Increasing cyclic electron flow is related to Na\(^+\) sequestration into vacuoles for salt tolerance in soybean

Yi He\(^1\), Junliang Fu\(^1\), Chenliang Yu\(^1\), Xiaoman Wang\(^1\), Qinsu Jiang\(^1\), Jian Hong\(^3\), Kaixing Lu\(^4\), Gangping Xue\(^6\), Chengqi Yan\(^5\), Andrew James\(^6\), Ligen Xu\(^1\), Jianping Chen\(^5\) and Dean Jiang\(^1\),\(^*\)

\(^1\) State Key Laboratory of Plant Physiology and Biochemistry, College of Life Sciences, Zhejiang University, Hangzhou 310058, China
\(^2\) Department of Plant Sciences, University of Cambridge, Cambridge CB2 3EA, UK
\(^3\) Institute of Biotechnology, Zhejiang University, Hangzhou 310058, China
\(^4\) Laboratory of Plant Molecular Biology, Ningbo University, Ningbo 315211, China
\(^5\) State Key Laboratory Breeding Base for Zhejiang Sustainable Pest and Disease Control, Institute of Virology and Biotechnology, Zhejiang Academy of Agricultural Sciences, 310021 Hangzhou, China
\(^6\)CSIRO Agriculture Flagship, Queensland 4067, Australia

\(^*\) To whom correspondence should be addressed. E-mail: dajiang@zju.edu.cn

Received 25 May 2015; Revised 17 July 2015; Accepted 24 July 2015

Editor: Hideki Takahashi

Abstract

In land plants, the NAD(P)H dehydrogenase (NDH) complex reduces plastoquinones and drives cyclic electron flow (CEF) around PSI. It also produces extra ATP for photosynthesis and improves plant fitness under conditions of abiotic environmental stress. To elucidate the role of CEF in salt tolerance of the photosynthetic apparatus, Na\(^+\) concentration, chlorophyll fluorescence, and expression of NDH B and H subunits, as well as of genes related to cellular and vacuolar Na\(^+\) transport, were monitored. The salt-tolerant *Glycine max* (soybean) variety S111-9 exhibited much higher CEF activity and ATP accumulation in light than did the salt-sensitive variety Melrose, but similar leaf Na\(^+\) concentrations under salt stress. In S111-9 plants, *ndhB* and *ndhH* were highly up-regulated under salt stress and their corresponding proteins were maintained at high levels or increased significantly. Under salt stress, S111-9 plants accumulated Na\(^+\) in the vacuole, but Melrose plants accumulated Na\(^+\) in the chloroplast. Compared with Melrose, S111-9 plants also showed higher expression of some genes associated with Na\(^+\) transport into the vacuole and/or cell, such as genes encoding components of the CBL10 (calcineurin B-like protein 10)–CIPK24 (CBL-interacting protein kinase 24)–NHX (Na\(^+\)/H\(^+\) antiporter) and CBL4 (calcineurin B-like protein 4)–CIPK24–SOS1 (salt overly sensitive 1) complexes. Based on the findings, it is proposed that enhanced NDH-dependent CEF supplies extra ATP used to sequester Na\(^+\) in the vacuole. This reveals an important mechanism for salt tolerance in soybean and provides new insights into plant resistance to salt stress.

Key words: ATP, CEF, Na\(^+\) accumulation, NDH complex, soybean.

Introduction

Soil salinity represents an increasingly prominent problem in agriculture. It is estimated that at least one-third of the irrigated land in the world is now affected by salinity (Zhu, 2001; Munns and Tester, 2008). Because it is physically difficult to remove salt from the soil, improving crop tolerance to high salt becomes a critical task for breeders, and
identifying molecular components conferring salt tolerance in plants can provide genetic markers for achieving this goal. Salinity affects plant growth by inducing secondary stresses such as metabolic toxicity, attenuated nutrient acquisition, membrane disorganization, accumulation of reactive oxygen species (ROS), and inhibition of photosynthesis (Hasegawa et al., 2000). Meanwhile, salt injury to plants is caused by ionic toxicity that is specific to a particular ion (such as Na+) and by osmotic stress (Yeo, 1998; Hasegawa et al., 2000).

Salt tolerance in plants requires three interconnected cellular functions that (i) prevent or alleviate damage, (ii) re-establish homeostatic conditions in the new, stressful environment, and (iii) resume growth, albeit at a reduced rate (Zhu, 2001). Although salt-tolerant plants display complex molecular responses, these processes generally consume ATP. In plants, ATP is one of the most important products of photophosphorylation, which is a highly regulated process that integrates different electron transfer pathways to convert light energy into ATP and NADPH and balance this production of chemical energy with its utilization (Johnson et al., 2014). In addition, photosynthesis is the most important source of plant dry matter production. Accordingly, maintaining a high photosynthetic rate is important to protect the photosynthetic apparatus from damage by excess light energy and ROS under stress conditions.

