

Early screening of new accumulating versus non-accumulating tree species for the phytomanagement of marginal lands

Lisa Ciadamidaro, J. Parelle, F. Tatin-Froux, C. Moyen, A. Durand, C. Zappelini, N. Morin-Crini, D. Soupe, D. Blaudez, M. Chalot

▶ To cite this version:

Lisa Ciadamidaro, J. Parelle, F. Tatin-Froux, C. Moyen, A. Durand, et al.. Early screening of new accumulating versus non-accumulating tree species for the phytomanagement of marginal lands. Ecological Engineering, 2019, 130, pp.147-156. 10.1016/j.ecoleng.2019.02.010. hal-02089637

HAL Id: hal-02089637 https://hal.science/hal-02089637

Submitted on 18 Apr 2019 $\,$

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	Early screening of new accumulating versus non-accumulating tree species
2	for the phytomanagement of marginal lands
3	
4	Lisa Ciadamidaro ^a , J. Parelle ^a , F. Tatin-Froux ^a , C. Moyen ^a , A. Durand ^a , C. Zappelini ^a ,
5	N. Morin-Crini ^a , D. Soupe ^b , D. Blaudez ^c and M. Chalot ^{a,d}
6	
7	^a Université de Bourgogne Franche-Comté, UMR CNRS 6249 Laboratoire Chrono-
8	environnement, Pôle Universitaire du Pays de Montbéliard, 4 place Tharradin, BP 71427, F-
9	25211, Montbéliard, France.
10	^b Pépinières Daniel SOUPE S.A.S., Les Lazares – Route de Thoissey, 01400 Châtillon sur
11	Chalaronne, France.
12	^c Université de Lorraine, CNRS, LIEC, F-54000 Nancy, France.
13	^d Université de Lorraine, F-54000 Nancy, France.
14	*email: lisa.ciadamidaro@univ-fcomte.fr; Telephone: +33 3 81 66 57 14
15	
16	
17	
18	
19	

20 Abstract

The use of fast-growing trees producing a high quantity of biomass can bring significant 21 22 practical and economic benefits to the reclamation of marginal lands. The present study aims to identify new shrub/tree species to offer a wider range of shrubs/trees useful for 23 phytomanagement practices. We implemented three experimental sites in France of 1 ha each 24 (Thann, Carrières-sous-Poissy and Leforest) contaminated by different potentially toxic 25 26 elements (PTE) with a total of 38 different tree species. After two years of growth, the 27 element concentrations in stem and leaf biomasses, tree survival rate and growth of plants were assessed. Although the three sites had elevated concentrations of total PTE and nutrients 28 29 in their soil, the element contents in the trees strongly differed depending on the species. 30 Alnus subcordata, Platanus orientalis, Ulmus pumila, Ostrya carpinifolia and the Acer species appeared to be well adapted to the drastic conditions of the sites and presented the 31 32 lowest PTE concentrations in their aboveground biomass. Conversely, the Salix, Populus, Betula and Quercus species, especially Salix aquatica grandis, exhibited the highest 33 34 accumulations of Cd, Zn and/or Mn at the three sites. Inoculation with the endomycorrhizal 35 fungus *Rhizophagus irregularis* did not have a significant impact on the growth of the tree species at the three sites after two growing seasons. Overall, the present study offers two 36 options for the phytomanagement of marginal lands. The first option is based on the 37 38 production of clean biomass, which is useful for plant-based industrial processes (e.g., 39 biomaterials, bioenergy) that could valorize this biomass. The second option is based on the 40 production of TE-enriched biomass that could be better exploited in the eco-catalysis process.

41

42 Key words: Non-accumulating tree species, trace elements, phytomanagement, *Salix*43 *aquatica grandis*

44 **1. Introduction**

45 Pollution has been identified by the European Commission as a major threat to soils. In EU countries, the number of potentially contaminated sites adds up to nearly 3 million 46 (Europe's environment - The fourth assessment). More than 250,000 polluted sites in the 47 member states require urgent clean up. Due to several anthropogenic activities, such as 48 mining, industries and the production of agricultural wastewater, the spread of PTE in the 49 environment has become a major problem (Khan et al., 2010; Sheoran et al., 2010). 50 51 Therefore, the remediation of polluted soils is crucial to ensure that soil remains a key natural 52 resource for human society and to promote sustainable environment and economic 53 development. As such, pollution treatment represents an economic need, which often remains 54 unanswered by conventional civil engineering methods due to their inappropriateness, environmental impact and costs (notably for large sites). Currently, several phytotechnologies 55 56 can be considered and applied to PTE polluted soils: (1) phytostabilization, which uses 57 perennials able to sorb and immobilize potentially toxic PTE in the root zone, avoiding their 58 transfer towards groundwater and aerial parts, preventing their bioaccumulation in the food 59 chain, as well as their dispersion by natural agents (wind erosion, water); and (2) phytoextraction, which is based on root-to-shoot transfer and the storage of potentially toxic 60 PTE in harvestable tree parts (Pilon-Smith, 2005). These eco-innovative phytotechnologies 61 62 can remediate soil layers in contact with the roots and at the same time provide tree biomass 63 (Robinson et al., 2009), which can be used to reach the targets for the use of renewable energy sources (Mench et al., 2009, Ciadamidaro et al., 2017). 64

The suitability of a certain plant for PTE remediation is determined by various plant properties, such as: (i) heavy metal tolerance; (ii) size, growth rate and rooting depth; (iii) heavy metal accumulation in above-ground plant parts; and (iv) climatic adaptation and pest resistance (Kirkham, 2006; Pulford and Watson, 2003). Over the years, several studies have

3

been carried out to optimize the method and to find the most suitable plants. Poplars and 69 70 willows have been extensively tested for the phytoremediation of land polluted by PTE (Dickinson, 2006; French et al., 2006; Meers et al., 2007; Ciadamidaro et al., 2014). Their 71 72 potential resides in large biomass production, extensive root systems, considerable tolerance to PTEs, and high accumulation of PTE in the biomass (Pulford and Watson, 2003). Other 73 studies (Mertens et al., 2007; Evangelou et al., 2012) have tested different trees, such as birch 74 75 (Betula pendula), oak (Quercus robur), ash (Fraxinus excelsior) and maple (Acer 76 pseudoplatanus) and demonstrated different behaviors and adaptation characteristics to PTE 77 contamination. These differences have had impacts on the final outcome of phytomanagement 78 strategies, and a careful selection of appropriate tree species/clones seems to be a prerequisite 79 for any field-based phytoremediation attempts (Pulford and Watson, 2003).

