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Transcriptome Changes in *Hirschfeldia incana* in Response to Lead Exposure

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INTRODUCTION

Heavy metals including Cu, Mn, or Zn, play an essential role in many plant physiological processes but can be toxic if accumulated at high concentrations. Other metals including Cd, As, or Pb, have no biological functions and are extremely toxic even at low concentrations. Lead, a non-essential heavy metal, is widespread in the environment as a result of many human activities including mining and smelting, burning coal, cement manufacture and agricultural practices. It is widely accepted that lead is a serious pollutant, and is toxic not only for plant roots where Pb is taken up, but also when translocated to aboveground part where it can accumulate...
Numerous previous studies have reported a wide range of negative effects following plant exposure to Pb; the visible symptoms of Pb toxicity are rapid inhibition of seed germination, reduced growth and the appearance of chlorosis. In addition, Pb can cause oxidative damage by stimulating the formation of free radicals and reactive oxygen species (ROS), resulting in oxidative stress and DNA damage (Seregin and Ivanov, 2001; Schutzendubel and Polle, 2002). However, some plant species tolerate the presence of Pb and, more interestingly, several species, including Noccaea caerulescens, Agrostis tenuiss, and \( \text{Pb} \), and more interestingly, several species, including Noccaea caerulescens, Agrostis tenuiss, or Festuca ovina, have developed the capacity to accumulate large amounts of lead in their root tissues with limited translocation to the aboveground parts (Vangronsveld et al., 2009). Hirschfeldia incana, commonly known as bucanweeds, hoary mustard, or Mediterranean mustard, is a medium perennial shrub belonging to the Brassicaceae family. It has been identified as a potential hyperaccumulator of various toxic metals including lead (Auguy et al., 2013). Interestingly, \( H. \text{incana} \) was shown to be capable of accumulating more than 3% (dry weight) of lead in its shoots when grown in hydroponic solution containing 100 \( \mu \text{M} \) \( \text{Pb(NO}_3\text{)}_2 \) without any marked symptoms of toxicity. Such plant species have evolved physiological and molecular mechanisms to enable them to thrive under Pb metal stress. Many studies have already been published on the effects of lead on plants and on their cellular detoxification mechanisms and several molecular players in the Pb homeostatic network have been identified so far. For instance, the tobacco plasma membrane protein \( \text{NiTCP} \) and the \( \text{Arabidopsis} \) gene \( \text{CNGCl} \) have been shown to be components of a transport pathway responsible for Pb entry into plant cells (Sinkar et al., 2000). An \( \text{Arabidopsis} \) \( \text{P-type ATPase}, \text{HMA3}, \) has been reported to improve tolerance by sequestering Pb in vacuoles (Gravot et al., 2004; Morel et al., 2009). It has also been suggested that \( \text{HMA4}, \) another \( \text{P-type ATPase}, \) may play a role in Pb efflux in \( \text{N. caerulescens} \) and \( \text{H. incana} \) (Papoyan and Kochian, 2004; Auguy et al., 2013). In \( \text{Arabidopsis} \), three members of the ABC (ATPase-binding cassette) transporter family \( \text{AtATM3}, \text{AtPDR12}, \) and \( \text{AtPDR8} \) contribute to Pb resistance (Lee et al., 2005; Kim et al., 2006, 2007). \( \text{ACBP1} \), an acyl-CoA-binding protein, has been reported to be involved in mediating Pb tolerance through accumulation in shoots (Xiao et al., 2008), and \( \text{AtMRP3} \) transcription has been shown to be strongly induced by Pb treatment in \( \text{Arabidopsis thaliana} \) (Zientara et al., 2009). Finally, chelation is an important mechanism controlling heavy metal tolerance involving small molecules such as metallothioneins, phytochelatins and glutathione (Cobbett and Goldsbrough, 2002).

Recent research has focused on identifying the mechanisms that allow organisms to adapt to or alleviate damage caused by metal stress, and in this context, microarray technology is a convenient tool for rapid analysis of plant gene expression patterns under a variety of environmental conditions. The use of cross-species hybridization (CSH), in which the target RNA and microarray probe come from different species, has increased in the last few years. CSH has been used to examine both closely and distantly related species. In the particular case of heavy metals, Becher et al. (2004) hybridized \( \text{A. halleri} \) RNA samples to \( \text{A. thaliana} \) Affymetrix microarrays and analyzed the effect of Zn treatments on gene expression. Similarly, using the same probe-transcript complex, Weber et al. (2006) analyzed the gene profiles after exposure to Cd. In the same line of thought, Hammond et al. (2006) compared Zn gene regulation by hybridizing \( \text{N. caerulescens} \) and \( \text{Thlaspi arvense} \) RNA to \( \text{A. thaliana} \) Affymetrix microarrays. Van de Mortel et al. (2006) examined the performance of CSH in cDNA microarrays of \( \text{A. thaliana} \) with RNA from \( \text{N. caerulescens} \) treated or not with excess Zn. \( \text{H. incana} \), like \( \text{A. thaliana} \), belongs to the Brassicaceae family. Based on eight cDNA sequences, from 400 to 1100 bp in length, cloned, and sequenced in a previous work, we estimated that \( \text{A. thaliana} \) and \( \text{H. incana} \) shared an average of 89% nucleotide identity within coding regions (Auguy et al., 2013). This level of identity is similar to those obtained between \( \text{A. thaliana} \) and \( \text{N. caerulescens} \) comparison, with on average 88.5% DNA identity in coding regions (Rigola et al., 2006) and 87% DNA identity in the intergenic transcribed spacer regions (Peer et al., 2003). Based on these data, we hypothesized that the use of \( \text{Arabidopsis} \) cDNA microarrays with RNA from \( \text{H. incana} \) should work and would provide information on changes in the transcriptome that occur during plant exposure to Pb. We performed transcriptome analysis of Pb responses in \( \text{A. thaliana} \) and \( \text{H. incana} \) roots and shoots by comparing the responses of a normal plant, \( \text{A. thaliana} \), and a lead-hyperaccumulating metallophyte, \( \text{H. incana} \) (Auguy et al., 2013). Our aim was to identify any differential responses to Pb that would advance our understanding of metal-tolerance mechanisms. Based on the assumption that the metal responsiveness of putative signal-transduction components points to the functional involvement of the encoded proteins in mediating metal responses, we also hoped to identify candidate genes that could be analyzed further using reverse-genetic approaches.

