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ATAF1 transcription factor directly regulates abscisic acid biosynthetic gene NCED3 in Arabidopsis thaliana

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Abstract

ATAF1, an Arabidopsis thaliana NAC transcription factor, plays important roles in plant adaptation to environmental stress and development. To search for ATAF1 target genes, we used protein binding microarrays and chromatin-immunoprecipitation (ChIP). This identified T[AC,G]CGT[AC] and T[T,C]AACCGT as ATAF1 consensus binding sequences. Co-expression analysis across publicly available microarray experiments identified 25 genes co-expressed with ATAF1. The promoter regions of ATAF1 co-expressors were significantly enriched for ATAF1 binding sites, and TTCCGTA was identified in the promoter of the key abscisic acid (ABA) phytohormone biosynthetic gene NCED3. ChIP-qPCR and expression analysis showed that ATAF1 binding to the NCED3 promoter correlated with increased NCED3 expression and ABA hormone levels. These results indicate that ATAF1 regulates ABA biosynthesis.

Introduction

Abscisic acid (ABA) controls numerous physiological processes in plants and is best known for its regulatory role in abiotic stress responses [1,2]. Upon drought and high salinity, ABA promotes desiccation tolerance by stomatal closure, enabling plants to adapt to water stress. ABA also regulates developmental processes such as seed germination, vegetative growth and bud dormancy [3–5]. More recent studies have shown that ABA also impacts plant biotic stress signaling [6,7].

Consequently, although the pathways of ABA biosynthesis and catabolism are largely defined (reviewed by Nambara and Marion-Poll [8]), understanding the regulation of these pathways is important. In particular, the cleavage of 9-cis-epoxydocosanoids to xanthoxin catalyzed by 9-cis-epoxydocosanoid dioxygenases (NCEDs) during ABA biosynthesis, which is believed to be the key regulatory step of ABA biosynthesis [9], deserves elucidation. In rice, Yaish et al. reported that over-expression of the APETALA-2-like transcription factor (TF) OsAP2-39 is associated with the up-regulation of the ABA biosynthetic gene OsNCED-I leading to an increase in endogenous ABA levels [10]. Among the five NCED genes in Arabidopsis, NCED3 plays a key role in ABA biosynthesis during water deficit [11,12], and NCED3 mutants exhibit increased water loss and reduced ABA levels at vegetative tissues [12]. Recently, Jiang et al. reported the identification of a gain-of-function acquired drought tolerance (adt) mutant to be a WRKY TF conferring increased drought tolerance, ABA levels and direct NCED3 promoter binding [13]. Apart from APETALA-2-like OsAP2–39 and adt, no other direct transcriptional regulators of NCED genes have been reported.

We previously highlighted NAC (petunia NAM and Arabidopsis ATAF1, ATAF2, and CUC2) TFs as components related to ABA and biotic stress signaling [6,14]. Overall, NAC genes encode a large, plant-specific family of TFs with roles in many aspects of growth, development and environmental stresses [15,16]. The N-terminal region of NAC proteins contains the highly conserved NAC domain encompassing a homo- and heterodimerization region indispensable for DNA-binding [17]. Moreover, a number of reports have identified core NAC
DNA-binding sites [18–20], and the consensus binding site (BS) \(|T[A,C,G]CGT[G,A]| \) has been proposed from studies of *Arabidopsis* ANAC019 [17]. Indeed, phylogenetically distant members of the NAC TF family bind this NAC-BS *in vitro*, albeit with various affinities [21]. This suggests that there may be non-canonical k-mers relevant for various NAC TF family members that are not yet defined.

NAC members of the ATAF1 clade of the NAC family exhibit strong and transient expression patterns to ABA treatment and environmental stress [22–24]. Additionally, ATAF1 is ubiquitously expressed in various organs, including stomatal guard cells [23]. We previously reported that ataf1 mutants are ABA-hyposensitive during seedling development and germination [14]. In line with this, plants over-expressing ATAF1 were shown to be ABA hypersensitive [24]. Also, ATAF1 was identified in a yeast two-hybrid screen to interact with Sucrose nonfermenting 1 (SNF1)-related serine/threonine-protein kinase 1 (SnRK1) subunits AKIN10 and AKIN11 [25], positive regulators of ABA metabolism and key integrators of transcription networks in response to stress and energy signaling [26,27].

