholder engagement and empowerment activities (after REVIT Project, 2007). Note that the lower arrow shows direction of increasing depth of stakeholder interaction and engagement and is not intended to show a “flow” of activities, as stakeholder engagement activities are frequently iterative and non-linear in nature and may involve the full range of these involvement measures (see text for discussion).
Development of a decision support tool

Phase 1 (Feasibility)
- Definitions and scope of GRO; contaminant matrix; “success stories”.

Is Gentle Remediation an Option?
- Y
- N

Phase 2
- Semi-quantitative assessment (stakeholder engagement; sustainability assessment; outline cost-calculator “modules”)

Y
N

Phase 3
- Technical assessment (detailed cultivar, amendment etc details, “operating windows”)

Increasing complexity and time investment

Site / risk assessment

Options appraisal

Implementation of remediation strategy

National guideline / DST

Onwubuya et al (2009), modified