**MATERIALS AND METHODS**

**Plant Material and RNA Extraction**

Four weeks old \( \text{H. incana} \) and \( \text{A. thaliana} \) seedlings were treated in hydroponic cultures with Pb for 3 days, by adding 100 or 40 \( \mu \text{M Pb(NO}_3\text{)}_2 \), respectively, in a fresh BD medium (Broughton and Dilworth, 1971) without phosphate. These two Pb concentrations correspond to approximately 50% of reduction of primary root growth for both species without any visible symptoms (data not shown). In control experiments, BD medium was replaced by fresh BD medium without phosphate.

RNA was extracted separately from the shoots and roots of the control and of the treated \( \text{H. incana} \) and \( \text{A. thaliana} \) seedlings. Total RNA extraction was performed with two different kits depending on the tissue concerned, RNeasy plant mini kit (Qiagen, USA) for roots and SV Total RNA isolation system (Promega, USA) for shoots. A post-treatment with Turbo DNA free (Ambion, USA) removed contaminated DNA. RNA quality was checked and confirmed using Nanodrop 2000 (Thermo Scientific, USA) analysis and non-denaturing gel electrophoresis. Three independent experiments were performed with 8–9 seedlings per treatment and per repetition and used for both
transcriptome (27 235 cDNA). Two hundred ng of array, which comprised 43,803 probes, covered the entire totalRNAwereusedtosynthesize cRNA,incorporating the Cy-3 for the control samples and the Cy-5 for the Pb treated samples. After amplification, 825 ng of fragmented cRNA were hybridized to each array at 60°C for 17 h following the manufacturer’s instructions.

**Microarray Data Processing and Analysis**

Images were acquired with the Agilent G2505C scanner and treated with the Feature Extraction Agilent software (version 10.7.3). Two normalizations were applied: first, we applied quartile normalization to minimize variance between chips, and second, probe normalization using the median calculated for all the samples. A Gaussian distribution was obtained with the LOG transformation. Only probes for which all replicates for one condition had values higher than the background were retained. Finally, a Student’s t-test between treatments was applied with the following parameters: asymptotic p-value, p-value < 0.05 and Benjamini–Hochberg correction. Microarray data from this article were submitted to the public NCBI Gene Expression Omnibus database (GEO) accession GSE65334 (Edgar et al., 2002). The microarray data is MIAME compliant.

Functional classifications of statistically significant general stress genes were obtained using the web-based Functional Classification SuperViewer (Provart and Zhu, 2003). This classification tool is based on functional information available from the Munich Information Center for Protein Sequences (MIPS) database (Schoof et al., 2004). Class scores were obtained to determine whether certain functional classes were over-represented among statistically significant general stress genes (Provart and Zhu, 2003). Class score means and standard errors were computed on the basis of 100 bootstrap samples of the input gene list, as described in Provart and Zhu (2003). It should be noted that with SuperViewer, genes can belong to more than one classification. Genevestigator software was used to compare the expression profiles of selected genes with other expression profiles provided in the database.

**QRT-PCR Validation**

To validate the microarray results, the expression profile of a subset of differentially regulated genes was checked by qRT-PCR in *H. incana* and *A. thaliana*. Total RNA was extracted in both species in the same way as described for the microarray. Primer sets were designed with Primer 3 software (Additional File 1 in Supplementary Material) from conserved gene sequences obtained from the Arabidopsis Information Resource database (TAIR^3^). QRT-PCR uses the method already described by Auguy et al. (2013). Dissociation (melting) curves for all the genes were checked for the presence of primer dimers or spurious and not specific products. The correlation coefficients between qRT-PCR and microarray values were calculated.

**Identification of Arabidopsis mt2b T-DNA Insertion Mutants**

Multiple alignments of nucleotide sequences revealed high sequence identity between *HiMT2b* and *AtMT2b*. In addition, phylogenetic trees placed *HiMT2b* as a putative ortholog of *AtMT2b* (unpublished data). Consequently, Arabidopsis homozygote plants of T-DNA insertion lines Salk_144899 and Salk_037601 for the gene At5g02380 (AtMT2b) were identified by PCR using three different primers. In both T-DNA insertion lines, T-DNA specific primers (LBb1, 5′-GGACAAAGATCGTTGACAGC-3′) and two *AtMT2b* specific primers (AtMT2b-F, 5′-GATCCACAACACACGCTTCC-3′ and AtMT2b-R, 5′-GGACAAAGATCGTTGACAGC-3′) were used. The genotype of the F3 individuals was checked by PCR using gene-specific primers and T-DNA primers. Individual homozygous mutants were backcrossed twice with Arabidopsis wild-type Col-0. Root growth and Pb content analysis were performed on *mt2b* mutants and Col-0 wild-type after 13 days culture on media with or without 40 μM Pb(NO₃)₂ as previously described (Auguy et al., 2013).

