

OsHAC1;1 and OsHAC1;2 Function as Arsenate Reductases and Regulate Arsenic Accumulation¹

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Rice is a major dietary source of the toxic metalloid arsenic (As). Reducing its accumulation in rice (*Oryza sativa*) grain is of critical importance to food safety. Rice roots take up arsenate and arsenite depending on the prevailing soil conditions. The first step of arsenate detoxification is its reduction to arsenite, but the enzyme(s) catalyzing this reaction in rice remains unknown. Here, we identify OsHAC1;1 and OsHAC1;2 as arsenate reductases in rice. *OsHAC1;1* and *OsHAC1;2* are able to complement an *Escherichia coli* mutant lacking the endogenous arsenate reductase and to reduce arsenate to arsenite. *OsHAC1;1* and *OsHAC1;2* are predominantly expressed in roots, with *OsHAC1;1* being abundant in the epidermis, root hairs, and pericycle cells while *OsHAC1;2* is abundant in the epidermis, outer layers of cortex, and endodermis cells. Expression of the two genes was induced by arsenate exposure. Knocking out *OsHAC1;1* or *OsHAC1;2* decreased the reduction of arsenate to arsenite in roots, reducing arsenite efflux to the external medium. Loss of arsenite efflux was also associated with increased As accumulation in shoots. Greater effects were observed in a double mutant of the two genes. In contrast, overexpression of either *OsHAC1;1* or *OsHAC1;2* increased arsenite efflux, reduced As accumulation, and enhanced arsenate tolerance. When grown under aerobic soil conditions, overexpression of either *OsHAC1;1* or *OsHAC1;2* also decreased As accumulation in rice grain, whereas grain As increased in the knockout mutants. We conclude that OsHAC1;1 and OsHAC1;2 are arsenate reductases that play an important role in restricting As accumulation in rice shoots and grain.

Arsenic (As) is a toxic metalloid and is listed as a class-one carcinogen (National Research Council, 2001). Humans are exposed to As mainly through drinking

water and food. Rice, the staple food for more than half of the world population, is the most important dietary source of As for populations in south and southeast Asia (Mondal and Polya, 2008; Meharg et al., 2009; Zhao et al., 2010b; Li et al., 2011), and there is evidence linking high As exposure in rice (*Oryza sativa*) with genotoxic effects in humans (Banerjee et al., 2013). A study on pregnant women in the US also found a significant association between rice consumption and urinary As excretion, a biomarker of As exposure (Gilbert-Diamond et al., 2011). Precooked milled rice is a common ingredient of baby food, and high As levels in some baby rice products present a particular concern (Meharg et al., 2008). It is therefore of critical importance to reduce As accumulation in rice grain.

Rice roots take up arsenate [As(V)] or arsenite [As(III)] depending on the prevailing soil conditions. As(III) is the main As species in anaerobic flooded paddy soil. However, rice grown under upland or water-saving cultivation conditions experience long periods when field soils becomes aerobic. Under such aerobic conditions, As(V) is the main form of As rice roots are exposed to (Xu et al., 2008). In addition, As(III) can also be oxidized in the rhizosphere even during flooded

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paddy cultivation due to the release of oxygen from rice roots (Liu et al., 2006; Seyfferth et al., 2010). As(III) and As(V) are taken up into roots by the silicic acid and phosphate transporters, respectively (Abedin et al., 2002; Ma et al., 2008; Wu et al., 2011). As(III) is detoxified by complexation with phytochelatins (Ha et al., 1999; Raab et al., 2005; Liu et al., 2010) and transported into the vacuoles via ABCC transporters (Song et al., 2010, 2014). Vacuolar sequestration of As(III)-thiol complexes helps restrict the translocation of As to rice grain (Song et al., 2014; Chen et al., 2015). The first step of As(V) detoxification is the reduction to As(III). Most plant species have an inherently high As(V) reduction capacity, because As(III) is found to be the predominant As species in plants exposed to As(V) (Dhankher et al., 2006; Xu et al., 2007). Reduction of As(V) to As(III) allows the latter to be detoxified via the mechanisms of phytochelatin complexation and vacuolar sequestration. Importantly, As(III) can also be extruded into the external environment following As(V) uptake, with As(III) efflux typically accounting for 60% to 80% of the As(V) uptake by roots of rice and other plants (Xu et al., 2007; Liu et al., 2010; Zhao et al., 2010a). Therefore, As(III) efflux is an efficient way for reducing the cellular As burden without the risk of losing phosphate, a chemical analog of As(V).

Despite the importance of As(V) reduction in plant As metabolism and detoxification, rather little was known about the enzymes catalyzing the reduction reaction until recently. Earlier studies suggested that plant ACR2 proteins, which are homologs of the yeast (*Saccharomyces cerevisiae*) As(V) reductase and belong to CDC25 phosphatases, may be responsible for As(V) reduction in plant cells (Bleeker et al., 2006; Dhankher et al., 2006; Ellis et al., 2006; Duan et al., 2007). However, these studies are mainly based on heterologous functional assays in *Escherichia coli* or yeast, which may not reflect the in planta functions of the genes. In the study of Dhankher et al. (2006), RNAi silencing of the *Arabidopsis* (*Arabidopsis thaliana*) ACR2 was found to lead to As(V) sensitivity and As hyperaccumulation in shoots. However, these observations could not be reproduced in studies using T-DNA insertion ACR2 null mutants (Liu et al., 2012; Chao et al., 2014). Recently, Chao et al. (2014) and Sánchez-Bermejo et al. (2014) independently identified a new As(V) reductase in *Arabidopsis*, named HAC1 (for High As Content 1) or ATQ1 (for Arsenate Tolerance QTL 1). The protein is a member of the rhodanase-like family but lacks the HCX₅R active site found in the yeast ACR2 (Mukhopadhyay and Rosen, 2001). HAC1/ATQ1 is able to reduce As(V) to As(III) both in vitro and in planta. Weak or null alleles of HAC1/ATQ1 in *Arabidopsis* accessions are associated with decreased tolerance to As(V) (Chao et al., 2014; Sánchez-Bermejo et al., 2014) and elevated As accumulation in shoots (Chao et al., 2014). Knockout mutants of HAC1 have greatly decreased As(III) efflux to the external medium following As(V) uptake, which causes As hyperaccumulation in shoots (Chao et al.,

2014). This study therefore demonstrates a crucial role of HAC1 in mediating As(V) reduction and limiting As accumulation in the above-ground tissues.

There are more than 10 *AtHAC1*-like genes in the rice genome (Supplemental Fig. S1), but their functions have not been characterized. Here, we show that OsHAC1;1 and OsHAC1;2, close homologs of *AtHAC1*, function as As(V) reductases and play an important role in regulating As accumulation in rice shoots and grain.