80 During the last two decades, we have witnessed the emergence of using different tree 81 species in combination with microbial biotechnologies (Mench et al., 2010). It is now widely 82 recognized that microorganisms are of utmost importance for the efficacious establishment of 83 phytomanagement strategies (Moreira et al., 2016). Indeed, it is now proved that mycorrhizal 84 fungus associations enhance plant growth at field levels (Ciadamidaro et al., 2017) and vitality on TE-disturbed habitats and reduce metal toxicity, affecting plant metal uptake and 85 further accumulation in plant tissues (Phanthavongsa et al., 2017). Moreover, mycorrhizal 86 87 fungi enhances plant growth and their resistance to adverse conditions including toxicity produced by TEs, affecting the phytoavailability of TEs in soil and the uptake of metals by 88 plants from soil and translocation from root to shoot (Yilmaz and Parlak, 2011, Meier et al., 89 90 2012). Most importantly, the selection of adequate trees and microbes is a key feature in a phytomanagement approach (Ciadamidaro et al., 2017). However, current knowledge about 91 92 the performance of trees and their associated microbes in phytomanagement strategies is particularly limited to a few genera, such as Populus and Salix (Dominguez et al., 2008; 93

94 Ciadamidaro et al., 2014, Phanthavongsa et al., 2017).

We hypothesized that testing a large number of woody species on various marginal 95 lands would increase the panel of trees relevant for phytomanagement. The purpose of the 96 present study was to identify a panel of woody species with phytoremediating capacities, 97 98 either within a phytostabilization strategy (high productivity, low PTE accumulation), or 99 within a phytoextraction strategy (high productivity, high PTE accumulation), which would 100 allow greater efficiency and ensure the biodiversity needed to restore the ecosystem. We 101 chose to work on a short time scale to be able to rapidly select species useful for 102 phytomanagement. To better address the question of the replicability of our data, we 103 implemented three different sites with different contamination histories. We also aimed to test 104 the impact of endomycorrhizal inoculation on the PTE uptake by various tree species.

105 **2. Materials and methods**

106 **2.1. Site description and soil preparation before plantation**

107 The experiment was carried out at three different sites, i.e., Thann, Carrières-sous-108 Poissy and Leforest, where phytomanagement has been identified as a relevant strategy to 109 remediate soil pollution.

110 The experimental site of Thann is located in the valley of the Thur in Alsace-France 111 (47°47'48.4"N 7°08'20.8"E) near the border with Germany and Switzerland, on a 15 hachemistry-based industrial complex. The Thann plant owned by the Cristal company is one of 112 113 the most important sites for TiO₂ production in Europe and is the second-largest production 114 facility in the world (Assad et al., 2017). The Ti extraction process generates tailings made of 115 red gypsum from the neutralization and precipitation of effluents containing sulfuric acid, 116 which is used to dissolve the PTE contained in the ore. Red gypsum, a solid residue enriched 117 with Fe, S and Mn, is stored on the Ochsenfeld landfill (Alsace, France), located on an 80-ha landfill 3 km away from the industrial complex. The landfill site was prepared before 118

plantation by adding a 30-cm layer of soil obtained from a local source and incorporated into the red gypsum layer by plowing to a depth of 50 cm. Previous assays have indeed demonstrated the need for reconstructing a soil layer to allow for tree growth prior to plantation. Direct implementation on the red gypsum substrate would result in poor growth and high mortality at this site.

The experimental site at Carrières-sous-Poissy (48°57'39.7"N 2°02'09.6"E) was watered with raw wastewater of the Paris conurbation from 1899 to 2002, hence becoming highly enriched in nutrients and organic matter (OM) and accelerating the production of market vegetables until the late 1990's (Lamy et al., 2006). However, PTE accumulation in the soil led to multi-pollution characterized by Pb, Zn and Cd concentrations 10 times higher than those in a non-irrigated reference soil. Before plantation, the soil was plowed to a depth of 30 cm.

131 The experimental site at Leforest is located close to Noyelles-Godault, in Northern France (50°25'40.5"N 3°02'40.5"E), in the proximity of the Metaleurop plant, which is one of 132 133 the biggest Zn and Pb production units in Europe (Douay et al., 2009). It was built in 1894 134 and produced approximately 170,000 tons of Pb and 105,000 tons of Zn per year until it was 135 closed in 2003. This plant produced a significant quantity of dust, and its fallout contaminated 136 the adjacent area to a distance of several km, with high amounts of Cd, Zn and Pb. Studies 137 have been undertaken to investigate the nature of the contamination (Sterckeman et al., 1996) 138 and the transfer of contaminants to local vegetation (Azimi et al., 2003; Migeon et al., 2009; 139 Pourrut et al., 2011) and macrofauna (Pauget et al., 2013). Before plantation, the soil was 140 plowed to a depth of 30 cm.

141 **2.2. Experimental design**

The three experimental sites were established in November 2013 (Carrières-sousPoissy) and April 2014 (Thann and Leforest). Each site was divided into 8 different plots, in

half of them the rooted trees were inoculated (4 inoculated plots *x* tree species *x* site) with a commercial mycorrhizal inoculum and the other half was left non-inoculated (4 control plots *x* tree species *x* site). The fungal inoculum consisting of the AM *Rhizophagus irregulare* DAOM 197198 strain was provided by the Agronutrition company (Toulouse, France). The inoculation was performed at the nursery prior to plantation by soaking the roots into a mixture of propagules / peat (200000 propagules / 5 L of peat).

150 The experimental designs slightly differed from site to site as detailed hereafter. At the 151 Thann site (8250 m^2) , each plot consisted of 18 different tree species (594 trees per plot, i.e., a 152 total of 4752 trees) and each tree species was represented by 264 individuals distributed 153 equally in each of the 8 plots (33 individuals per tree species per plot). The trees were planted in lines with a spacing of 0.60 cm, resulting in a final density of 5760 trees/ha. At the 154 Carrières-sous-Poissy (9840 m²) and Leforest (8706 m²) sites, each plot consisted of 16 155 156 different tree species (496 trees per plot, i.e., a total of 3968 trees), and each tree species was represented by 248 individuals distributed equally in each of the 8 plots (31 individuals per 157 158 tree species per plot). The trees were planted in lines with a spacing of 0.70 cm, resulting in 159 final densities of 4033 and 4558 trees/ha for Carrières-sous-Poissy and Leforest, respectively. 160 The criteria for the selection of tree species at each site were as follows: recognized 161 environmental adaptations to local soil conditions, endogenous characteristics (spontaneous 162 presence at the site), level of production at the nursery, and, in some cases, the lack of data in 163 the phytomanagement literature. The three sites contained three tree species in common 164 (Ostrya carpinifolia, Pterocarya stenoptera and Salix aquatica grandis). The Carrières-sous-165 Poissy and Leforest sites had 4 additional tree species in common (Populus oxford, Quercus 166 petraea, Quercus cerris and Quercus pedunculata). The Thann and Leforest sites had 2 167 additional tree species in common (Platanus orientalis and Salix alba). A detailed list of the 168 tree species implemented at each site is reported in Table 1.