**Lead Quantification**

Roots and shoots of both *H. incana* and *A. thaliana* seedlings treated or not with Pb were washed at 4°C twice with 0.2 mM CaSO₄ and rinsed with cold distilled water. Samples were dried at 72°C for at least 7 days. The dried tissues were subjected to acid hydrolysis and the concentration of lead in the samples was determined by inductively coupled plasma-atomic emission (ICP AES Ultima 21Y, USA) according to the methods previously described (Temminghoff and Houba, 2004; Margui et al., 2007).

**RESULTS AND DISCUSSION**

**Differences in Pb Content Between *H. incana* and *A. thaliana***

Optimal Pb concentrations for *H. incana* and *A. thaliana* were chosen based on the results we obtained in a previous experiment (Auguy et al., 2013). Pb content was measured in the roots and shoots of *H. incana* and *A. thaliana* cultivated in hydroponic conditions 3 days after treatment with, respectively, 100 and 40 μM Pb(NO₃)₂ (Table 1). The amount of Pb in roots was of the same order of magnitude in both the two species and showed very high accumulation [65.5 and 82.9 mg Pb/g DW (dry weight), respectively, in *H. incana* and *A. thaliana*]. In contrast, a marked

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1. https://genevestigator.com/gv/
2. http://primer3.wi.mit.edu/
3. http://www.arabidopsis.org/
difference in Pb content was measured in the shoots of the two species: 0.346 mg Pb/g DW in *H. incana* and 0.006 mg Pb/g DW in *A. thaliana*. As previously reported [5], Pb transfer from roots to shoots was observed in *H. incana* but not in *A. thaliana* in which almost all Pb only accumulated in the roots. This result confirms that *A. thaliana* has developed a metal exclusion strategy to cope with metal toxicity in the soil by limiting the amount of Pb translocated from the roots to the shoots (Baker, 1981). In contrast, *H. incana* was previously described to tolerate and accumulate Cu, Zn, Tl, and Pb (Poschenrieder et al., 2001; Gisbert et al., 2006; Madejon et al., 2007; Auguy et al., 2013), and indeed, in our experiment, *Hirschfeldia* plants accumulated significantly higher amounts of Pb in aboveground shoots than *A. thaliana* (Table 1). This significant difference between the two species confirmed the rightness of our choice of comparing their transcriptome in response to Pb treatment. The response of the non-tolerant and non-accumulating species *A. thaliana* to Pb was considered to be the standard plant response to Pb and was used as a filter to keep only the specific response to Pb in the tolerant Pb accumulating plant *H. incana*.

### Overview of the Transcriptome Response to Pb Treatment

In order to understand the molecular events underlying the response of *H. incana* to Pb exposure, we measured gene expression in the shoots and roots of *H. incana* plants treated or not with 100 μM of Pb(NO$_3$)$_2$ for 3 days, using the Agilent 44k *Arabidopsis* array. In parallel, to evaluate differential genes expressed in a Pb tolerant plant versus a non-tolerant plant, we investigated the transcriptome response of *A. thaliana* treated or not with 40 μM of Pb(NO$_3$)$_2$ for 3 days also using the Agilent 44k *Arabidopsis* array.

In this study, the number of Pb-regulated genes was 2,108 for *H. incana* and 14,800 for *A. thaliana*, with a false detection rate (FDR) < 0.1. Additional Files 2–5 in Supplementary Material list the 20 most Pb-regulated genes in the roots and shoots of *H. incana* and *A. thaliana*. A total of 68.5% of Pb-regulated genes were distributed in the roots and 31.5% in the shoots of *H. incana*, and 93.5% in the roots and 6.5% in the shoots of *A. thaliana* (Table 2). The ratio of up- and down-regulated genes in each type of tissue was approximately the same and reached 50%. The marked difference between the number of Pb-regulated genes in *H. incana* and *A. thaliana* could be due to the CHS technique used. Even if *H. incana* and *A. thaliana* are closely related species, it cannot be excluded that some *H. incana* sequences diverged too much from *A. thaliana* sequences and consequently prevented hybridization on the *A. thaliana* arrays. On the other hand, the small number of Pb-regulated genes detected in *Arabidopsis* shoots could be related to the weak concentration of Pb measured in this tissue after 3 days of treatment with 40 μM of Pb(NO$_3$)$_2$ (Table 1).

To validate our microarray results, we performed qRT-PCR to determine the levels of expression of 33 *H. incana* and 6 *A. thaliana* genes randomly selected from the list of genes differentially expressed after Pb treatments. In *H. incana*, the qRT-PCR gene expression results are highly correlated with the microarray gene expression data (Figure 1). The coefficient of determination ($r^2$) between microarray and qRT-PCR data was 0.92, indicating good consistency between the two methods. The genes we tested varied in the same way in the microarray and the qRT-PCR results (Additional File 6 in Supplementary Material). This clearly validates the transcriptomic results obtained in *H. incana* with Agilent microarray. In *A. thaliana*, in a similar way but with fewer genes, qRT-PCR data were similar to those obtained with the microarray (Additional File 7 in Supplementary Material), thus validating the *A. thaliana* results obtained with the same microarray.

### Genes Specifically Regulated by Pb Treatment in *H. incana*

In order to highlight genes that were specifically regulated by Pb exposure in *H. incana*, we compared its transcriptome with the transcriptome of the Pb-sensitive plant *A. thaliana*. We focused particularly on genes that were specifically Pb-regulated in *H. incana* roots and shoots. (Pb-specific genes), and genes that were regulated in both species (Pb-common genes). These comparisons are illustrated by Venn diagrams (Figure 2). The number of Pb-specific genes was higher in shoots than in roots, with 602 and 341 genes, respectively, suggesting a stronger acclimation response by the shoots. Conversely, the number of Pb-common genes was much higher in the roots, with 1,102 Pb-regulated genes in comparison to only 63 genes in the shoots (Figure 2). The distribution of up- and down-regulated genes was similar in shoots and roots (55% up-regulated genes). In the Pb-common gene group, we distinguished four categories: genes up-regulated in both roots and shoots, genes down-regulated in both roots and shoots, genes up-regulated in shoots and down-regulated in roots, and genes up-regulated in roots and down-regulated in shoots. The distribution of genes in these four categories was similar in the roots and shoots (Figure 2).