RESULTS

OsHAC1;1 and OsHAC1;2 Function as Arsenate Reductase

We identify two genes encoding rhodanase-like proteins (Loc_Os02g01220 and Loc_Os04g17660) from rice (cv Nipponbare), which have a high homology (84% and 81% similarity in the amino acid sequence, respectively) with *Arabidopsis AtHAC1*. These two genes share 90% amino acid sequence similarity and are thereafter named *OsHAC1;1* and *OsHAC1;2*, respectively (Supplemental Fig. S1). To test if *OsHAC1;1* and *OsHAC1;2* are able to reduce As(V) to As(III), we expressed the two rice genes in a strain of *E. coli* lacking the endogenous arsenate reductase *ArsC*. This mutant strain is sensitive to As(V), because it is not able to reduce the absorbed As(V) to As(III) to allow the latter to be extruded from the cell (Oden et al., 1994). Heterologous expression of either *OsHAC1;1* or *OsHAC1;2* restored the growth of the *E. coli* strain in the Luria-Bertani (LB) medium in the presence 1 mM As(V) (Fig. 1A). Furthermore, As speciation analysis using high performance liquid chromatography - inductively coupled plasma - mass spectrometry (HPLC-ICP-MS) showed the production of As(III) in the medium in the presence 10 μ M As(V) by the *E. coli* Δ *arsC* strain expressing *OsHAC1;1* or *OsHAC1;2*, in contrast to the empty vector control that produced no detectable As(III) (Fig. 1B).

The Expression Patterns and Subcellular Localization of *OsHAC1;1* and *OsHAC1;2* in Rice

To investigate the expression patterns of the two HAC1 genes in rice, we created stable transgenic rice lines expressing *OsHAC1;1-GFP* and *OsHAC1;2-GFP* chimeric protein constructs driven by their native promoters. Based on the GFP signals, we found that both *OsHAC1;1* and *OsHAC1;2* predominantly accumulate in root, with the epidermis and the pericycle cells, as well as root hairs in the mature zone of roots, showing particularly strong accumulation of *OsHAC1;1* (Fig. 2). In contrast, *OsHAC1;2* is more abundantly found in the epidermis, the exodermis, the outer layer of cortex, and the endodermis cells (Fig. 2). The expression patterns are similar between the different root zones from the root tip to the mature zone. For both gene constructs, very faint signals of GFP were observed in the shoot tissues (data not shown).

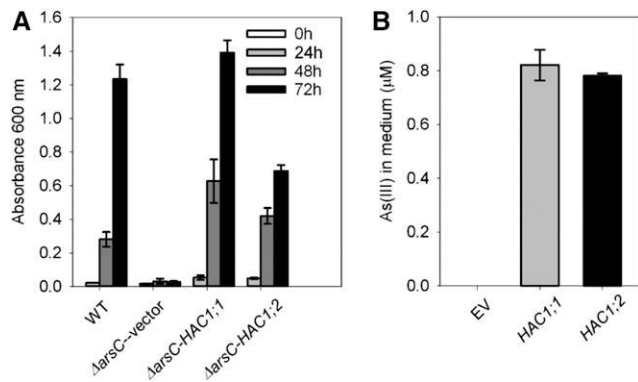


Figure 1. *OsHAC1;1* and *OsHAC1;2* encode arsenate reductases. A, Expression of *OsHAC1;1* or *OsHAC1;2* suppresses the As(V) sensitivity of the *E. coli* mutant lacking the *arsC* arsenate reductase. Strains were grown at 16°C and cell density measured at OD₆₀₀ nm after exposure to 1 mM As(V) for 0 to 72 h. Wild type = *E. coli* wild type (W3110); $\Delta arsC$ = *arsC* mutant in WC3110; Vector = empty pET29a; *arsC*-HAC1;1 = pET-29a vector containing *OsHAC1;1*; $\Delta arsC$ -HAC1;2 = pET-29a vector containing *OsHAC1;2*. B, Production of As(III) in LB medium after *E. coli* expressing the empty vector (EV), *OsHAC1;1* or *OsHAC1;2* was exposed to 10 μM As(V). n.d., not detected.

To investigate the subcellular localization of the *OsHAC1;1* and *OsHAC1;2*, we isolated protoplasts from the transgenic rice roots expressing *OsHAC1;1*-GFP or *OsHAC1;2*-GFP. For both gene constructs, the GFP signals were localized in the cytoplasm (Supplemental Fig. S2). To further investigate the subcellular localization of the two proteins, we constructed N-terminal *OsHAC1;1* or *OsHAC1;2* fusions with GFP with expression driven by the cauliflower mosaic virus 35S promoter and transfected the derived expression vector into rice protoplasts. We observed that both the *OsHAC1;1*::GFP and *OsHAC1;2*::GFP fusion proteins are localized in the cytoplasm and nucleus (Fig. 3). Because of the relatively small molecular sizes of the two proteins, the possibility of their diffusion from the cytoplasm to the nucleus cannot be ruled out.

We used quantitative real-time PCR (qRT-PCR) to investigate the expression pattern of *OsHAC1;1* and *OsHAC1;2* in response to As(V) exposure. Three-week-old rice plants (cv Nipponbare) were exposed to 0 or 10 μM As(V) in a nutrient solution without phosphate for up to 24 h. Phosphate was withdrawn during this short-term experiment to facilitate As(V) uptake. In the control treatment [no As(V)], *OsHAC1;1* and *OsHAC1;2* were predominantly expressed in roots and moderately in shoots, and there were no temporal changes in their relative expression levels over the 24-h time course (Fig. 4). Exposure to As(V) significantly enhanced the expression of both *OsHAC1;1* and *OsHAC1;2* during the first 12 h, with *OsHAC1;1* showing a greater response than *OsHAC1;2* (Fig. 4). In contrast, exposure to 10 μM As(III) decreased the mRNA levels of *OsHAC1;1* and *OsHAC1;2* in both roots and shoot (Supplemental Fig. S3).

Knocking Out *OsHAC1;1* or *OsHAC1;2* Affects Arsenate Reduction and Arsenic Accumulation in Rice

To investigate the in planta function of *OsHAC1;1* and *OsHAC1;2*, we created two independent knockout lines of *OsHAC1;1*, *hac1;1-1* and *hac1;1-2*, in the cv Zhonghua 11 background using CRISPR-Cas9 technology (Supplemental Fig. S4). We also obtained two independent homozygous T-DNA insertion mutants of *OsHAC1;2* (*hac1;2-1* and *hac1;2-2* in the cv Zhonghua 11 and Dongjin background, respectively; Supplemental Fig. S4). In addition, we obtained a homozygous double mutant *hac1;1 hac1;2* in the cv Zhonghua 11 background by crossing *hac1;1-1* with *hac1;2-1*. Analysis using qRT-PCR showed that the expressions of *OsHAC1;1* and *OsHAC1;2* were abolished in these mutants (Supplemental Fig. S4). If *OsHAC1;1* and *OsHAC1;2* play a role in As(V) reduction, knocking out of *OsHAC1;1* or *OsHAC1;2* may impact As speciation in the plants. To test this hypothesis, mutant and wild-type plants were exposed to 10 μM As(V) for 48 h, and As speciation in roots and shoots were determined using HPLC-ICP-MS. *hac1;1-1*, *hac1;1-2*, *hac1;2-1* and *hac1;1 hac1;2* and their common wild type (Zhonghua 11) were compared in the same experiment, and *hac1;2-2* and its wild type (Dongjin) in a separate experiment. As(III) and As(V) were the only two As species detected in the plant tissues, with As(III) being the predominant As species. The extraction method does not preserve As(III)-thiol complexes (Raab et al., 2005; Liu et al., 2010), which would be dissociated and determined as As(III) by the method used. Knocking out of *OsHAC1;1* resulted in 3.1 times higher As(V) concentration in roots compared with wild type, while the mutation in *OsHAC1;2* increased root As(V) concentration by 40% to 80% (Fig. 5, A and C). In the double mutant, root As(V) concentration was 4.7 times higher than wild type. All mutants had significantly higher concentrations of both As(V) and As(III) in shoots than wild-type plants (Fig. 5, B and D).