169 **2.3. Soil and tree analyses**

170

2.3.1 Soil physico-chemical characterization

171 At site implementation, 10 top-soil (0-20 cm) samples were gathered from each plot 172 with a hand auger after site preparation and mixed together to create composite samples. The 173 24 soil composite samples (3 sites x 8 composite samples) were analyzed for physico-174 chemical characterization. The soil samples were dried at 40 °C in a forced air oven to a 175 constant weight and ground with a grinder (agate mortar, Retsch RM100). The samples were 176 sent to a certified laboratory (SADEF, France) for the following analyses: particle size 177 distribution, exchangeable Ca (CaO), Mg (MgO), K (K₂O) and Na (Na₂O), cation exchange capacity (CEC) (NF X 31-130), organic matter (OM) (NF ISO 14235), total CaCO₃ (NF ISO 178 179 10693), total nitrogen (Nt) (NF ISO 13878), total phosphorus (Joret-Hebert method) (NF X 180 31-161) and soluble boron (B) (NF X 31-122).

181

2.3.2 Soil and plant trace element analyses

182 The total element concentrations (Al, Cd, Fe, Mn, Pb, S, Zn) in the soil at the start 183 time were determined using inductively coupled plasma atomic emission spectrometry (ICP-184 AES, Thermo Fischer Scientific, Inc., Pittsburgh, USA) following the acid digestion of 500 mg of sample (DigiPREP system, SCP Sciences, Courtaboeuf, France) using a mix of 2 mL of 185 186 67% nitric acid, 6 mL of 34% hydrochloric acid and 2 mL of 48% hydrofluoric acid. The available element concentrations in the soil were assessed using a 0.01 M CaCl₂-extraction 187 188 with a sample extraction ratio of 1:10 (Houba et al., 1996) via ICP-AES. The total and 189 available elemental concentrations in the soils are reported in Table 3.

At each sampling site, leaves and stems from 6 trees per plant species per plot were sampled in autumn 2015, for a total of 2400 analyses. Leaf and stem samples were washed with distilled water, dried at 70°C for at least 48 h, and ground using a stainless-steel mill. The studied elements (Al, Cd, Fe, Mn, Pb, S and Zn) were determined by ICP-AES following the acid digestion with concentrated HNO₃ (DigiPREP system). All samples were run
together with certified reference materials, including oriental basma tobacco leaves (INCTOBTL-5, LGC Promochem, Molsheim, France) and a loamy clay soil (CRM052, LGC
Promochem, Molsheim, France). The percentage of recovery of the studied elements ranged
between 77 and 110%.

199

2.3.3 Tree survival rate and growth estimation

200 The survival rates of plants were estimated in 2015. To avoid destructive sampling at this 201 stage, after two years of growth, tree development was estimated by measuring the tree 202 heights (Fig. 1) of all trees at the three sites in October 2015 and compared to the nursery 203 standard. The nursery trees were grown in soil for the same length of time, without any 204 fertilizers nor irrigation. However, they did not experience the transplantation event. The height of each tree was estimated in the following ranges expressed in cm: 40/60; 60/80; 205 206 80/100; 100/120; 120/150; 150/175; 175/200; 200/250. The initial height of the planted trees 207 was 40/60. Once the growth report was completed, an average value was assigned to each 208 tree.

209

2.4. Statistical analyses

Statistical analyses were carried out using R 3.2.0 software (R Development Core Team, 2015) for Windows, and the results are expressed as mean values with standard deviations. All tests were considered significant when p < 0.05. Normality of variable or residual values were tested with a Shapiro-Wilk test and homoscedasticity with a Bartlett test.

The mean comparison between treatments (Control and Inoculated) for the results of nutrients and trace elements in soil was performed using post hoc tests following a one-factor analysis of variance (ANOVA) considering the sites separately and each site as the independent variable. To test the effects of the inoculation and tree species on PTE uptake in trees, a multifactor ANOVA (MANOVA) was performed to obtain the F values and significance ($P \le 0.05$) of each studied variable. Significant differences in soil variables between treatments were established by the Tukey test at p < 0.05. PCA analyses were performed using the FactoMinR package: data below the limit of quantification were considered to be null for the calculation of the principal components, and ellipses were drawn at the 95% confidence interval of the barycenter of each species.

224 **3. Results**

3.1. Soil characteristics

226 The main characteristics of the three studied soils are reported in Table 2. The average 227 pH values of the three sites were close to neutrality or slightly acidic (7.4, 7.2 and 6.5 for 228 Thann, Carrières-sous-Poissy and Leforest, respectively). The soil texture was sandy-silt, 229 sandy and silty-loam for Thann, Carrières-sous-Poissy and Leforest, respectively. The organic 230 status reported in Table 2 demonstrated that Carrières-sous-Poissy presented much higher values of C and N (39.6 g/kg of Corg, 68.5 g/kg of OM and 3.78 of Ntot) in comparison with 231 232 the other two sites, especially the Thann site. In general, for the exchangeable oligos, higher 233 values were observed for Carrières-sous-Poissy and Leforest, except for Na2Oex at Carrières-234 sous-Poissy.

235 Although a set of elements in the soil was analyzed, only the most abundant and the 236 major contaminants are shown for this study (Table 3). The results showed high total 237 concentrations in soil for all of the elements reported in Table 3, except for Cd at Thann. 238 According to these values, Thann presented much higher contents of Fe, Mn and S, whereas 239 Carrières-sous-Poissy and Leforest exhibited higher values of Cd, Pb and Zn and were similar 240 to those obtained in previous studies of metal-contaminated sites in France (Assad et al., 241 2017, Foulon et al., 2016a, b; Douay et al., 2013; Lamy et al., 2006; Pourrut et al., 2011). The 242 CaCl₂ extractable fractions also differed between sites and followed the same trends of the 243 total concentrations, except for Mn at Thann. Indeed, the Mn CaCl₂ extractable fractions at Leforest accounted for approximately 5% of the total Mn, whereas at Thann it accounted for less than 0.03%. Pb was not detected in the $CaCl_2$ extractable fractions for any of the sites. Despite its elevated total concentrations of most elements, the Thann soil was less appropriate for plant growth, as the availability of its nutrients was rather low.