To improve our understanding of the regulatory potential of ATAF1, we here delineate the DNA-binding specificity of ATAF1 using protein binding microarrays (PBM), co-expression analyses and chromatin-immunoprecipitation (ChIP). This identifies abscisic acid biosynthetic *NCED3* as an ATAF1 regulatory target gene. In plants over-expressing ATAF1, this correlates with increased *NCED3* transcript abundance and, most importantly, increased ABA phytomone levels. Taken together, our data indicate that ATAF1 is a regulator of ABA biosynthesis in *Arabidopsis*.

**Results**

**ATAF1 consensus-binding site**

We used protein-binding microarrays (PBM) as an unbiased strategy to search for ATAF1 consensus-binding motifs. PBM permits the identification of TF DNA binding specificities at single base resolution [28,29]. Since *Arabidopsis* NACs only bind DNA as dimers [17], we first established whether ATAF1 can homodimerize. Yeast-2-hybrid experiments showed that ATAF1 homodimerizes independently from the ATAF1 C-terminal transcriptional regulatory domain (Fig. 1A). We then holographically expressed and purified a GST-tagged version of the ATAF1 DNA-binding NAC domain (residues 1–165; Fig. 1B) and incubated PBMs using this protein. Subsequent PBM analysis identified T[A,C,G]CGT[A,G] and T[T,A,C,G]CGT 6-mers as the most significant descriptors for ATAF1 binding. The ATAF1 binding specificity position weight matrix (PWM), derived from all relevant 8-mers bound by ATAF1, is graphically illustrated in Fig. 1C (see also Supplementary Fig. S1).

![Fig. 1. ATAF1 homodimerization and consensus binding site. (A) Fusion proteins of Gal4-(DBD)-ATAF1(1–165), Gal4-(AD)-ATAF1(1–289), Gal4-(AD)-ATAF1(1–165), and empty Gal4-(DBD) were co-transformed, expressed in yeast, and screened after 7 days for transcription activity of H53 and ADE2 reporter genes. (B) SDS-PAGE and Coomassie Blue staining of gel molecular-mass-markers (lane 1; molecular masses in kDa at left) and approx. 5 μg of affinity-purified recombinant GST-ATAF1(1–165). (C) Consensus binding site of ATAF1 from duplicate PBM experiments.](https://example.com/fig1)

**ATAF1 directly regulates the abscisic acid biosynthetic gene *NCED3***

In addition to ABA-inducible expression, the list of ATAF1 co-expressed genes also includes the key regulatory ABA biosynthetic gene *NCED3*. We performed two experiments to investigate whether ATAF1 directly regulates ABA biosynthesis. First, to investigate the correlation between ATAF1 and ABA hormone biosynthesis in * planta*, we produced plants over-expressing ATAF1 (35S:ATAF1-HA). In agreement with earlier studies [24,25,34], these plants showed stunted growth and delayed flowering (Fig. 3A–C, and Supplementary Fig. S2). The observed phenotype of these plants correlated with increased ATAF1 transcript levels and were not associated with transgene silencing of ATAF1 and other ABA subclade members, as reported by Kleinow et al. [25], Figs. 3B and 4A. Using these plants, we observed ATAF1 over-expressing plants to have significant (approx. 6- and 7.5-fold) increased ABA levels (P < 0.01) compared to wild-type and ataf1 mutants, respectively (Fig. 3D).