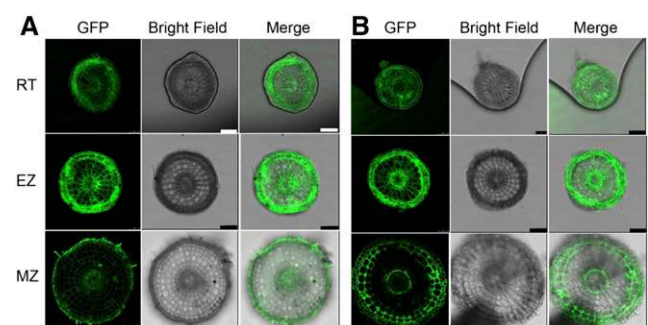


Figure 2. Expression patterns of *OsHAC1;1* and *OsHAC1;2* revealed by the accumulation of the *OsHAC1;1*-GFP (A) or *OsHAC1;2*-GFP (B) fusion proteins driven by their native promoters. Roots were cut by hand at different zones: EZ, Elongation zone; MZ, mature zone; RT, root tip. Scale bar = 100 μm .

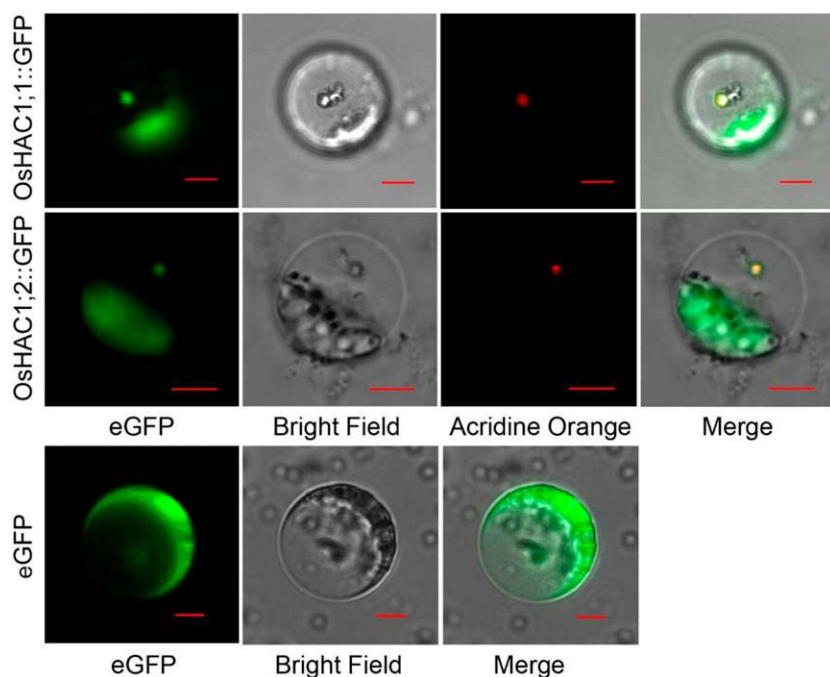


Figure 3. Subcellular localization of OsHAC1;1 and OsHAC1;2. Representative microscopic images of rice protoplasts expressing the OsHAC1;1-GFP (top) or OsHAC1;2-GFP (middle) fusion protein or eGFP (bottom) driven by the cauliflower mosaic virus 35S promoter. Scale bars = 5 μm .

Compared with wild type, *hac1;1*, *hac1;2* and the double mutant had 170%, 150% to 190%, and 230%, respectively, higher total As [sum of As(V) and As(III)] concentration in shoots. The effect of *OsHAC1;1* or *OsHAC1;2* mutations is also evident from the changes in As(III) as a percentage of the total As in roots, decreasing from 82% in wild type (Zhonghua 11) to 62%, 72%, and 57% in *hac1;1*, *hac1;2-1*, and the double mutant, respectively, and from 77% in wild type (Dongjin) to 71% in *hac1;2-2*. In the shoot tissues, As(III) as a percentage of the total As also decreased from 93% in wild type (Zhonghua 11) to 90% in the three single mutants and 81% in the double mutant. These results support a role for OsHAC1;1 and OsHAC1;2 in As(V) reduction in rice roots, with the double mutant having a greater effect than the single mutants and the single mutants of OsHAC1;1 having a greater effect than those of OsHAC1;2.

Chao et al. (2014) showed that As(III) efflux from roots to the external medium diminished greatly in mutants with a loss of *AtHAC1* function, resulting in a markedly increased As accumulation in Arabidopsis shoots. To test if mutations in *OsHAC1;1* or *OsHAC1;2* also affect As(III) efflux in rice, plants were exposed to 10 μM As(V) for 48 h. As(V) uptake and As(III) efflux were estimated by measuring the changes in As speciation in the culture solution. There were no differences in As(V) uptake between mutants and wild type (Fig. 5, E and G). In contrast, As(III) efflux from roots was significantly decreased in all single mutants compared with wild-type plants, and a larger decrease was found in the double mutant than the single mutants (Fig. 5, F and H). The As(III) efflux efficiency, calculated as a ratio of As(III) efflux to As(V) uptake, was 0.80 to 0.83 in wild type, 0.56 to 0.66 in the single mutants, and 0.32 in the

double mutant. A decreased As(III) efflux to the external medium could explain the enhanced As accumulation in mutant shoots.

In a further experiment, we tested the effect of *OsHAC1;1* or *OsHAC1;2* mutations on As accumulation over a range of As(V) concentration from 2 to 20 μM . Knocking out of *OsHAC1;1* or *OsHAC1;2* resulted in a significant increase in As accumulation in roots at all As(V) concentrations and in shoots at all but the 2- μM As(V) treatment (Fig. 6, A and B).

Furthermore, we observed no significant change in the concentrations of As(V) and As(III) in roots or shoots of single or double mutants compared with wild types when plants were exposed to 10 μM As(III) for 48 h (Supplemental Fig. S5), suggesting that the effect of OsHAC1;1 and OsHAC1;2 is specific to As(V).

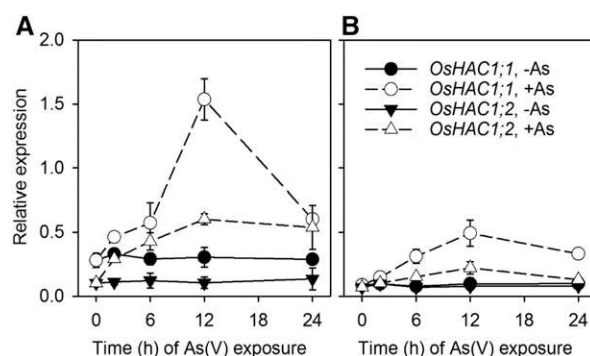


Figure 4. Induction of *OsHAC1;1* and *OsHAC1;2* expression in roots (A) and shoots revealed by qRT-PCR. Plants were exposed to 0 or 10 μM As(V) for 24 h. Expression of each gene was calculated as $2^{-\Delta\text{CT}}$ relative to *OsActin*. Data are means \pm SD ($n = 3$ biological replicates).