248

3.2. Tree development at the three experimental sites

249 For each species and each site, the survival rates are given for the 8 plots (Table S4). 250 The data were compared with the average rate of survival seen in nurseries (an average of 251 90% after 2 years, under favorable soil and crop conditions). Due to the high mortality after 252 the first year for unknown reasons, the Betula species needed to be replanted in January 2016. 253 After 2 years of growth, the average survival rates at the Thann, Leforest and Carrières-sous-254 Poissy sites were 73%, 77%, and 85%, respectively, which seems acceptable considering the 255 soil constraints (high PTE loads) of the sites and the drastic weather conditions during 256 summer 2015, which were marked by a strong drought.

257 During the year 2015, non-destructive plant measurements were undertaken, as 258 described in the "materials and methods" section. The levels of tree growth at the Thann and 259 Leforest sites were 42% and 20% lower than the nursery standards, respectively (Fig. 1). This 260 reduced growth could be attributed to different factors, such as: i) site-specific soil-climatic 261 conditions; ii) less follow-up and care than in nurseries; iii) an exceptional level of drought in 262 the summer of 2015; iv) animal (rabbits and wild boar) grazing. The nursery data are provided 263 in our manuscript as indicators of the optimal nursery performance for commercial purposes, but they cannot be considered as experimental controls. As is often the case in field 264 265 experimental design, it was not possible to have field controls, as the studied sites lacked non-266 contaminated areas. Climatic conditions during the experimental period are reported in Table 267 S1. The 2013 to 2015 data were in the range of the overall weather data at the three sites and comparable. The 2015 summer (June or July) was however remarkably drier and warmer thanthe previous years, at the three sites.

270 Contrasting differences were reported for the following tree species at the Thann 271 site: i) Z. serrata, with a growth rate 34% higher than that of the standards; ii) the Salix, 272 *Platanus, Ulmus* and *Ostrya* species slightly grew less than the nursery standards; and iii) and 273 a clear difference observed for the other species, for which tree growth was reduced by 61% 274 on average and by up to 75% for the three Quercus species (Fig. 1). At the Carrières-sous-275 Poissy site, tree growth was overall only 14% lower than that of the nursery standards (Fig. 276 1). Most of the tree species performed quite well, with the Acer, Eleagnus, Fraxinus, Ostrya 277 and Syringa species exhibiting heights equaling or exceeding the nursery standards. The 278 Paulownia species showed the lowest growth rate. At the Leforest site, the Alnus, Platanus, 279 Populus and Salix (3 species) showed worthy performances compared to the nursery 280 standards. The growth of the two Quercus species was significantly lower than that of the 281 standards (Fig. 1). Moreover, P. stenoptera as well as S. aquatica grandis and S. caprea 282 appeared to be particularly impacted by the site conditions.

283

3.3. Elements in trees (leaves and stems)

The element concentrations of leaves and stems are detailed in Tables S2 and S3. For 284 285 all the studied elements in leaves, a MANOVA was performed (Table S5) in order to 286 highlight the effects of treatments (I), tree species (S) and interaction $(I \times S)$ between these 287 two factors. The species (S) is the dominant factor affecting PTE accumulation in leaves at all 288 sites. In general, inoculation (I) had no significant effect on PTE accumulation at the 3 sites 289 (Table S5). Only at the Thann site, an interaction effect between treatment and species $(I \times S)$ 290 slightly influenced the Al, Fe and Pb concentrations in leaves and that of Al at the Leforest 291 site (Table S5). Therefore, according to these MANOVA results, data from the control and 292 inoculated trees were pooled in all the following analyses.

The complete panel of analyzed elements (Fig. 2) was investigated using a 293 294 multivariate analysis (PCA). Based on the PCA, the Salix, Populus and Betula species for the 295 three sites and, additionally, the 3 Quercus species for Thann site were closely correlated with 296 the major PTE contents (Cd, Pb, Zn and Mn). The strongest correlations were observed for S. 297 *aquatica grandis*, one of the three common species in all the sites, for Cd, Zn, Ni and Co (Fig. 298 2, a-f), and for B. verrucosa with Mn at the Thann site (Fig. 2, a and b). In more detail, the 299 Salix, Populus and Betula species showed the highest accumulation capacities for Cd and Zn 300 in their leaves, with especially very high values for the Salicaceous species growing at 301 Leforest (Table S2). In particular, S. aquatica grandis demonstrated the highest capacity to 302 accumulate Cd (>100 µg/g DM) and Zn (>2500 µg/g DM). P. stenoptera at the Leforest site 303 was the only species never tested before in phytomanagement, which demonstrated an 304 accumulation capacity for Zn in leaves but at lower levels than those observed for the 305 Salicaceous species. Concerning Mn, only species grown at the Thann site accumulated higher Mn contents compared with the range considered to be "physiological" in tree leaves. 306 307 Species of the genera Salix, Betula and Quercus showed high Mn uptake capacities. At the 308 same time, they were also able to accumulate Fe and S (the other principal elements at the 309 Thann site) in leaves above the range considered physiological in trees, reaching values \approx 310 400 μ g/g Mn for *Q. rysophylla* and *B. papyrifera* and >300 μ g/g Mn for *S. aquatica grandis* 311 (Table S2). For the three sites, all the other elements analyzed were in the background range 312 for PTE in plants (Table S2) according to Kabata-Pendias and Pendias (1992) and for Fe 313 according to Bowen (1979).

In contrast, the PTE contents and PCA analysis revealed that *P. orientalis*, *U. pumila*, *O. carpinifolia* and the 3 studied *Acer* species showed poor or no correlation at all with any of the elements measured in the leaves at the three sites. In this work, species of the genera *Acer*, *Alnus, Eleagnus, Fraxinus, Hippophae, Quercus, Ostrya*, and *Paulownia* (which have only seldom been tested in phytomanagement studies), did not show any accumulative trait for theelements measured.

320 We further analyzed the elemental concentrations in stems (Table S3). However, this 321 analysis was restricted to those species that accumulated PTE in their leaves, since the stem 322 element contents are usually lower than the leaf contents. For a general interpretation of the PTE concentrations in stems depending on the selected tree species, the data are presented as 323 324 sunray plots, and the values of each tree species were transformed to their corresponding 325 logarithms in order to fit them into the graphs (Fig. 3). In general, the PTE concentrations in 326 stems were 5-10 times lower than the PTE concentrations in leaves (Tables S2 and S3). 327 Nevertheless, the results confirmed the trends observed in leaves for all tree species, i.e., the higher accumulation of Cd and Zn at the Leforest site for S. aquatica grandis and that of Mn 328 329 at the Thann site for *Q. cerris*, *Q. pedunculata* and *B. papyrifera*.