Second, to determine whether ATAF1 binds the promoter of *NCED3* in vivo, we performed ChIP on wild-type and 35S:ATAF1-HA plants (Fig. 3A). Subsequent qPCR identified a region (position ~1134 to ~1265 bp) including a TGGCGTA ATAF1 binding motif to be enriched in ChIPs from ATAF1 over-expressing plants (Fig. 3E). ATAF1 did not bind a region between ~120 and ~218 bp (non-binding; NB), confirming ATAF1 binding specificity. As a technical control, the FT locus targeted by the HA-tagged TFL2 TF was included [35] (Fig. 3E). Finally, to assess the regulatory potential of ATAF1 we determined the transcript levels of *NCED3* and found ~10-fold increase in ATAF1 over-expressing plants compared to wild-type. In contrast, mean *NCED3* levels were significantly lower in ataf1 mutants (Fig. 3F), substantiating the strong positive correlation between ATAF1 and *NCED3* transcript levels (Fig. 2A). In addition to *NCED3*, transcript levels of several other top-ranking ATAF1 co-expressed genes displayed ATAF1-dependent expression perturbations, though with a narrower dynamic range compared to *NCED3* (Fig. 4B).

![Fig. 1. ATAF1 homodimerization and consensus binding site. (A) Fusion proteins of Gal4-(DBD)-ATAF1(1–165), Gal4-(AD)-ATAF1(1–289), Gal4-(AD)-ATAF1(1–165), and empty Gal4-(DBD) were co-transformed, expressed in yeast, and screened after 7 days for transcription activity of H53 and ADE2 reporter genes. (B) SDS-PAGE and Coomassie Blue staining of gel molecular-mass-markers (lane 1; molecular masses in kDa at left) and approx. 5 μg of affinity-purified recombinant GST-ATAF1(1–165). (C) Consensus binding site of ATAF1 from duplicate PBM experiments.](https://example.com/fig1)
Collectively, our data indicate that ATAF1 activates ABA hormone biosynthesis in plants, through transcriptional activation of NCED3.

Discussion

Here we identify ATAF1 as a positive regulator of ABA biosynthesis. We show that ATAF1 and NCED3 are co-expressed, and that ATAF1 binds the NCED3 promoter in vivo. Most importantly, ATAF1-mediated induction of NCED3 in plants over-expressing ATAF1 correlates with increased ABA levels. In support of our observations, ATAF1 exhibits strong expression in stomatal guard cells and in the vasculature [23], and plants over-expressing ATAF1 have reduced stomatal aperture [24]. Interestingly, NCED3 has a constrained spatial expression in vascular tissues [30], yet transient expression of NCED3 in guard cells causes a decrease in stomatal aperture [37]. Hence, both at the transcript level and at the physiological level, the overlap between ATAF1 and NCED3 abundances and functionalities is evident. Hypersensitivity to ABA and increased endogenous ABA levels are often associated with increased tolerance to salt and drought stresses [38,39]. Thus, reduced ABA levels in plants may be associated with drought sensitivity [40]. We have previously reported that ataf1 mutants are ABA-hyposensitive during seedling development and germination [14], and plants over-expressing ATAF1 have been shown to be hypersensitive to ABA and drought tolerant [24]. Moreover, plants over-expressing ATAF1 display stunted growth and delayed flowering, alike ABA-hypersensitive plants over-expressing the ATAF1 interaction partner SnRK1.1/AKIN10 [25,26,41]. This agrees with reports on ABA-deficient mutants displaying early flowering [42], and exogenous ABA application to delay flowering [43].

In addition to NCED3, several other ATAF1 co-expressors showed displayed ATAF1-dependent expression perturbations. Specifically, significant changes in expression levels of both ABI2 and DREB2A were observed in aaf1–2 and ATAF1-overexpressing plants, respectively, compared to wild-type plants (Fig. 4B). DREB2A encodes a transcription factor regulating drought and osmotic-inducible genes [44,45], and ABI2, and other clade A type 2C protein phosphatases (PP2Cs), are known to be negative regulators of ABA signaling by dephosphorylation of ABA-activated Sucrose nonfermenting 1 (SNF1)-related serine/threonine-protein kinases (SnRKs) [46–48]. We speculate that the positive correlation between ATAF1 and transcript levels of genes encoding PP2Cs (Fig. 2, Table 1, and Fig. 4A) may reflect a negative feed-back loop needed to dampen the increased endogenous ABA

### Table 1

Top 25 ATAF1 co-expressed genes.