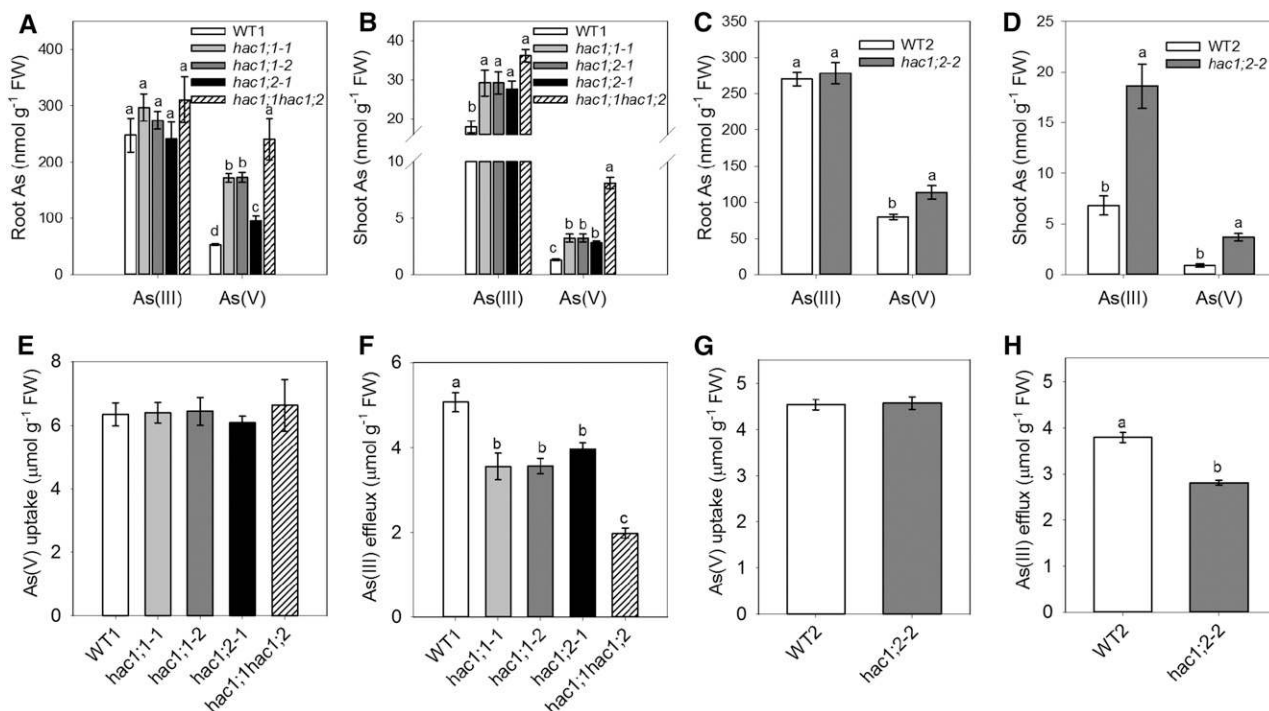


Figure 5. Knocking out *OsHAC1;1* or *OsHAC1;2* affects As(V) reduction and As accumulation in rice. A to D, As speciation in roots (A and C) and shoots (B and D) after wild-type and knockout single or double mutants were exposed to 10 μM As(V) for 48 h. E to H, Uptake of As(V) (E and G) and efflux of As(III) (F and H) after wild-type and mutant plants were exposed to 10 μM As(V) for 48 h. WT1, cv Zhonghua 11; WT2, cv Dongjin. Data are means \pm SE ($n = 4$ biological replicates). Different letters above bars represent significant difference at $P < 0.05$.

Overexpression of *OsHAC1;1* or *OsHAC1;2* Increases Arsenate Reduction and Decreases Arsenic Accumulation

To further investigate the role of *OsHAC1;1* and *OsHAC1;2* in As metabolism, we overexpressed *OsHAC1;1* and *OsHAC1;2* in rice (cv Nipponbare) using the Ubiquitin promoter. Three independent lines for each gene were selected for further investigation. qRT-PCR analysis showed that all overexpressing lines had greatly enhanced expression of *OsHAC1;1* or *OsHAC1;2* in roots compared with wild-type plants (Fig. 7, A and E). After exposure to 10 μM As(V) for 48 h, there was no significant difference in As(V) uptake between different transgenic plants and wild-type plants (Supplemental Fig. S6). In contrast, transgenic plants overexpressing *OsHAC1;1* or *OsHAC1;2* had 34% to 50% and 20% to 28%, respectively, larger As(III) efflux into the external medium than wild-type plants (Fig. 7, B and F). As(III) efflux as a proportion of As(V) uptake increased from 0.65 in wild type to 0.83 in the *OsHAC1;1* overexpression lines, and from 0.76 in wild type to 0.90 in the *OsHAC1;2* overexpression lines. As a result, overexpression of *OsHAC1;1* or *OsHAC1;2* significantly decreased the concentrations of As(III), As(V), and total As in both shoots and roots compared with wild-type plants, with the effect being greater on shoot As concentration than on root As concentration (Fig. 7, C, D, G, and H).

In a further experiment, plants were exposed to a range of As(V) concentrations varying from 2 to 20 μM for 48 h. Arsenic accumulation in roots and shoots was determined. Overexpression of *OsHAC1;1* or *OsHAC1;2* resulted in a significant decrease in root As concentration at all four As(V) exposure concentrations, as well as a significant decrease in shoot As concentration in all but the 2 μM As(V) treatment (Fig. 6, C and D).

In contrast, overexpression of *OsHAC1;1* or *OsHAC1;2* had no significant effect on As(V) and As(III) concentrations in roots and shoots compared with wild type when plants were exposed to 10 μM As(III) (Supplemental Fig. S7).

Knockout or Overexpression of *OsHAC1;1* or *OsHAC1;2* Affects As Speciation in Xylem Sap

If *OsHAC1;1* or *OsHAC1;2* plays a role in As(V) reduction in roots, knocking out or overexpression of these genes may affect As speciation in xylem sap. To test this hypothesis, we analyzed As speciation in xylem sap collected from plants exposed to 10 μM As(V) for 24 h. As(III) was found to be the predominant species of As in xylem sap. The concentrations of both As(V) and As(III) in the xylem sap from *OsHAC1;1* or *OsHAC1;2* single mutants were significantly higher than those from wild type, whereas the double mutant