In the Pb-specific gene group, only regulated genes with a twofold change (FC) in gene expression were retained. They represented 121 genes in roots and 331 in shoots (Table 3).
For the Pb-common gene category, we introduced another selection step involving a comparison between *H. incana* and *A. thaliana*: only genes differentially expressed in *H. incana* with a FC *H. incana*/FC *A. thaliana* > 2.0 or < 0.5 were retained. This category represented 315 genes in roots and 28 in shoots (Table 3). Within this differentially expressed gene category, in the same way as Pb-specific genes, only regulated genes (those with a FC > 2.0 or FC < 0.5) were selected. After this second step, the Pb-common gene list included 227 genes in roots and 26 in shoots (Table 3). Finally, including specific and common genes, the selected gene lists comprised 348 genes in roots and 356 genes for roots and in shoots (Table 3, Additional Files 8 and 9 in Supplementary Material). Among these, only 42 genes were regulated both in roots and shoots (in bold in Additional Files 8 and 9 in Supplementary Material). As mentioned in the introduction, several genes were already known to be involved in plant tolerant response to Pb exposure including *ACBP1*, *AtATM3*, *NtCBP4*, *CNGC1*, *HMA3*, *HMA4*, *AtMRP3*, *AtPDR8*, and *AtPDR12*. Contrary to the data in the literature, no hybridization signal was measurable for *ACBP1*, *AtATM3*, *NtCBP4*, *CNGC1*, *HMA3*, *HMA4*, *AtMRP3*, *AtPDR8*, and *AtPDR12*. Functional Classification of Pb-Responsive Genes

To evaluate the functional significance of the differentially expressed genes in response to Pb exposure in *H. incana*, the biological processes with over-represented regulated genes were identified in our analysis using Classification SuperViewer tools (Provart and Zhu, 2003) available at the Bio-Array Resource for Plant Functional Genomics (BAR) website with MapMan classification source. Several biological processes, categorized as photosynthesis, cell wall, and metal handling, were particularly enriched by Pb exposure in both roots and shoots (Figure 3).

Photosynthesis is considered to be one of the most sensitive metabolic processes to Pb toxicity (Singh et al., 1997). Lead toxicity has multifunctional adverse effects on photosynthetic CO₂ fixation and reduces the level of photosynthetic pigments, alters chloroplast ultra-structure and reduces the enzymatic activity of CO₂ assimilation (Parys et al., 1998; Islam et al., 2008; Belatik et al., 2013). In the present study, several genes directly involved in photosystem II encoding, respectively, a light-harvesting chlorophyll-a/b (Lhc) protein (*At2g05070*), a Mog1/PsbP/DUF1795-like protein (*At3g56650*), a subunit of the NAD(P)H dehydrogenase complex (*At1g14150*), a PsbP-like protein 1 (*At3g55330*) and a photosystem II reaction center subunit W (*At2g30570*) were all down-regulated in shoots (Table 4). Three genes involved in the Calvin cycle (*At3g12780*, *At1g56190*, and *At1g73110*) encoding phosphoglycerate kinase proteins were also down-regulated. Pb may play a role similar to that of Mg, which at high concentrations non-competitively inhibits phosphoglycerate kinase activity (Larsson-Rażnikiewicz, 1967). Interestingly, increased expression of photosynthetic genes was observed in roots, with the exception of *At1g10960* encoding a ferredoxin
Auguy et al. Transcriptome Changes in Hirschfeldia incana to Lead

FIGURE 2 | Venn diagrams representing the distribution of regulated genes between H. incana and Arabidopsis thaliana in roots (A) and shoots (B) after Pb exposure. +, up-regulated; −, down-regulated; ++, up-regulated in both species; −−, down-regulated in both species; +−, up-regulated in H. incana and down-regulated in A. thaliana and −+, down-regulated in H. incana and up-regulated in A. thaliana.

1 for which the gene expression was down regulated by 0.4 (Table 5). Because roots are thought to be a non-photosynthetic organ, the biological relevance of this phenomenon has received little attention but the majority of the genes affected (8/11) are members of Lhc family of photosynthesis-associated nuclear genes (At1g29910, At1g29930, At2g34420, At2g34430, At3g47470, At3g54890, At5g28450, and At5g54270) and can be expressed in specialized territories, including the root tip (Sawchuk et al., 2008). The putative interactions between Lhc gene expression, root localization and Pb exposure are somewhat unclear but what is particularly interesting is that abscisic acid (ABA) was required for full expression of different Lhc members and physiologically high levels of ABA enhanced Lhc expression (Liu et al., 2013).

The second biological process group particularly enriched by Pb exposure contained genes encoding cell wall proteins in both shoots and roots (Tables 4 and 5). Recent studies in different plant species have shown that the plant cell wall could be modified in response to Pb (Krzeslowska, 2011). Modifications of the cell wall mainly concern an increase in the amount of polysaccharides, in particular pectins. In the present study, Pb treatment induced a reduction in xyloglucan endotransglucosylase gene expression (At2g06850, At2g23270, and At4g03210) and could play an important role in Pb-induced root growth inhibition by causing cell wall modification and reduction of cell elongation. Similar observations have been reported for Al toxicity in Arabidopsis (Yang et al., 2011).