330 4. Discussion

Overall, in the present study, we tested the growth performance and element accumulation of 38 tree species at three different marginal lands. This set of data allowed us to identify two groups of trees that could be useful for phytomanagement strategies.

334 The first group includes species that grew rather well and did not accumulate PTEs. 335 Our results based on growth data (Fig. 1 and Table S4) and PCA analysis (Fig. 2) showed that 336 O. carpinifolia performed very well on the three sites compared to the nursery standard and accumulated PTE in the leaf tissues within normal physiological levels (Table S2) (Kabata-337 338 Pendias and Pendias, 2001; Bowen, 1979). To our knowledge, this tree species has never 339 before been tested in a phytomanagement context. Similarly, P. orientalis showed good 340 growth capabilities at two of the three sites (Thann and Leforest). In addition, 2 Fraxinus and 2 Syringa species, the Acer, Alnus, Carpinus, Hippophae, Ulmus and Zelkova species, 341 342 performed rather well on at least one experimental site, showing no accumulation of PTE. The

343 satisfying potential growth of these species makes them good candidates for the restoration of 344 marginal lands at no risk, since the produced biomass will be clean enough to further limit the 345 recycling of contaminants through leaf fall. There is almost no data on the phytomanagement 346 capacity of P. orientalis, U. pumila, O. carpinifolia, A. saccharinum and Z. serrata trees. 347 Similar results were only found by Mertens et al. (2007), in which A. pseudoplatanus was able to reduce the mobilization of PTE in a contaminated site. According to our findings, 348 349 these tree species could be considered relevant for phytomanagement strategies due to their 350 capacity of reducing PTE uptake, exploiting tree transpiration and root growth in order to 351 decrease leaching and control erosion (Robinson et al., 2003). Indeed, roots can help prevent 352 the formation of reduced PTE species, which have often been reported to be more toxic and 353 more mobile than oxidized species. The roots can also add organic matter to the substrate that 354 binds the PTE (Robinson et al., 2009). Two of these tree species (O. carpinifolia and F. 355 ornus) have been proposed for the stabilization of a mining area after soil reconstruction in NW Greece (Zagas et al., 2010). 356

357 The second group of relevant tree species includes those that grew well and 358 accumulated PTE. During the screening and analysis of data, our results indeed showed that 359 of the 38 total studied trees species from the three sites, 4 genera exhibited a clear capacity to 360 accumulate PTE in their aboveground biomass. Generally, the Betula, Populus, Quercus and 361 Salix species accumulated significantly more PTE compared with the other tree species. The 362 accumulation of Zn and Cd by members of the Salicaceous family is now well established 363 (Ciadamidaro et al., 2014; Madejon et al., 2013; Robinson et al., 2006). In more detail, 364 S. aquatica grandis, P. oxford and B. pubescens accumulated Cd, Pb, and Zn at the Carrières-365 sous-Poissy and Leforest sites, whereas Fe, Mn and S were accumulated by S. aquatica 366 grandis, Q. rysophylla, and B. papyrifera at the Thann site. However, in some cases, the rate 367 of PTE accumulation was significantly different between the studied sites. In our work, for 368 example, S. aquatica grandis was able to accumulate the highest concentrations of Cd and Zn 369 in all sites, reaching maximum values of $\approx 128 \ \mu g/g D$ Wt for Cd and $\approx 2800 \ \mu g/g D$ Wt for Zn in leaves (Table S2). The Cd accumulation rate in leaves was somehow linked to the CaCl₂ 370 extractable Cd fraction. At the Leforest site, the leaf Cd and the CaCl₂ extractable contents 371 were 4- and 5-fold higher than those at the Carrières-sous-Poissy site, respectively. The 372 373 lowest Cd content in S. aquatica grandis leaves (< 2.5 µg/g D Wt) was recorded at the Thann 374 site, where the CaCl₂ extractable Cd fraction was lower than the detection limit. Zn concentrations, in leaf and soil samples were in the same order of magnitude at the two 375 Carrières-sous-Poissy and Leforest sites. In this context, among the trees used in 376 377 phytomanagement, the species able to tolerate and accumulate high concentrations of PTE 378 (Ali, 2013) in their tissues without visible toxicity symptoms are considered 379 hyperaccumulators. S. aquatica grandis may possibly be considered as a Cd and Zn hyperaccumulator in our study (Leforest site). It remains to be determined whether its growth 380 381 will be affected in the long term by the high availability of Cd and Zn at the Leforest site.

At the Thann site, Q. rysophylla and B. papyrifera showed the best accumulation 382 383 capacities for Mn but it seems that there was no relation between the Mn in leaf tissues and that in the CaCl₂ extractible fraction. For the two *Quercus petraea* and *Q. pedunculata* species 384 385 present at both the Leforest and Carrières-sous-Poissy sites, the leaf Mn levels were similar, 386 whereas the Mn contents in the soil at the Leforest site were 6 times as high as those observed 387 at Carrières-sous-Poissy. These results could support the hypothesis that Quercus genera 388 presents accumulation capacities for Mn independently of soil physic-chemical characteristics 389 and Mn concentrations in soil.

390 It is worth highlighting that the trees used for the phytoextraction of PTE from the soil 391 must be efficient in accumulating PTE mostly in leaves and stems (Gomes et al., 2012; Rascio 392 and Navari- Izzo, 2011). In the present study, although the highest PTE concentrations were

found in leaves compared to stems, the correlation coefficient between PTE in leaves and 393 394 stems showed significant positive correlations for all elements, except for the Pb and S 395 concentrations in the Carrières-sous-Poissy site and for Fe in the Thann and Leforest sites 396 (Table 4). In general, the strongest correlations in all three sites were observed for Zn and Cd, 397 especially considering that Zn and Cd seem to have similar geochemical and environmental 398 properties, and they can interact during plant uptake, transport and accumulation in leaves and 399 stems (Das et al., 1997, Han et al., 2010). In the case of Cd, Pulford and Watson (2003) 400 determined that the compartmentalization of PTE within trees is considered to vary greatly by 401 species and clones. Yang et al. (2015) showed that in the aboveground tissues of willows, Cd 402 is usually sequestered in vacuoles, by which the toxic effects of Cd can be greatly minimized. 403 Moreover, Salt et al. (1995) and Vassilev et al. (2005) concluded that the distribution and 404 translocation of Cd to above ground tissues were primarily driven by the transpiration stream. 405 In the case of Zn, previous studies (Maxted et al., 2007; Migeon et al., 2009) agreed with our 406 results and found significantly more Zn in the leaves than in the stems of *Salicaceous* species.