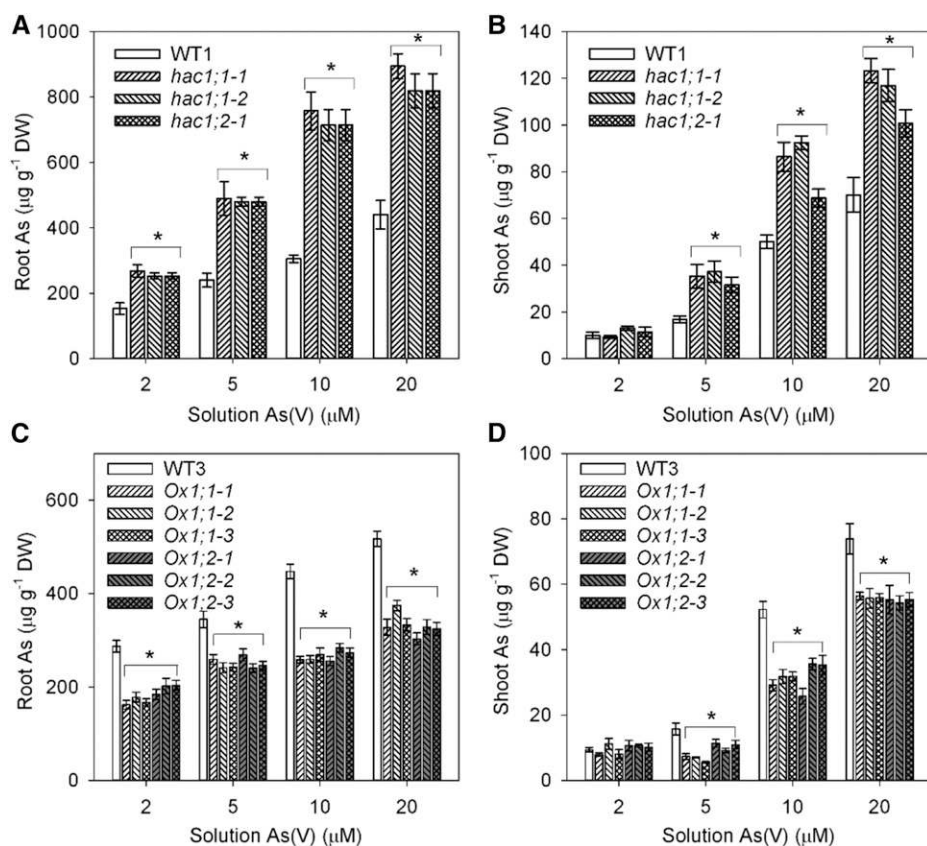


Figure 6. Knockout or overexpression *OsHAC1;1* or *OsHAC1;2* affects As accumulation in roots and shoots of knockout mutant and wild-type (WT1, Zhonghua 11) plants (A and B) and the overexpression lines and wild-type (WT3, Nipponbare) plants (C and D). Plants were exposed to different As(V) concentrations for 48 h. *Ox1;1-1*, *Ox1;1-2*, *Ox1;1-3* represent independent overexpression lines of *OsHAC1;1*. *Ox1;2-1*, *Ox1;2-2*, *Ox1;2-3* represent independent overexpression lines of *OsHAC1;2*. Data represent means \pm SE ($n = 4$ biological replicates). *Significant difference from wild type at $P < 0.05$. DW, dry weight.

also had a significantly higher As(V) concentration than the single mutants (Fig. 8A). The percentage of As(III) in the xylem sap total As was higher in wild type (80%) than in single mutants (73% to 76%) or double mutant (66%). In contrast, transgenic plants overexpressing either *OsHAC1;1* or *OsHAC1;2* showed lower As(V) and As(III) concentrations in the xylem sap compared with wild type (Fig. 8B). The differences were significant in all except one of the *OsHAC1;2* overexpression lines for As(V) concentration. These results are consistent with a role of *OsHAC1;1* and *OsHAC1;2* in As(V) reduction in rice roots.

Overexpression of *OsHAC1;1* or *OsHAC1;2* Enhances Tolerance To Arsenate

Because overexpression of *OsHAC1;1* or *OsHAC1;2* increased As(III) efflux to the external medium, we hypothesized that the overexpression lines might be more tolerant to As(V). In a short-term root elongation assay, root elongation of rice seedlings during 24 or 48 h under different As(V) concentrations was measured. The assay was conducted in the absence of phosphate to heighten the toxicity of As(V). Because the response patterns were similar between the 24- and 48-h exposure, only the data of 24-h exposure are shown (Fig. 9; Supplemental Fig. S8). Root growth of wild-type seedlings was inhibited by more than 90% by 2.5 μ M As(V)

and completely arrested by 4 μ M As(V). In contrast, *OsHAC1;1* or *OsHAC1;2* overexpression lines had significantly larger root elongation than wild type in the presence of 2.5 to 4 μ M As(V) (Fig. 9), indicating an increased tolerance to As(V).

OsHAC1;1 and *OsHAC1;2* Affect Grain As Accumulation in Soil-grown Rice

The experiments described above were conducted in hydroponic cultures with young rice plants. To determine if *OsHAC1;1* and *OsHAC1;2* play a role in regulating As accumulation in rice grain, plants were grown up to maturity in a paddy soil amended with an environmentally relevant dose of As(V) (20 mg kg⁻¹; Zhao et al., 2010b). The soil was irrigated regularly with free drainage, aerobic conditions under which As(V) was likely to be the main species of As in the soil solution (Xu et al., 2008). Under aerobic conditions, *hac1;1* and *hac1;2* mutants had 36% and 20%, respectively, higher As concentration in the brown rice than wild type (Fig. 10A), whereas the *OsHAC1;1* and *OsHAC1;2* overexpression lines had approximately 20% lower grain As concentration than wild type (Fig. 10B). Grain yield and straw biomass were not significantly different between the mutants and wild type or between the overexpressing lines and wild type (data not shown).