The last biological group enriched by Pb exposure that emerged from this analysis encompasses the group of genes involved in metal handling. The frequency of up-regulated genes in roots was greater than 10, i.e., it was the most enriched category of the data (Figure 3A). Among the genes associated with this category, four belonged to the metallochaperone-like protein family (At4g39700, At5g17450, At1g22990, and At4g08570). Expression of these genes was increased by Pb-exposure with a fold-change ranging from 2.6 to 13.9 (Table 5). The function of these metalloproteins is unknown, but two of them (At1g22990 and At4g08570) are known to be involved in Cd tolerance (Tehseen et al., 2010). Another gene in the metal handling category, At2g28660, encodes putative soluble proteins with a heavy metal binding domain like Cys-x-x-Cys and a putative chloroplast targeting sequence is associated with the Cu chaperone family (Abdel-Ghanya et al., 2005). The expression of this gene was up regulated 6.2-fold in H. incana roots treated with Pb compared to the control. This protein possesses a heavy metal fixation domain and could act as a putative Pb fixation site. Only three genes up-regulated in shoots were identified in the metal handling category (Table 4) and two genes code for metallothioneins MT2a (At3g09390) and MT2b (At5g02380). Expression levels

TABLE 3 | Selection steps applied to highlight H. incana candidate genes regulated in response to Pb exposure in roots and shoots.

| Category         | Treatment | Roots | Shoots |
|------------------|-----------|-------|--------|
| Specific genes   | Total     | 341   | 601    |
|                  | FC > 2.0 or FC < 0.5 | 62 Up-reg | 59 Down-reg | 192 Up-reg | 138 Down-reg |
| Common genes     | Total     | 1102  | 63     |
|                  | FC Hi/FC At > 2.0 or < 0.5 | 315 | 28 |
|                  | FC > 2.0 or FC < 0.5 | 125 Up-reg | 102 Down-reg | 18 Up-reg | 8 Down-reg |
| Candidate genes  | 187 Up-reg | 161 Down-reg | 210 Up-reg | 146 Down-reg |

H. incana specific genes were directly chosen on the basis of their fold change (FC) ratio (FC > 2.0 or FC < 0.5). H. incana common genes were first selected on the basis of their FC related to those from A. thaliana (FC Hi/FC At > 2.0 or < 0.5) and then FC on the basis of the FC ratio (FC > 2.0 or FC < 0.5). (Fold Change, FC; Hi, H. incana; At, A. thaliana; down-reg, down-regulated genes; up-reg, up-regulated genes).
FIGURE 3 | Biological process classification of Pb responsive selected transcripts. The gene ontology was obtained using the Classification SuperViewer software with MapMan classification source for selected up- (A) and down-regulated (B) genes. Normed frequency was calculated as follows: (Number in class input set/Number in classified input set)/(Number in class reference set/Number in classified reference set). * Significant class (p > 0.05), o, size less than 5 genes.

of these two genes were, respectively 4.5 and 2.4 in shoots treated with Pb and in the control (Table 4). Although the protective role of metallothioneins against Cd is well known in mammals (Klaassen et al., 1999), their role in plant tolerance to heavy metals is less well known. MT2a is known to be localized the cytosol and could chelate heavy metals, but is not involved in vacuolar sequestration (Lee et al., 2004). In a previous study, we demonstrated the role
of MT2a in Pb tolerance using Arabidopsis T-DNA insertion mutants (Auguy et al., 2013). Treatment with Pb highly significantly reduced primary root length in mt2a (48%) mutants. This reduction in primary root growth reflected increased sensitivity to Pb in Arabidopsis T-DNA insertion mutants and suggests that the MT2a gene is involved in lead tolerance. No effect of the mutation was observed on the Pb content in shoots and in roots of mt2a-mutant compared to wild-type plants (Auguy et al., 2013). Another metallothionein gene identified in the present study was MT2b (At5g02380). MT2b was previously described as being expressed in the phloem of all organs (Guo et al., 2008) and involved in Cu tolerance in Silene vulgaris or in Cd tolerance in Tobacco (Van Hoof et al., 2001; Grispen et al., 2011). In order to examine the functions of MT2b gene in Pb tolerance in Arabidopsis, we used a reverse-genetic approach with two independent Arabidopsis T-DNA insertion lines (Salk_144899 and Salk_037601) for the MT2b gene obtained from the Salk institute (Figure 4A). We measured the Pb content in roots and shoots of the 2 week-old wild-type and mt2b-mutants. Roots of both mutant lines contained 1.5-fold more Pb than in shoots of the 2 week-old wild-type and mt2b-mutants. Treatment with Pb highly significantly increased Pb content in roots of both mutant lines compared to wild-type plants. No effect of the mutation was observed on the Pb content in shoots of the 2 week-old wild-type and mt2b-mutants. The Pb content in shoots of both mutant lines was 0.44-fold more Pb than in shoots of wild-type plants.
mutant lines contained 3.3-fold less than those of wild-type plants (Figure 4C). No effect of the mutations was observed on the primary root growth of mt2b mutants compared to the wild-type plants (data not shown). These results suggest a role of MT2b in Pb accumulation through a perturbation of root-to-shoot translocation by reducing Pb content in leaves and increasing in roots. Very recently, using a MT quadruple mutant (mt1a/mt2a/mt2b/mt3), Benatti et al. (2014) showed that Arabidopsis metallothioneins are important for the accumulation and distribution of Cu in leaves and seeds, confirming the role of MT in the accumulation of metals in plants.