For Mn, significant correlations were obtained, especially at the Thann site, between leaf and stem contents (Table 4). This could be related to the ability of Mn to be rapidly taken up and translocated within plants (Kabata-Pendias and Pendias, 2001). It is worth noting that Mn was efficiently taken up in the *Betula* and *Quercus* species, despite its very low $CaCl_2$ availability at the Thann site (Table 3). This may be due to either intrinsic capabilities or to a specialized microbial community that may reduce the Mn mostly present in the soil as Mn oxides (Zappelini et al., in preparation).

Concerning Pb, previous studies (Baker, 1981; Borisěv et al., 2009; Stoltz and Greger,
2002) observed restricted translocation from roots to stems and leaves due to a PTE exclusion
mechanism in roots by which plants avoid damages in their photosynthetic processes.
Moreover, Pb is considered to have low solubility and therefore a low availability to plants

17

because it precipitates as phosphates and sulfates found in the rhizosphere of plants, as
exemplified by Blaylock and Huang (2000). Indeed, we could not recover the Pb in the CaCl₂
fraction, despite its elevated total concentration, especially at the Carrières-sous-Poissy site.

421 Although many studies have evinced that mycorrhizal fungus association could 422 enhance tree growth and vitality on TE-disturbed habitats and reduce PTE toxicity, affecting tree PTE uptake and accumulation in plant tissues (Ciccatelli et al., 2010; Liu et al., 2014), no 423 424 significant effect of mycorrhizal inoculation on tree development or PTE accumulation in 425 trees was observed in our experimental conditions. It is well known that the effect of AM 426 fungi on plant parameters depends on many factors, including tree and fungus species, the 427 growth conditions of the tree, tree age, soil properties, and the type and concentration of PTE 428 in the soil (Arriagada et al., 2005; Mrnka et al., 2012). The lack of beneficial effect, in 429 contrast to those obtained in our previous study (Ciadamidaro et al. 2017), is probably due to the fact that a single endomycorrhizal fungal species was used here and that some of the 430 431 tested trees are not as perceptive as poplars to endomycorrhizal colonization in their early 432 growth stage. Despite differences in the characteristics of the three soils and of their original 433 contamination, the behavior in growth and PTE uptake of the different tree species was quite similar at all sites, indicating that the overall effect species is more important than the effect 434 of the inoculation, as stated by the MANOVA analysis. 435

436 **5.** Conclusions

Among the 38 total studied species, 4 species (*A. subcordata*, *P. orientalis*, *U. pumila*, *O. carpinifolia* and the 3 studied *Acer*), only seldom used before in a phytomanagement strategy, showed the highest growth capacity. Moreover, these tree species that produced a clean biomass could be considered as good candidates for the phytomanagement of marginal lands, for their valuation in various industrial sectors. Indeed, while it is necessary to treat the by-product fractions enriched in PTE when using contaminated biomass (Chalot et al., 2012,

Asad et al., 2017, Bert et al., 2017), using this non-accumulating biomass would allow 443 444 researchers to by-pass this additional step. In contrast, S. aquatica grandis, P. oxford, Q. rysophylla and B. papyrifera trees were able to take up high quantities of one or more of 445 446 the analyzed PTE without presenting toxic symptoms. For this reason, they could be classified as phytoextracting species and used with regard to the restoration objectives and a PTE 447 management strategy. Indeed, these species with TE-enriched biomass could lead to the 448 449 marketing of a truly eco-innovating production chain that could meet the needs of an 450 emerging, high-prospect market within the bio-economy, such as eco-catalysis (Grison, 451 2015). These innovative eco-solutions for the treatment of polluted soils respond perfectly to 452 the needs of sustainable development.

Moreover, the most promising tree species could be retained, and a model stabilizer 453 and accumulator/hyperaccumulator tree could be used as a control to study fundamental 454 455 processes. This will permit (i) the recovery of PTE-contaminated sites from belowground to 456 aboveground biomass and (ii) the production of valuable materials and fuels, focusing on the 457 catalysis of industrial chemicals, performance and high-tech products, e.g., pharmaceutical, 458 cosmetics, and flavors. A future comparative analysis of catalytic systems derived from 459 hyperaccumulating and accumulating trees will be useful for a better understanding of phytomanagement processes. 460

461

462 Acknowledgements

We acknowledge Dr. Caroline Amiot for the ICP-AES analyses. We thank Jean Michel Colin
(CRISTAL Co., France), Elsa Borujerdi (Grand Paris Seine & Oise, France) and Guillaume
Lemoine (Etablissement Public Foncier Nord-Pas de Calais, France) for providing us access
to the Thann, Carrières-sous-Poissy and Leforest experimental sites, respectively. The authors
declare no conflicts of interest.

468 Funding sources

- 469 This work was supported by the French National Research Agency [PHYTOCHEM ANR-13-
- 470 CDII-0005-01], the French Environment and Energy Management Agency [PROLIPHYT
- 471 ADEME-1172C0053], the Région Franche-Comté [Environnement-Homme-Territoire 2014-
- 472 069] and the Pays de Montbéliard Agglomération [13/070-203-2015].

473 **References**

- Ali, H., Khan, E., Sajad, M.A., 2013. Phytoremediation of heavy metals—Concepts and
 applications. Chemosphere. 91: 869-881.
- Arriagada, C., Herrera, M.A., Ocampo, J.A., 2005. Contribution of arbuscular mycorrhizal
 and saprobe fungi to the tolerance of Eucalyptus globulus to Pb. Water Air and Soil Pollution.
 166: 31-47.
- Asad, M., Menana, Z., Ziegler-Devin, I., Bert, V., Chalot, M., Herzig, R., Mench, M., Brosse,
 N., 2017. Pretreatment of trace element-enriched biomasses grown on phytomanaged soils for
- 481 bioethanol production. Industrial Crops and Products. 107: 63-72.
- Assad, M., Tatin-Froux, F., Blaudez, D., Chalot, M., Parelle, J., 2017. Accumulation of trace
 elements in edible crops and poplar grown on a titanium ore landfill. Environmental Science
 and Pollution Research. 24: 5019-5031.
- Azimi, S., Ludwig, A., Thévenot, D.R., Colin, J.-L., 2003. Trace metal determination in total
 atmospheric deposition in rural and urban areas. Science of the Total Environment. 308: 247256.
- Baker, A.J.M., 1981. Accumulators and excluders strategies in the response of plants to
 heavy metals. Journal of Plant Nutrition. 3: 643-654.