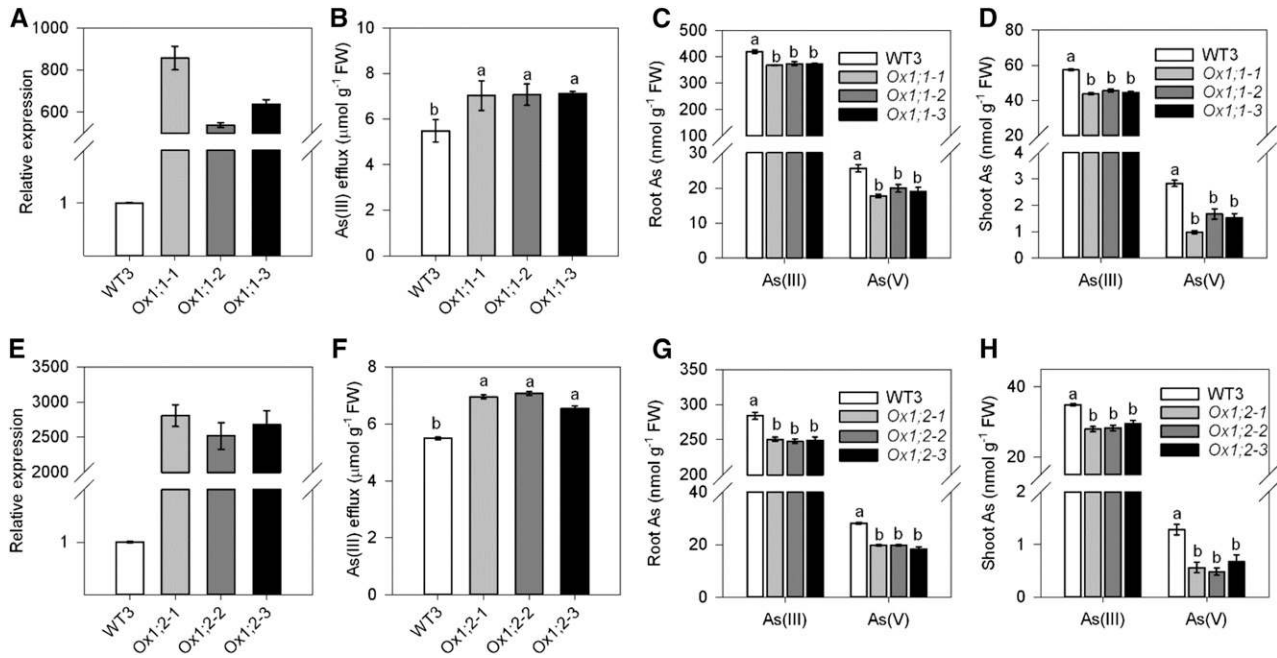


Figure 7. Overexpression of *OsHAC1;1* or *OsHAC1;2* increases As(III) efflux and decreases As accumulation in rice shoots. A and E, The expression levels of *OsHAC1;1* (A) or *OsHAC1;2* (E) in wild-type (WT3, Nipponbare) and transgenic lines by qRT-PCR. B and F, Efflux of As(III) after wild-type and overexpression lines of *OsHAC1;1* (B) or *OsHAC1;2* (F) were exposed to $10 \mu\text{M}$ As(V) for 48 h. C, D, G, and H, As speciation in roots (C and G) and shoots (D and H) after wild-type and overexpression lines of *OsHAC1;1* (C and D) or *OsHAC1;2* (G and H) were exposed to $10 \mu\text{M}$ As(V) for 48 h. Data are means \pm SE ($n = 4$ biological replicates). Different letters above bars represent significant difference at $P < 0.05$.

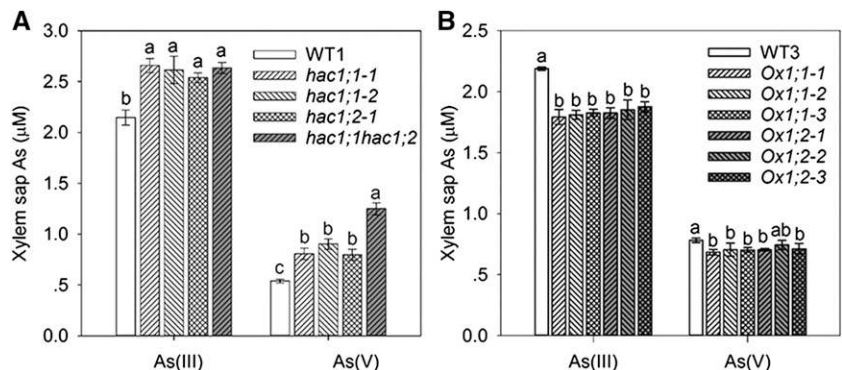
DISCUSSION

In the current study, we show that *OsHAC1;1* and *OsHAC1;2* function as As(V) reductases and are involved in the reduction of As(V) to As(III) in rice plants. *OsHAC1;1* and *OsHAC1;2* are the closest homologs of the Arabidopsis *AtHAC1/ATQ1*, which was discovered recently as representing a new type of As(V) reductase in plants (Chao et al., 2014; Sánchez-Bermejo et al., 2014). Similar to *AtHAC1*, both *OsHAC1;1* and *OsHAC1;2* were able to complement the As(V)-sensitive *E. coli* mutant lacking the endogenous As(V) reductase *ArsC* (Fig. 1). The *E. coli* mutant expressing either *OsHAC1;1* or *OsHAC1;2* was able to reduce As(V) and extrude As(III) into the external medium, which is a key

mechanism of As(V) detoxification widely employed by microorganisms (Rosen, 2002). Further evidence for a role of *OsHAC1;1* and *OsHAC1;2* in As(V) reduction in rice plants can be seen in the altered As speciation in the mutants or overexpression lines of the two genes; mutations in either *OsHAC1;1* or *OsHAC1;2* resulted in an increased proportion of As(V) and a decreased proportion of As(III) in rice roots and xylem saps, whereas overexpression of either gene produced the opposite effect (Figs. 5, 7, and 8). The effect was greater when both genes were knocked out in the double mutant.

We show that *OsHAC1;1* protein accumulates predominantly in the root epidermis, root hairs, and the stele, and *OsHAC1;2* accumulates mainly in the

Figure 8. Knockout or overexpression of *OsHAC1;1* or *OsHAC1;2* affects As speciation in xylem sap. Concentrations of As(V) and As(III) in xylem sap of knockout single or double mutants and wild-type (WT1, Zhonghua 11) plants (A) and the overexpression lines and wild-type (WT3, Nipponbare) plants (B). Plants were exposed to $10 \mu\text{M}$ As(V) for 24 h. Data represent means \pm SE ($n = 4$ biological replicates). Different letters above bars represent significant difference at $P < 0.05$.



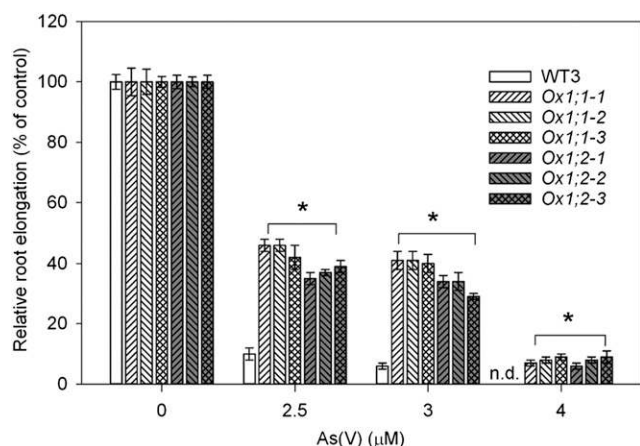


Figure 9. Overexpression of *OsHAC1;1* or *OsHAC1;2* enhances As(V) tolerance. Root growth of rice seedlings during 24 h under different As(V) concentrations was measured. *Ox1;1-1*, *Ox1;1-2*, *Ox1;1-3* represent independent overexpression lines of *OsHAC1;1*. *Ox1;2-1*, *Ox1;2-2*, *Ox1;2-3* represent independent overexpression lines of *OsHAC1;2*. Data represent means \pm SE ($n = 10$ biological replicates). *Significant difference from wild type (WT3, Nipponbare) at $P < 0.05$.