Comparison of Profiles with Other Transcriptomic Experiments

Data were analyzed using Genevestigator software (Nebion AG, Switzerland) with the Genevestigator tool “signature”. Selected genes in both roots (348 genes) and shoots (356 genes) that responded specifically to Pb exposure in the Pb-tolerant H. incana were compared to the Genevestigator “Perturbation” database (Tables 6 and 7, respectively). A comparison of the complete profiles for roots and shoots is given in Additional Files 10 and 11 in Supplementary Material, respectively. In the Perturbation database, experiments with the most

### TABLE 6 | Top 10 most similar profiles for H. incana roots from perturbation category (Genevestigator database).

| Sample identification from Genevestigator | Relative similarity |
|-------------------------------------------|---------------------|
| Osmotic study 2 (late)/untreated root (late) | 1.238 |
| Salt study 5 (cpc-1 try-82)/mock treated primary root tip (cpc-1 try-82) | 1.164 |
| Salt study 5 (wer-1 myb23-1)/mock treated primary root tip (wer-1 myb23-1) | 1.158 |
| Salt study 5 (col-0)/mock treated primary root tip (col-0) | 1.150 |
| Osmotic study 2 (early)/untreated root (early) | 1.149 |
| Salt study 5 (scm-2)/mock treated primary root tip (scm-2) | 1.148 |
| Dicamba herbicide (10 h)/H2O treated seedling (10 h) | 1.114 |
| ABA study 6 (srk2cf)/untreated plant (srk2cf) | 1.112 |
| Salt study 2 (early)/untreated root (early) | 1.111 |
| ABA study 4 (shoot)/mock treated seedling (3 h) | 1.111 |

Relative Similarity indicates the degree of their resemblance: the higher value the higher similarity relative to the average similarity.

### TABLE 7 | Top 10 most similar profiles for H. incana shoots from perturbation category (Genevestigator database).

| Sample identification from Genevestigator | Relative similarity |
|-------------------------------------------|---------------------|
| Osmotic (late)/untreated green tissue (late) | 1.468 |
| Drought study 2 (Trans.)/untreated leaf (Trans.) | 1.414 |
| Drought study 11 (hai1-2)/mock treated seedling (hai1-2) | 1.412 |
| Salt (late)/untreated green tissue (late) | 1.411 |
| Salt study 3 (atmy44)/H2O treated rosette leaf (atmy44) | 1.399 |
| ABA study (srk2cf)/untreated plant (srk2cf) | 1.386 |
| ABA study (col-0)/untreated plant (col-0) | 1.366 |
| Drought (wt)/untreated leaf (col) | 1.362 |
| Drought study 11 (col-0)/mock treated seedling (col-0) | 1.354 |
| Osmotic study 4 (shoot)/mock treated col-0 shoot | 1.347 |

Relative Similarity indicates the degree of their resemblance: the higher value the higher similarity relative to the average similarity.
significant similarity to our Pb experiment include data from abiotic stress-related studies, mainly salt stress-related, osmotic-related and drought experiments as well as abscisic acid (ABA) study (Tables 6 and 7). Furthermore, it is important to note that, from the biological process classification of Pb responsive selected transcripts (Figure 3), the gene composition of the hormone metabolism class underline the over-representation of ABA subclass (Additional File 12 in Supplementary Material). To confirm this hypothesis, total expression data from our Pb experiment were re-analyzed. Several genes involved in the biosynthesis of ABA were shown to be up-regulated in H. incana roots and shoots treated with lead (Figure 5), suggesting induction of ABA biosynthesis when H. incana plants were exposed to Pb treatment. Interestingly, even the Atg52400 gene involved in the ABA catabolism pathway, via phaseic acid (PA), was largely down-regulated, also leading to potential ABA accumulation. Abscisic acid, as a stress signal, is known to enhance plant tolerance to several environmental stresses, including low temperature, salt, drought, and heavy metals (Bellaire et al., 2000; Verslues and Zhu, 2005; Hong et al., 2013; Li et al., 2014). The increase in tolerance is partly due to the enhancement of the antioxidant defense system, which prevents the accumulation of ROS (Bellaire et al., 2000; Jiang and Zhang, 2002). On the other hand, in plants in contact with Pb, transpiration is decreased (Barcelo and Poschenrieder, 1990). This decrease in transpiration could be due to a reduction in growth, or at least to a reduction in leaf surface area and/or to the fact that when Pb is fixed to the cell wall it reduces plasticity and eventually disturbs the osmotic balance. Accumulation of Pb in the cell leads to accumulation of ABA in the shoots, results in stomata closure and reduces loss of water through transpiration (Parys et al., 1998; Pourrut et al., 2011). Taken together, these data indicate...
an intricate relationship between plant tolerance to Pb and ABA pathways. Recently a similar conclusion was reached by Shukla et al. (2014), who suggested that ABA-mediated signaling could be a major mechanism in response to metal gold exposure in Arabidopsis.

CONCLUSION

The comparative transcriptomic analysis between the Pb-hyperaccumulating and Pb-tolerant plant H. incana and the Pb-sensitive model plant A. thaliana identified a set of genes differentially expressed in response to Pb exposure. These genes were particularly over-represented in the photosynthesis, cell wall structure, and metal handling biological processes. In addition several genes involved in the ABA biosynthetic pathway were up regulated in response to lead exposure suggesting that ABA-mediated signaling is involved in plant response to lead. In addition H. incana could be considered as a good experimental model to identify genes involved in lead tolerance and accumulation in plants.

AVAILABILITY OF SUPPORTING DATA

The data discussed in this publication have been deposited in NCBI's GEO (Edgar et al., 2002) and are accessible through GEO Series accession number GSE65334 (http://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE65334).

AUTHOR CONTRIBUTIONS

AF and PD conceived and designed the experiment. AF, MF, and PM collected the experimental data. ME, AF-M, and GB contributed reagents/materials/analysis tools. AF, AS, and PD analyzed data. AF and PD wrote the manuscript. GB assisted with the interpretation of the results and provided editorial support for the manuscript. All authors have read, edited, and approved the current version of the manuscript.