<table>
<thead>
<tr>
<th>AGI</th>
<th>Pear. corr. coeff</th>
<th>Description</th>
<th>TTVCGT</th>
<th>TVCGTR</th>
</tr>
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<tr>
<td>AT5G61820</td>
<td>0.7855</td>
<td>Unknown protein</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>AT5G05410</td>
<td>0.7050</td>
<td>DRE-binding protein 2A (DREB2A)</td>
<td>+</td>
<td></td>
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<td>AT1G77450</td>
<td>0.7477</td>
<td>NAC domain containing protein 32</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AT3G19580</td>
<td>0.7384</td>
<td>Zinc-finger protein 2</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AT3G62260</td>
<td>0.7287</td>
<td>Protein phosphatase 2C family protein</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AT5G59220</td>
<td>0.7167</td>
<td>Highly ABA-induced PP2C gene 1 (HA1)</td>
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<td>+</td>
</tr>
<tr>
<td>AT5G63790</td>
<td>0.7147</td>
<td>NAC domain containing protein 102</td>
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<td>+</td>
</tr>
<tr>
<td>AT3G17770</td>
<td>0.7132</td>
<td>Dihydroxyacetone kinase</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AT1G61340</td>
<td>0.7052</td>
<td>F-box family protein</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AT1G21410</td>
<td>0.7037</td>
<td>F-box/RING-like superfamily protein</td>
<td>+</td>
<td>+</td>
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<tr>
<td>AT5G02020</td>
<td>0.6946</td>
<td>Encodes a protein involved in salt tolerance, names SIS</td>
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<td>Unknown protein</td>
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<td>+</td>
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<tr>
<td>AT2G33700</td>
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<td>Protein phosphatase 2C family protein</td>
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<td>+</td>
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<tr>
<td>AT4G27410</td>
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<td>NAC (No Apical Meristem) domain protein</td>
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<td>+</td>
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<tr>
<td>AT1G05100</td>
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<td>Mitogen-activated protein kinase kinase kinase 18</td>
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<td>+</td>
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<tr>
<td>AT5G62020</td>
<td>0.6889</td>
<td>Heat shock transcription factor B2A</td>
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<td>+</td>
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<tr>
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<td>Cysteine proteinases superfamily protein</td>
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<td>+</td>
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<td>AT3G14440</td>
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<td>Nine-cis-epoxydocotenoid dioxygenase 3 (NCED3)</td>
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<td>+</td>
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<tr>
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<td>Glutaredoxin family protein</td>
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<td>+</td>
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<td>AT5G04340</td>
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<td>Zinc finger of Arabidopsis thaliana 6</td>
<td>+</td>
<td>+</td>
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<tr>
<td>AT1G60190</td>
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<td>ARM repeat superfamily protein</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AT4G23050</td>
<td>0.6556</td>
<td>PAS domain-containing tyrosine kinase protein</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

* Using 403 microarray samples from 87 different conditions where ATAF1 was >2-fold regulated in treated samples compared to control samples.