- Bert, V., Allemon, J., Sajet, P., Dieu, S., Papin, A., Collet, S., Gaucher, R., Chalot, M.,
 Michiels, B., Raventos, C., 2017. Torrefaction and pyrolysis of metal-enriched poplars from
 phytotechnologies: Effect of temperature and biomass chlorine content on metal distribution
 in end-products and valorization options. Biomass and Bioenergy. 96: 1-11.
- Blaylock, M.J., Huang, J.W., 2000. Phytoextraction of metals. In: Raskin I, Ensley BD,
 editors. Phytoremediation of toxic metals: using plants to clean up the environment. Toronto:
 John Wiley and Sons, Inc. p. 303.
- Boris^{*}ev, M., Pajevic['], S., Nikolic['], N., Pilipovic['], A., Krstic['], B., Orlovic['], S., 2009.
 Phytoextraction of Cd, Ni, and Pb using four willow clones (Salix spp.). Polish Journal of
 Environmental Studies. 18: 553-561.
- 500 Bowen, H.J.M., 1979. Environmental Chemistry of the Elements. Academic Press, London.
- 501 Chalot, M., Blaudez, D., Rogaume, Y., Provent, A.-S., Pascual, C., 2012. Fate of trace
 502 elements during the combustion of phytoremediation wood. Environmental Science and
 503 Technology. 46: 13361-13369.
- 504 Ciadamidaro, L., Madejòn, E., Robinson, B., Madejòn, P., 2014. Soil plant interactions of
 505 Populus alba in contrasting environments. Journal of Environmental Management. 132: 329506 337.
- 507 Ciadamidaro, L., Girardclos, O., Bert, V., Zappelini, C., Yung, L., Foulon, J., Papin, A., Roy,
 508 S., Blaudez, B., Chalot, M., 2017. Poplar biomass production at phytomanagement sites is
 509 significantly enhanced by mycorrhizal inoculation Environmental and Experimental Botany.
 510 139: 48-56.
- 511 Ciccatelli, A., Lingua, G., Todeschini, V., Biondi, S., Torrigiani, P., Castiglione, S., 2010.

- Arbuscular mycorrhizal fungi restore normal growth in a white poplar clone grown on heavy
 metal-contaminated soil, and this is associated with upregulation of foliar metallothionein and
 polyamine biosynthetic gene expression. Annals of Botany. 106: 791-802.
- 515 Das, P., Samantaray, S., Rout, G.R., 1997. Studies on cadmium toxicity in plants: a review.
 516 Environmental Pollution. 98: 29-36.
- 517 Dickinson, N.M., 2006. Phytoremediation of industrially- contaminated sites using trees.
 518 NATO Science Series. 68: 229-240.
- Domínguez, M.T., Marañón, T., Murillo, J.M., Schulin, R., Robinson, B.H., 2008. Trace
 element accumulation in woody plants of the Guadiamar Valley, SW Spain: A large-scale
 phytomanagement case study. Environmental Pollution. 152: 50-59.
- Douay, F., Pruvot, C., Waterlot, C., Fritsch, C., Fourrier, H., Loriette, A., et al., 2009.
 Contamination of woody habitat soils around a former lead smelter in the North of France,
 Science of the Total Environment. 407: 5564-5577.
- 525Europe'senvironment–Thefourthassessment526(http://www.eea.europa.eu/publications/state_of_environment_report_2007_1).
- 527 Evangeloua, M.W.H., Deramb, A., Gogosa, A., Studera, B., Schulin, R., 2012. Assessment
 528 of suitability of tree species for the production of biomass on trace element contaminated
 529 soils. Journal of Hazardous Materials. 209-210: 233-239.
- French, Ch.J., Dickinson, N.M., Putwain, P.D., 2006. Woody biomass phytoremediation of
 contaminated brown- field land. Environmental Pollution. 141: 387-395.
- 532 Gomes, M.P., Marques, T.C.L.L.S.M., Carneiro, M.M.L.C., Soares, Â.M., 2012. Anatomical
- 533 characteristics and nutrient uptake and distribution associated with the Cd-phytoremediation

capacity of Eucalyptus camaldulenses Dehnh. Journal of Soil Science and Plant Nutrition. 12:481-496.

Grison, C., 2015. Combining phytoextraction and ecocatalysis: a novel concept for greener
chemistry, an opportunity for remediation. Environmental Science and Pollution Research.
22: 5589–5591.

- Han, S., Kim, D., Lee, J., 2010. Cadmium and zinc interaction and phytoremediation potential
 of seven Salix caprea clones, Journal of Ecological Environment. 33: 245-251.
- Houba, V.J., Lexmond, Th.M., Novozamsky, I., Van der Lee, J.J., 1996. The state of the art
 and future developments in soil analysis for bioavailability assessment. Science of the Total
 Environment. 178: 21-28.
- 544 Kirkham, M.B., 2006. Cadmium in plants on polluted soils: effects of soil factors,
 545 hyperaccumulation, and amendments. Geoderma. 137: 19-32.
- Lamy, I., van Oorti, F., Dere, C., Baize, D., 2006. Use of major- and trace-element
 correlations to assess metal migration in sandy Luvisols irrigated with wastewater. European
 Journal of Soil Science. 57: 751-740.
- Leyval, C., Joner, E.J., del Val, C., Haselwandter, K., 2002. Potential of arbuscular
 mycorrhizal fungi for bioremediation. In Mycorrhizal Technology in Agriculture. Edited by:
 Gianinazzi S, Schuepp H, Barea JM, Haselwandter K. Switzerland: Birkhäuser Verlag, 175186.
- Liu, L., Gong, Z., Zhang, Y., Li, P., 2014. Growth, cadmium uptake and accumulation of
 maize (Zea mays L.) under the effects of arbuscular mycorrhizal fungi. Ecotoxicology. 23:
 1979-1986.

- Kabata-Pendias, H. Pendias, Trace Elements in Soils and Plants, CRC Press, Boca Raton, FL,
 2001.
- 558 Khan, S., Hesham, A.E.L., Qiao, M., Rehman, S., He, J.Z., 2010. Effects of Cd and Pb on soil
- 559 microbial community structure and activities. Environmental Science and Pollution Research.
- 560 17: 288-296.
- Madejón, P., Ciadamidaro, L., Marañón, T., Murillo, J.M., 2013. Long-Term Biomonitoring
 of Soil Contamination Using Poplar Trees: Accumulation of Trace Elements in Leaves and
 Fruits. International Journal of Phytoremediation. 15: 602-614.
- Maxted, A.P., Black, C.R., West, H.M., Crout, N.M.J., McGrath, S.P., Young, S.D., 2007.
 Phytoextraction of cadmium and zinc by Salix from soil historically amended with sewage
 sludge. Plant and Soil. 290: 157-172.
- Meers, E., Vandecasteele, B., Ruttens, A., Vangronsveld, J., Tack, F.M.G., 2007. Potential of
 five willow species (Salix spp.) for phytoextraction of heavy metals. Environmental and
 Experimental Botany. 60: 57-68.
- Meier, S., Borie, F., Bolan, N., 2012. Phytoremediation of metal-polluted soils by arbuscular
 mycorrhizal fungi. Critical Reviews in Environmental Science and Technology. 42: 741-775.
- Mench, M., Schwitzguébel, J.P., Schroeder, P., Bert, V., Gawronski, S., Gupta, S., 2009.
 Assessment of successful experiments and limitations of phytotechnologies: contaminant
 uptake, detoxification and sequestration, and consequences for food safety. Environmental
 Science and Pollution Research. 16: 876-900.
- 576 Mench, M., Lepp, N., Bert, V., Schwitzguébel, J.P., Gawronski, S.W., Schröder, P.,
 577 Vangronsveld, J., 2010. Successes and limitations of phytotechnologies at field scale:

- 578 outcomes, assessment and outlook from COST Action 859. Journal of Soils and Sediments.579 10: 1039-1070.
- 580 Mertens, J., Van Nevel, L., De Schrijver, A., Piesschaert, F., Oosterbaan, A., Tack, F.M.G.,
- Verheyen, K., 2007. Tree species effect on the redistribution of soil metals. EnvironmentalPollution. 149: 173-181.
- Migeon, A., Richaud, P., Guinet, F., Chalot, M., Blaudez, D., 2009. Metal accumulation by
 woody species on contaminated sites in the north of France. Water, Air and Soil Pollution.
 204: 89-101.
- 586 Moreira, H., Pereira, S.I.A., Marques, A.P.G.C., Range, A.O.S.S., Castro, P.M.L., 2016. Mine 587 land valorization through energy maize production enhanced by the application of plant 588 growth-promoting rhizobacteria and arbuscular mycorrhizal fungi. Environmental Science 589 and Pollution Research. 23: 6940-6950.
- Mrnka, L., Kuchár, M., Cieslarová, Z., Matějka, P., Száková, J., Tlustoš, P., Vosátka, M.,
 2012. Effect of endo- and ectomycorrhizal fungi on physiological parameters and heavy
 metals accumulation of two species from the family Salicaceae. Water Air and Soil Pollution.
 223: 399-410.
- Pauget, B., Gimbert, F., Coeurdassier, M., Crini, N., Pérès, G., Faure, O., Douay, F., Richard,
 A., Grand, C., de Vaufleury, A., 2013. Assessing the in situ bioavailability of trace elements
 to snails using accumulation kinetics. Ecological Indicators. 34: 126-135.
- 597 Phanthavongsa, P., Chalot, M., Papin, A., Lacercat-Didier, L., Roy, S., Blaudez, D., Bert, V.,
 598 2017. Effect of mycorrhizal inoculation on metal accumulation by poplar leaves at
- 599 phytomanaged sites. Environmental and Experimental Botany. 143: 72-81.
- 600 Pilon-Smits, E.A.H., 2005. Phytoremediation. Annual Revision of Plant Biology. 56: 15-39.

- 601 Pourrut, B., Lopareva-Pohu, A., Pruvot, C., Garçon, G., Verdin, A., Waterlot, C., Bidar, G.,
- 602 Shirali, P., Douay, F., 2011. Assessment of fly ash-aided phytostabilisation of highly
- 603 contaminated soils after an 8-year field trial. Part 2. Influence on plants. Science of the Total
- 604 Environment. 409: 4504-4510.
- Pulford, I.D., Watson, C., 2003. Phytoremediation of heavy metal-contaminated land by trees
 a review. Environmental Interantional. 29: 529-540.
- Rascio, N., Navari-Izzo, F., 2011. Heavy metal hyperaccumulating plants: How and why do
 they do it? And what makes them so interesting? Plant Science. 180: 169-181.
- 609 Robinson, B., Green, S., Mills, T., Clothier, B., van der Velde, M., Laplane, R., Fung, L.,
- Deurer, M., Hurst, S., Thayalakumaran, T., van den Dijssel, C., 2003. Phytoremediation:
 using plants as biopumps to improve degraded environments. Australian Journal of Soil
 Research. 41: 599-611.
- Robinson, B., Schulin, R., Nowack, B., Roulier, S., Menon, M., Clothier, B., Green, S., Mills,
 T., 2006. Phytoremediation for the management of metal flux in contaminated sites. Forest
 Snow and Landscape Research. 80: 221-234.
- Robinson, B., Bañuelos, G., Conesa, H.M., Evangelou, M.W.H., Schulin, R., 2009. The
 phytomanagement of trace elements in soil. Critical Reviews in Plant Science. 28: 240-266.
- 618 Salt, D.E., Prince, R.C., Pickering, I.J., Raskin, I., 1995. Mechanism of cadmium mobility and
- accumulation in Indian mustard. Plant Physiology. 109: 1427-1433.
- 620 Sheoran, V., Sheoran, A.S., Poonia, P., 2010. Soil reclamation of abandoned mine land by
- revegetation: a review. International Journal of Soil Sediment and Water. 3: 1-21.

- 622 Sterckeman, T., Gomez, A., Ciesielski, H., 1996. Soil and waste analysis for environmental
 623 risk assessment in France. Science of the Total Environment. 178: 63-69.
- Stoltz, E., Greger, M., 2002. Accumulation properties of As, Cd, Cu, Pb and Zn by four
 wetland plant species growing on submerged mine tailings. Environmental and Experimental
 Botany. 47: 271-280.
- Vassilev, A., Perez-Sanz, A., Semane, B., Carleer, R., Vangronsveld, J., 2005. Cadmium
 accumulation and tolerance of two Salix genotypes hydroponically grown in presence of
 cadmium. Journal of Plant Nutrition. 28: 1-19.
- Zagas, T., Tsitsoni, T., Ganatsas, P., Tsakaldimi, M., Skotidakis, T., Zagas, D., 2010. Land
 Reclamation and Ecological Restoration in a Marine Area. International Journal of
 Environmental Research. 4: 673-680.
- Yang, J., Li, K., Zheng, W., Zhang, H., Cao, X., Lan, Y., Yang, C., Li, C., 2015.
 Characterization of early transcriptional responses to cadmium in the root and leaf of Cdresitant Salix matsudana Koidz. BMC Genomics. 16: 705.
- Yilmaz, D.D. and Perlak, K.U., 2011. Nickel-induced changes in lipid peroxidation,
 antioxidative enzyme and metal accumulation in *Lemna gibba*. Internation Journal of
 Phytoremediation. 13: 25-35.