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REFERENCES

Abdel-Ghany, S. E., Burkheada, J. L., Gogolina, K. A., Andrés-Colásh, N., Bodecker, J. R., Puigh, S., et al. (2005). AICS is a functional homolog of the yeast copper chaperone Ccs1/lys7. FEBS Lett. 279, 2307–2312. doi: 10.1016/j.felslet.2005.03.025

Auguy, F., Fahr, M., Moulin, P., Brugel, A., Laplaze, L., El Mzibri, M., et al. (2013). Lead tolerance and accumulation in Hirschfeldia incana, a Mediterranean Brassicaceae from metalliferous mine spoils. PLoS ONE 8:e61932. doi: 10.1371/journal.pone.0061932

Baker, A. J. M. (1981). Accumulators and excluders-strategies in the response of plants to heavy metals. J. Plant Nutr. 3, 643–654. doi: 10.1080/01904168109362867

Barcelo, J., and Poschenrieder, C. (1990). Plant water relations as affected by heavy metal stress: a review. J. Plant Nutr. 13, 1–37. doi: 10.1080/0190416909364057

Becher, M., Talke, I. N., Krall, L., and Krämer, U. (2004). Cross-species microarray transcript profiling reveals high constitutive expression of metal homeostasis genes in shoots of the zinc hyperaccumulator Arabidopsis halleri. Plant J. 37, 251–268. doi: 10.1046/j.1365-313X.2003.01959.x

Belatik, A., Hotchandani, S., Tajmir-Riahi, H. A., and Carpentier, R. (2013). Alteration of the structure and function of photosystem I by Pb2+. J. Photochem. Photobiol. B 123, 41–47. doi: 10.1016/j.jphotobiol.2013.03.010

Bellaire, B. A., Carmody, J., Braud, J., Gossett, D. R., Banks, S. W., Lucas, M. C., et al. (2000). Involvement of a bcs2 acid-dependent and independent pathways in the upregulation of antioxidative enzyme activity during NaCl stress in cotton callus tissue. Free Radical Res. 33, 531–545. doi: 10.1080/1071575000301071

Benatti, R. M., Yookongkaew, N., Meetam, M., Guo, J. W., Punyasuk, N., AbuQamar, S., et al. (2014). Metallothionein deficiency impacts copper accumulation and redistribution in leaves and seeds of Arabidopsis. New Phytol. 202, 940–951. doi: 10.1111/nph.12718

Broughton, W. J., and Dilworth, M. J. (1971). Control of leghaemoglobin synthesis in snake beans. Biochem. J. 125, 1075–1080. doi: 10.1042/bj1251075

Cobbett, C., and Goldsbrough, P. (2002). Phytochelatins and metallothioneins: roles in heavy metal detoxification and homeostasis. Annu. Rev. Plant Biol. 53, 159–182. doi: 10.1146/annurev.arplant.53.100301.135154

Edgar, R., Domrachev, M., and Lash, A. E. (2002). Gene expression omnibus: NCBI gene expression and hybridization array data repository. Nucleic Acids Res. 30, 207–210. doi: 10.1093/nar/30.1.207

Gisbert, C., Clemente, R., Navarro-Avirió, J., Baixauli, C., Ginér, A., Serrano, R., et al. (2006). Tolerance and accumulation of heavy metals by Brassicaceae species grown in contaminated soils from Mediterranean regions of Spain. Environ. Exp. Bot. 56, 19–27. doi: 10.1016/j.envexpbot.2004.12.002

Gravot, A., Lieutaud, A., Verret, F., Auroy, P., Vasseur, A., and Richaud, P. (2004). AtHMA3, a plant P1B-ATPase, functions as a Cd/Pb transporter in yeast. FEBS Lett. 561, 22–28. doi: 10.1016/S0014-5793(04)00072-9

Grissen, V. M. J., Hakvoort, H. W. J., Bieke, T., Verkleij, J. A. C., and Schat, H. (2011). Combined expression of the Arabidopsis metallothionein MT2b and the heavy metal transporting ATPase HMA4 enhances cadmium tolerance and the root to shoot translocation of cadmium and zinc in tobacco. Environ. Exp. Bot. 72, 71–76. doi: 10.1016/j.envexpbot.2010.01.005

Guo, W. J., Meetam, M., and Goldsbrough, P. B. (2008). Examining the specific contributions of individual Arabidopsis metallothionein genes to copper distribution and metal tolerance. Plant Physiol. 146, 1697–1706. doi: 10.1104/pp.108.115782

Hammond, J. P., Bowen, H. C., White, P. J., Mills, V., Pyke, K. A., Baker, A. J., et al. (2006). A comparison of the Thlaspi caerulescens and Thlaspi arvense shoot transcriptomes. New Phytol. 170, 239–260. doi: 10.1111/j.1469-8137.2006.01662.x

Hong, J. H., Seih, S. W., and Xu, J. (2013). The root of ABA action in environmental stress response. Plant Cell Rep. 32, 971–983. doi: 10.1007/s00299-013-1439-9

Islam, E., Liu, D., Li, T., Yang, X., Jin, X., Mohmood, Q., et al. (2008). Effect of Pb toxicity on leaf growth, physiology and ultrastructure in the two ecotypes of Elsholtzia argyi. J. Hazard. Mater. 154, 914–926. doi: 10.1016/j.jhazmat.2007.10.121