exodermis, the outer layer of cortex, and the stele (Fig. 2). By mediating As(V) reduction in the root epidermis, root hairs, and possibly also the exodermis, *OsHAC1;1* and *OsHAC1;2* enable As(III) efflux from the outer layers of root cells to the external medium. In agreement with previous studies (Xu et al., 2007; Zhao et al., 2010a), As(III) efflux was found to represent a large proportion of As(V) influx in wild-type plants (approximately 80%). This proportion decreased to approximately 60% in the single mutants and to approximately 30% in the double mutant (Fig. 5). Efflux of As(III) following As(V) uptake is critical for controlling As accumulation in plant tissues. Decreased As(III) efflux in the mutants leads to more As accumulation in both roots and shoots (Figs. 5 and 6). In contrast, overexpression of either *OsHAC1;1* or *OsHAC1;2* increased As(V) reduction and As(III) efflux to the external medium, resulting in decreased As accumulation in both roots and shoots (Figs. 6 and 7). Furthermore, the localization of *OsHAC1;1* and *OsHAC1;2* in the stele implies a role of the two proteins in regulating As translocation from roots to shoots, possibly by blocking xylem loading of As(V) via phosphate transporters such as PHO1 (Poirier et al., 1991; Secco et al., 2010). Increased proportions of As(V) in the xylem sap of the knockout mutants (Fig. 8) are consistent with this interpretation. A previous study showed that As(III) is preferentially stored in the vacuoles of the pericycle and endodermal cells of rice roots (Moore et al., 2011), supporting the notion that these cells are important in regulating the root to shoot translocation of As. It is possible that *OsHAC1;1* and *OsHAC1;2* also contribute to As(V) reduction in the shoots. However, the altered phenotypes of As accumulation in the knockout mutants and the overexpression

lines can be attributed primarily to the function of the two enzymes in the roots.

The presence of substantial amounts of As(III) in the roots and shoots of the *oshac1;1 oshac1;2* double mutant indicates the presence of other As(V) reduction mechanisms in plants. There are more than 10 *HAC1*-like genes in the rice genome (Supplemental Fig. S1), some of which may also play a role in As(V) reduction. Another possibility is that As(V) could be reduced non-enzymatically by glutathione (Delnomdedieu et al., 1994), although the reaction may be slow. However, As(V) can participate in phosphorylation reactions (Byers et al., 1979), forming arsenate esters that are more easily reduced by thiols such as glutathione (Gregus et al., 2009). Unlike *AtHAC1*, *OsHAC1;1*, and *OsHAC1;2*, some of these additional As(V) reduction processes may not be linked to As(III) efflux, either because they do not interact with efflux transporters or are localized in cells not suited for As(III) efflux to the external medium (Chao et al., 2014). The presence of multiple As(V) reduction mechanisms explains why not only As(V), but also As(III), is elevated in the xylem sap and shoots of the mutants (Figs. 5 and 8).

OsHAC1;1- and *OsHAC1;2*-mediated As(V) reduction is also required for tolerance to As(V), as it likely lessens the cellular burden of As through efficient As(III) efflux. Furthermore, As(V) reduction allows the product As(III) to be complexed with phytochelatins and subsequently sequestered in the vacuoles (Zhao et al., 2009; Liu et al., 2010; Song et al., 2010). The expressions of *OsHAC1;1* and *OsHAC1;2* were strongly induced by As(V) exposure (Fig. 4), which is consistent with a role of the two genes in As(V) detoxification.

OsHAC1;1 appears to play a greater role in controlling As accumulation than *OsHAC1;2*. This difference could be attributed to a higher expression of *OsHAC1;1*

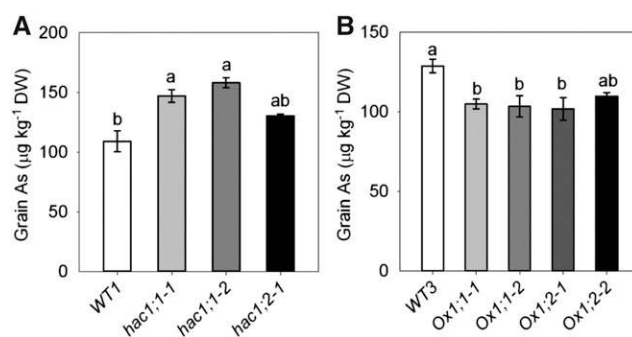


Figure 10. Knockout or overexpression of *OsHAC1;1* or *OsHAC1;2* affect arsenic accumulation in rice grain under aerobic soil conditions. A, As concentration in brown rice of *OsHAC1;1* or *OsHAC1;2* knockout mutants and wild-type (WT1, Zhonghua 11) plants. B, As concentration in brown rice of *OsHAC1;1* or *OsHAC1;2* overexpression lines and wild-type (WT3, Nipponbare) plants. Plants were grown in a soil amended with 20 mg As(V) kg^{-1} under aerobic conditions and rice grain were harvested at maturity. Data are means \pm SE ($n = 4$ biological replicates). Different letters above bars represent significant difference at $P < 0.05$.

(Fig. 4). The strong localization of OsHAC1;1 in the epidermis and root hairs would also make it more efficient in enabling As(III) efflux, as has been observed for AtHAC1 in Arabidopsis (Chao et al., 2014). Although *OsHAC1;1* and *OsHAC1;2* are similar to *AtHAC1* in a number of aspects discussed above, the impact of *OsHAC1;1* or *OsHAC1;2* single mutation is not as large as that of *AtHAC1* knockout reported by Chao et al. (2014). This difference can be explained by a degree of functional redundancy between *OsHAC1;1* and *OsHAC1;2*, which is clearly demonstrated by larger effects in the double mutant (Figs. 5 and 8). In addition, there are other *HAC1*-like genes in rice (Supplemental Fig. S1), whose functions remain to be investigated. Although *OsHAC1;1* and *OsHAC1;2*, as well as *AtHAC1*, function as As(V) reductases, their primary metabolic functions, if any, remain unknown. It is also intriguing that the rice genome contains a considerable number of *HAC1*-like genes. We observed no growth or developmental phenotypes in *oshac1;1*, *oshac1;2* or *athac1* mutants under non-As stressed conditions.

Previously, OsACR2, a CDC-25 protein and a homolog of the yeast As(V) reductase ScACR2, has been suggested to be involved in As(V) reduction in rice (Duan et al., 2007). However, this study was based on heterologous expression of *OsACR2* in yeast and in vitro characterization of the *OsACR2* enzyme. No knockout or knockdown lines of *OsACR2* were included in the study of Duan et al. (2007). Whether *OsACR2* plays a role in As(V) reduction in rice plants remains unclear. In the case of Arabidopsis, the report by Dhankher et al. (2006) that silencing *AtACR2* by RNA interference leads to As hyperaccumulation in the shoots could not be confirmed by recent studies using two independent T-DNA insertional knockout mutants of the gene (Liu et al., 2012; Chao et al., 2014). Because *AtACR2* and *AtHAC1* share sequence identity within the region used by Dhankher et al. (2006) to knock down expression of *AtACR2* by RNA interference, this sequence may also have suppressed *AtHAC1* expression in their RNAi lines, thus resulting in decreased As(V) tolerance and As hyperaccumulation in the shoots (Chao et al., 2014). Nahar et al. (2012) reported increased As(V) sensitivity and As accumulation in the shoots of a single T-DNA line (SALK_005882C) with a T-DNA insertion to the neighboring gene (At5g03452) of *AtACR2* (At5g03455), which appeared to knock-down the expression of *AtACR2*.