* V = [A,C,G] and R = [A,G]. + indicates number of ATAF1 binding 6-mers in 1 kb promoters.
Fig. 3. Ectopic expression of *ATAF1* arrests plant development and activates ABA biosynthesis. (A) Eight week-old short-day grown Col-0 wild-type and ataf1–2, compared to plants ectopically expressing HA-tagged *ATAF1*. Two independent 35S:*ATAF1*-HA lines (1:3 and 3:1) display growth reduction. (B) Quantitative expression profiles of endogenous and ectopic *ATAF1* in Col-0 wild-type, ataf1–2 and 35S:*ATAF1*-HA plants. Mean (±SEM) relative expression units (log 10 scale) are displayed using ACT2 as reference. Bars represent the mean of three biological replicates. (C) Expression of HA-tagged *ATAF1* using SDS–PAGE and Western blot. The blot was probed with an anti-HA antibody. Representative result from three replicates is shown. The unspecific band at 37 kDa serves as a loading control. (D) Endogenous levels of ABA were measured. Bars represent the mean of three biological replicates. Error bars represent ±1 standard deviation. Statistical analyses were performed using Student’s t-test of the differences between individual means compared to Col-0 (**P < 0.01). (E) Direct binding of *ATAF1* to the NCED3 promoter (between position -1136 and -1265 bp) was analyzed using ChIP-qPCR on 35S:*ATAF1*-HA over-expressing (ATAF1-HA) and Col-0 wild-type plants. A non-binding control (NB) 1 kb downstream of the ATAF1–NCED3 binding site, and a positive TFL2 TF binding-site control (FLOWERING LOCUS T (FT), [35]) were included. The ChIP results obtained by three independent replicate experiments are reported as percentage of input (%IP), and the error bars indicate ±1 standard deviation. (F) Expression of ABA biosynthetic gene NCED3 in *ATAF1* over-expressing plants compared to wild-type Col-0 and ataf1 mutants. Expression level of NCED3 was determined by qPCR in the indicated genotypes. Mean (±SEM) relative expression units are displayed using ACT2 as reference. Statistical analyses were performed using Student’s t-test of the differences between individual means compared to Col-0 (**P < 0.05, ***P < 0.01).

Fig. 2. *ATAF1* co-expression gene cluster is enriched for *ATAF1* binding sites. (A) Using 403 microarray samples from 87 conditions either significantly inducing or repressing *ATAF1* expression, identifies 25 co-expressed genes with a Pearson correlation coefficient > 0.66. (B) Bootstrapping analyses using POBGO [33] show that promoters of *ATAF1* co-expressed genes are significantly (P < 0.001) enriched for *ATAF1* consensus binding sites T[A,C,G][C][T][A,G] and T[A,C,G][C][T].

levels associated with *ATAF1* induction or over-expression.

Finally, we note that our unbiased PBM-approach recovered a binding-site similar to that reported for ANAC019 [17], and that functional redundancy has been reported for NAC TFs [49,50]. Overlapping polymorphisms within NAC binding sites, could also explain why residual *NCED3* and ABA levels are observed in *ataf1* mutant plants (Fig. 3D and F). This also includes the potentially physiologically relevant *ATAF1–ATAF2* heterodimerization reported by Wu et al. [24], and Supplementary Fig. S4). However, using PBM to uncover binding site preferences for all basic helix-loop-helix (bHLH) TFs from *C. elegans*, none of the bHLH proteins that participate in heterodimeric interactions were shown to exhibit significant sequence-specific DNA binding on their own [51]. In our study, *ATAF1* on its own shows sequence specificity to DNA-binding (Fig. 1C). Knowing that dimerization-deficient NAC mutants do not bind DNA [17], this indicates that top-ranking oligomers in this study are bona fide targets of *ATAF1* homodimers. In combination with stringent co-expression analysis using hundreds of genome-wide expression data sets, our data emphasize the value of in vitro-defined oligomers in estimating TF binding sites and identification of target genes. Ideally, probing all plant TFs using such analyses should uncover the complex transcriptional imprint required to fine-tune plant hormone homeostasis.
Fig. 4. Expression perturbations of ATAF subclade members and ATAF1 co-expressed genes. (A) Expression of genes encoding ATAF subclade NAC TFs. Expression level of candidate genes was determined by qPCR in the indicated genotypes. Mean (± SEM) relative expression units are displayed using ACT2 as reference. Bars represent the mean of three biological replicates. (B) Expression of ATAF1 co-expressed genes in ATAF1 over-expressing plants compared to wild-type Col-0 and ataf1 mutants. Statistical analyses were performed using Student’s t-test of the differences between individual means compared to Col-0 (*P < 0.05).