Jiang, M., and Zhang, J. (2002). Water stress induced abscisic acid accumulation triggers the increased generation of reactive oxygen species and up regulates
the activities of antioxidants in maize enzye life. J. Exp. Bot. 53, 2401–2410. doi: 10.1093/jxb/erf090
Kim, D. Y., Bovet, L., Kushnir, S., Noh, E. W., Martinioa, E., and Lee, Y. (2006). AtATM3 is involved in heavy metal resistance in Arabidopsis. Plant Physiol. 140, 922–932. doi: 10.1104/pp.105.074146
Kim, D. Y., Bovet, L., Maeshima, M., Martinioa, E., and Lee, Y. (2007). The ABC transporter AtPDR8 is a cadmium extrusion pump conferring heavy metal resistance. Plant J. 50, 207–218. doi: 10.1111/j.1365-313X.2007.03044.x
Klaassen, C. D., Liu, J., and Choudhuri, S. (1999). Metallothionein: an intracellular protein to protect against cadmium toxicity. Annu. Rev. Pharmacol. Toxicol. 39, 267–294. doi: 10.1146/annurev.pharmtox.39.1.267
Krzesłowska, M. (2011). The cell wall in plant cell response to trace metals: polysaccharide remodeling and its role in defense strategy. Acta Physiol. Plant. 33, 35–42. doi: 10.1007/s11738-010-0581-z
Larsson-Raazikiewicz, M. (1967). Kinetic studies on the reaction catalyzed by phosphoglucose kinase, Il - The kinetic relationships between 3-phosphoglycerate, MgATP2- and activating metal ion. Biochim. Biophys. Acta 132, 33–40. doi: 10.1016/0005-2744(67)90189-1
Lee, J., Shim, D., Song, W. Y., Hwang, I., and Lee, Y. (2004). Arabidopsis metallothioneins 2a and 3 enhance resistance to cadmium when expressed in Vicia faba guard cells. Plant Mol. Biol. 554, 805–815. doi: 10.1007/s11103-004-0190-6
Lee, M., Lee, K., Lee, J., Noh, E. W., and Lee, Y. (2005). AtPDR12 contributes to lead resistance in Arabidopsis. Plant Physiol. 138, 827–836. doi: 10.1104/pp.104.081107
Li, S. W., Leng, Y., Feng, L., and Zeng, X. Y. (2014). Involvement of abscisic acid in regulating antioxidative defense systems and IAA-oxidase activity and improving adventitious rooting in mung bean [Vigna radiata (L.) Wilczek] seedlings under cadmium stress. Environ. Sci. Pollut. Res. Int. 21, 525–537. doi: 10.1007/s11356-013-1942-0
Liu, R., Xu, Y. H., Jiang, S. C., Lu, K., Lu, Y. F., Feng, X. J., et al. (2013). Light-harvesting chlorophyll a/b-binding proteins, positively involved in abscisic acid signaling, require a transcription repressor, WRKY40, to balance their function. J. Exp. Bot. 64, 5443–5456. doi: 10.1093/jxb/ert307
Madejon, P., Murillo, J. M., Maranon, T., and Lepp, N. W. (2007). Factors affecting accumulation of thallium and other trace elements in two wild Brassicaceae spontaneously growing on soils contaminated by tailings dam waste. Chemosphere 67, 20–28. doi: 10.1016/j.chemosphere.2006.10.008
Margui, E., Queralt, I., Carvalho, M. L., and Hidalgo, M. (2007). Assessment of metal availability to vegetation (Betula pendula) in Pb-Zn ore concentrate residues with different features. Environ. Pollut. 145, 179–184. doi: 10.1016/j.envpol.2006.03.028
Morel, M., Crouzet, J., Gravot, A., Auroy, P., Leonhardt, N., Varasev, A., et al. (2009). ATRMA3, a P1B-ATPase allowing Cd/Zn/Co/Pb vacuolar storage in Arabidopsis. Plant Physiol. 149, 894–904. doi: 10.1104/pp.108.130294
Papoyan, A., and Kochian, L. V. (2004). Identification of Thlaspi caerulescens genes that may be involved in heavy metal hyperaccumulation and tolerance, Characterization of a novel heavy metal transporting ATPase. Plant Physiol. 136, 3814–3823. doi: 10.1104/pp.104.04503
Parys, E., Romanowska, E., Siedlecka, M., and Poskuta, J. W. (1998). The effect of lead on photosynthesis and respiration in detached leaves and in mesophyll protoplasts of Paspum sativum. Acta Physiol. Plant. 20, 313–322. doi: 10.1023/A:10037899-998-0064-7
Peer, W. A., Mamoudian, M., Lahner, B. Z., Reeves, R. D., Murphy, A. S., and Salt, D. E. (2003). Identifying model metal hyperaccumulator plants: germplasm analysis of 20 Brassicaceae accessions from a wide geographical area. New Phytol. 159, 421–430. doi: 10.1046/j.1469-8137.2003.00822.x
Puschenrieder, P., Bech, J., Llugany, M., Pace, A., Fenés, E., and Barceló, J. (2001). Copper in plant species in a copper gradient in Catalonia (North East Spain) and their potential for phytoremediation. Plant Soil 22, 247–256. doi: 10.1023/A:1010374732486
Pourrut, B., Shahid, M., Dumat, C., Winterton, P., and Pinell, E. (2011). Lead uptake, toxicity, and detoxification in plants. Rev. Environ. Contam. Toxicol. 213, 113–136.
Provat, N., and Zhu, T. (2003). A browser-based functional classification server for Arabidopsis genomics. C. C. Mol. Biol. 2003, 271–272.
**Arabidopsis thaliana** and **Nicotiana tabacum** plants is increased by cadmium, nickel, arsenic, cobalt and lead but not by zinc and iron. *J. Biotechnol.* 139, 258–263. doi:10.1016/j.jbiotec.2008.12.001

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