Although lowland rice is typically grown under flooded conditions, paddy water is usually drained periodically during the rice growing season. Upland rice often experiences dry periods due to water shortage. There is also an increasing trend of using aerobic to save water usage and to reduce greenhouse gas emissions from paddy fields (Bouman et al., 2005; Linqvist et al., 2015). All these agronomic factors lead to aerobic soil conditions under which As(V) is expected to be the dominant As species present in the soil solution and taken up by rice roots. Consequently, As(V) reductases may play an important role in As accumulation in rice

grain when plants are exposed to the aerobic soil conditions that can occur when rice is grown under normal field conditions. We tested this hypothesis by growing mutants and overexpression lines of *OsHAC1;1* and *OsHAC1;2* under aerobic soil conditions to maturity. Under the experimental conditions, loss-of-function mutants of *OsHAC1;1* or *OsHAC1;2* had a significantly higher concentration of As in rice grain than wild type, whereas overexpression lines contained significantly lower levels of As than wild type (Fig. 10). We therefore conclude that in the field, when rice roots are exposed to irregular oxidizing and reducing cycles, the ability to specifically reduce As(V) to As(III) through the action of the OsHAC1 arsenate reductases is important to restrict As accumulation in rice grain.

Our study has shed light on the mechanism of As(V) reduction in rice, a staple food crop with an unusually high contribution to dietary As intake by humans. Our results and those of Chao et al. (2014) and Sánchez-Bermejo et al. (2014) on Arabidopsis show that As(V) reduction is a key step in As metabolism that controls the accumulation of As in the above-ground tissues of plants. Our results point to a possible strategy for limiting grain As accumulation in rice cultivated under conditions in which the soil is aerobic for extended periods of time. Such a strategy would involve enhancing As(V) reductase activities in rice roots to both enhance As(III) efflux and limit its xylem loading and transport.

MATERIALS AND METHODS

Plant Materials

Rice (*Oryza sativa* ssp. japonica) cv Nipponbare, Zhonghua 11, or Dongjin were used as wild types in this study and for rice transformation. A T-DNA insertion mutant line *oshac1;2-1* (RMD_03Z11FF65) in the Zhonghua11 background was obtained from Huazhong Agricultural University, China. We obtained another T-DNA insertion mutant line *oshac1;2-2* (PFG_3A-02094) in the Dongjin background from Zhejiang University. The location of the T-DNA insertion in the mutant was determined by DNA sequence analysis using PCR. A homozygous T-DNA insertion line was identified by PCR using gene-specific primers in conjunction with T-DNA border primers (Supplemental Table S1). Two independent mutants of *OsHAC1;1*, *oshac1;1-1* and *oshac1;1-2*, were generated using the CRISPR/Cas9 technology (see below). Overexpression lines of *OsHAC1;1* and *OsHAC1;2* were generated in the cv Nipponbare background (see below). *hac1;1-1* and *hac1;2-1* (both in the Zhonghua 11 background) were crossed to generate a double mutant. A homozygous double mutant line was identified by PCR using gene-specific primers and sequencing.

Plant Growth Conditions

Rice seeds were surface sterilized in a 30% (v/v) hydrogen peroxide solution for 30 min, washed, and germinated for 3 d at 37°C in the dark. Ten-day-old seedlings were transferred to a one-half-strength Kimura nutrient solution. The composition of the nutrient solution was as follows (in mM): 0.091 KH₂PO₄, 0.273 MgSO₄, 0.182 (NH₄)₂SO₄, 0.091 KNO₃, 0.183 Ca(NO₃)₂, 0.003 H₃BO₃, 0.0005 MnCl₂, 0.001 (NH₄)₆Mo₇O₂₄, 0.0004 ZnSO₄, 0.0002 CuSO₄, 0.02 Fe(III)-EDTA. The pH of the solution was adjusted to 5.5. The nutrient solution was renewed every 2 d. Hydroponic experiments were conducted inside a growth room with a 14-h-light/10-h-dark period, 250 μmol m⁻² s⁻¹ light intensity, 25/20°C day/night temperatures, and a relative humidity at approximately 70%. Arsenic treatments were started by adding As(V) (Na₃AsO₄) or As(III) (NaAsO₂) to the nutrient solution at target concentrations.

A soil pot experiment was conducted with mutants, overexpression lines, and their wild type. A paddy soil was collected from an experimental farm of Nanjing

5 mM MES (pH 6.0) and immersed in 1 L of the same solution for 10 min to remove apoplastic As. Roots were blotted dry, weighed, and frozen in liquid nitrogen. Plant shoots were rinsed with deionized water, blotted dry, weighed, and frozen in liquid nitrogen. Shoots and roots were ground in liquid nitrogen to fine powder with a mortar and pestle. The finely ground materials were extracted with 10 mL phosphate-buffer solution containing 2 mM NaH_2PO_4 and 0.2 mM $\text{Na}_2\text{-EDTA}$ (pH 6.0) for 1 h under sonication in a 4°C room (Xu et al., 2007). The extract was filtered through a 0.22 μm membrane filter before analysis. Arsenic species were separated using an anion-exchange column (Hamilton PRP X-100, fitted with a guard column; Reno, NV) with a mobile phase of 6.0 mM $\text{NH}_4\text{H}_2\text{PO}_4$, 6.0 mM NH_4NO_3 , and 0.2 mM $\text{Na}_2\text{-EDTA}$ (pH 6.0), run isocratically at 1 mL min^{-1} . The solution from the separation column was mixed continuously with an internal standard solution (Indium) before being introduced into the ICP-MS. The instrument was set up in the kinetic energy discrimination mode with helium as the collision gas to reduce polyatomic interferences. Signals at $m/z^{75}\text{As}$ and ^{115}In were collected with a dwell time of 300 ms; the In counts were used to normalize the As counts. Arsenic species in the sample were quantified by external calibration curves using peak areas.

Accession Numbers

Sequence data from this article can be found in the GenBank/EMBL data libraries under accession numbers NP_001045596 and NP_001052130 for OsHAC1;1 and OsHAC1;2, respectively.

Supplemental Data

The following supplemental materials are available.

Supplemental Figure S1. Sequence analysis of *HAC* genes in rice and *Arabidopsis*.

Supplemental Figure S2. Subcellular localization of OsHAC1;1 and OsHAC1;2 in protoplasts isolated from transgenic rice plants expressing *pHAC1;1:OsHAC1;1-GFP* or *pHAC1;2:OsHAC1;2-GFP*.

Supplemental Figure S3. Exposure to As(III) decreases the expression of OsHAC1;1 and OsHAC1;2.

Supplemental Figure S4. Knockout mutants of *OsHAC1;1* (*hac1;1-1*, *hac1;1-2*) and *OsHAC1;2* (*hac1;2-1*, *hac1;2-2*).

Supplemental Figure S5. Knocking out OsHAC1;1 or OsHAC1;2 has no significant effect on As(III) uptake and As accumulation in rice.

Supplemental Figure S6. Overexpression of *OsHAC1;1* or *OsHAC1;2* has no significant effect on As(V) uptake.

Supplemental Figure S7. Overexpression of *OsHAC1;1* or *OsHAC1;2* has no significant effect on As(III) uptake and As accumulation in rice.

Supplemental Figure S8. Root elongation of *OsHAC1;1* and *OsHAC1;2* overexpression lines and wild-type plants exposed to different concentrations of As(V).

Supplemental Table S1. The primers used in this study.

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