Methods and materials

Plant materials and growth conditions

Arabidopsis thaliana wild-type accession Col-0 and ataf1–2 mutant plants (T-DNA insertion line SALK-057618) [23], were grown on soil in controlled environment chambers under an 8 h light regime (150–170 μE/m2 s) at 21 °C and 65% relative humidity.

Plasmid construction and plant transformation

The ATAF1-HA C-terminally tagged gene was generated by amplifying a full-length ATAF1 cDNA obtained from ABRC with forward and reverse primers; AAGAATTCCATTCAGAGATTATTAATGTGCG and CCGGATCCCAAGCTTATGGTCCGCAATCGTCCG-GATCGTAC, respectively, and cloned into pCAMBIA3300. Transformation of Col-0 plants was performed by the floral dip method [52] using Agrobacterium tumefaciens strain GV3101 (pMP90). Transgenic plants were selected by BASTA spraying, and homozygous T3 seeds from transormants expressing transgenes were used for subsequent analyses. The 35S:ATAF1-HA construct used in this study complements the ataf1 mutations [14], indicating that the addition of the HA epitope does not impair ATAF1 function.

Protein expression and purification

N-terminally GST-tagged, recombinant ATAF1(1–165) was cloned, expressed and purified as described [21].

Protein binding microarray

Microarray design, preparation, and PBM experiments were performed as described previously by Berger and Bulyk [53]. All experiments were performed using custom-designed “all 8-mer” arrays synthesized in a “4 × 44K” array format (Agilent Technologies, CA, USA) containing 4 copies of publicly available de Bruijn sequences [28,54]. Briefly, 200 nM of GST-ATAF1(1–165) protein was incubated on the microarray for 60′ at RT. TF–DNA interactions were detected by first incubating the array with a rabbit anti-GST polyclonal antibody (Invitrogen), followed by a Cy5 labeled anti-rabbit antibody (Jackson-Immuo, PA, USA). Blocking, protein binding and washing procedures were identical to standard PBM protocols [53].

Protein binding microarray data normalization and motif analysis

Microarrays were scanned using a SureScan scanner at a 2 μm resolution (Agilent Technologies, CA, USA), and spot intensities retrieved using Feature Extraction Software (Agilent Technologies, CA, USA). Data normalization and analysis were performed as described previously [53]. Resulting PWMs were graphically visualized using enoLOGOS [55].

Western blotting

Nuclear extracts were precipitated over-night with 80% acetone and proteins resuspended and boiled in SDS–PAGE loading buffer. Supernatants were separated by SDS–PAGE and proteins detected by Western blotting using monoclonal mouse anti-HA antibody (Sigma, MO, USA).

Yeast two-hybrid assays and qPCR analyses

Both methods were as described in [21]. Primers used to clone ATAF1(1–165) into pGBK7 were AAGAATTCCATTCAGAGATTATTAATGTGCG and CCGGATCCCAAGCTTATGGTCCGCAATCGTCCG-GATCGTAC. Primers for pGADT7-ATAF1(1–165) and pGADT7-ATAF1(1–289) used forward primer AAGAATTCCATTCAGAGATTATTAATGTGCG and reverse primers were CCGGATCCCAAGCTTATGGTCCGCAATCGTCCG-GATCGTAC, respectively. For quantitative real-time PCR (qPCR), Actin2 (ACT2) was used as a reference. For NCED3 we used AGCTCTTATACGGAACCGGAGCGCTCCTTGAATGCT, respectively. For quantitative real-time PCR (qPCR), Actin2 (ACT2) was used as a reference. For NCED3 we used AGCTCTTATACGGAACCGGAGCGCTCCTTGAATGCT, respectively. For quantitative real-time PCR (qPCR), Actin2 (ACT2) was used as a reference. For NCED3 we used AGCTCTTATACGGAACCGGAGCGCTCCTTGAATGCT, respectively.
MS–LC for hormone quantifications

Quantifications were performed as described [58]. Statistical analyses were performed using Student's t-test (**P < 0.01).

Accession numbers

The following accession codes were used: ATAF1, At1g01720; FL, At1g65480; NCED3, At3g14440.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fob.2013.07.006.

References