During plant evolution, the photosynthetic thylakoid membrane systems developed mechanisms to adapt to stress conditions (Münné-Bosch et al., 2005; Takabayashi et al., 2009). One of the available pathways for photoprotection is to accelerate cyclic electron flow (CEF) around PSI (Shikanai et al., 1998; Horváth et al., 2000; Munekage et al., 2004). Plants have two known pathways for CEF: the protein gradient regulation 5 (PGR5)/PGR-like 1 (PGRL1)–ferredoxin (Fd)-dependent pathway and the NAD(P)H dehydrogenase (NDH) complex-dependent pathway (Johnson et al., 2014). Examination of mutants in Arabidopsis thaliana showed that efficient photosynthesis requires PGR5/PGRL1–Fd-dependent CEF (Munekage et al., 2004). In contrast, knockout err mutations (impaired NDH activity) do not affect overall photosynthetic electron transport and phenotypes (Munekage et al., 2004), indicating that NDH complex-mediated CEF may not participate in normal photosynthetic processes. Instead, many studies have demonstrated that NDH complex-mediated CEF may play a critical role in protecting the photosynthetic apparatus under stress conditions (Wang et al., 2006; Yang et al., 2007; Huang et al., 2011). The amounts of the NDH complex significantly increase in Hordeum vulgare (barley) under photo-oxidative and osmotic stress (Casano et al., 2001; Guéra et al., 2005) and in Avena sativa (oat) under high light stress (Quiles, 2006). In addition, increased amounts of NDH complex in high mountain plant species may enhance adaptation to high light intensity and low temperature (Streb et al., 2005). Moreover, the NDH complex has been suggested to supply extra ΔpH of thylakoid membranes and additional ATP for optimal photosynthesis under stress conditions when CO₂ assimilation is limited (Wang et al., 2006; Shikanai, 2007). These results support the hypothesis that the NDH complex contributes to enhancing photosynthesis and stress tolerance under stress conditions. However, how the NDH complex might function in alleviating salt stress injury to plants, and its relationship to ATP biosynthesis from NDH-dependent CEF and to Na⁺ accumulation in the leaf all remain controversial.

It was previously reported that S111-9 soybean, a somatic hybrid descended from wild soybean ACC547 (cytoplasm donor) and Melrose cultivar (nucleus donor), partially inherited salt stress tolerance, maintaining a higher net photosynthetic rate and increased CEF in leaves compared with controls at the same leaf Na⁺ concentration (Yang et al., 2007). It was also found that Na⁺ accumulated in mesophyll cells of S111-9 and Melrose. High concentrations of Na⁺ in plant cells inhibit the activities of many enzymes (Tester and Davenport, 2003), so it is important to prevent Na⁺ from accumulating in cytoplasm and organelles other than the vacuole. These observations support the possibility of a mechanism that increases Na⁺ accumulation in the vacuole of salt-tolerant soybean S111-9.

The aim of this study was to clarify whether NDH-dependent CEF contributes to ATP biosynthesis, Na⁺ transport, and Na⁺ accumulation in mesophyll cells. The findings indicated that in S111-9 under salt stress, but not in Melrose, enhanced NDH-dependent CEF produces additional ATP, which is required for Na⁺ accumulation in the vacuole.

Materials and methods

Plant growth conditions

The salt-sensitive cultivar Melrose (Glycine max) and the salt-tolerant line S111-9, a stable line selected from somatic hybrid descendants of wild salt-tolerant ACC547 (G. cyrtoloba; Yang et al., 2007), were used in this study. When the first pair of leaves was fully expanded, the seedlings were transplanted into complete nutrient solution and cultured at 25/22 °C (12 h light/12 h dark) with ~70% relative humidity in a growth chamber. For experiments, 25-day-old plants were selected and transferred to complete culture solution (He et al., 2014; Wang et al., 2015) with 0 or 150 mM NaCl. The third fully expanded leaves were used for all analyses.

Visualization of Na⁺ ions

The third leaves of 25-day-old plants after salt treatment were cut into pieces (~5 × 2 mm), which were fixed on the plates with 2.5% (w/v) agar. Then, agar blocks with leaf pieces were cut from plates and placed on a vibratome for preparation of 140 μm thin sections. The sections were stained with 20 μM CoroNa Green AM (Invitrogen) in the presence of a final concentration of 0.02% (w/v) pluronic acid (Invitrogen) for 3 h (Oh et al., 2009). Where indicated, 5 μM FM4-64 (Invitrogen) was added after incubation with CoroNa Green (incubation for ~20–30 min with FM4-64). The palisade layer cells were selected for observation and all sections were observed by confocal microscopy (Zeiss LSM-710).

Elemental analysis

Tissue samples were collected and dried at 65 °C for 72 h to yield ~0.5 g of tissue for elemental analysis. After cooling, each sample was weighed and 0.1 g was used for analysis. All samples were digested with 6 ml of concentrated HNO₃ (68%, Sangon). After digestion, all samples were diluted to 50 ml with 18 MΩ water. The leaf, stem, and root tissue concentrations of Na⁺, K⁺, and Ca²⁺ were measured by inductively coupled plasma mass spectrometry
The supernatant was loaded onto a 1 g for 30 samples were centrifuged at 15 000 g. The subsequent steps were: Tris–HCl, pH 7.5, 0.3 M containing 30 and anti-NDH-H were confirmed as specifically binding antibodies. The synthesized peptide of 15 amino acids (DLTSDQKDISWFYFC) was 0.2 M thiogalactopyranoside at OD650 between 0.4 and 0.6, and cells were binant protein was induced by addition of 1 HI and Sal Bam B.Cells were bulked and resuspended in buffer A [50 mM NaCl, 7 mM β-mercaptoethanol, and 1 mM PMSF (phenylmethylsulphonyl fluoride)] (Yang et al., 2007). Redox changes of P700 were monitored by absorbance changes at 810–830 nm, and the t1/2 of P700’ re-reduction following far-red light (>705 nm, 5.2 μmol m–2 s–1) exposure for 1 min was calculated (Klughammer and Schreiber, 1998).

**Measurement of chlorophyll fluorescence and redox changes of P700**

The plants were adapted in the dark for 30 min prior to measurement. Chlorophyll (Chl) fluorescence and redox changes of P700 were performed using a Dual-PAM 100 Chl fluorescence analysr (Heinz Walz, Effeltrich, Germany) as described in Wang et al. (2006). The post-illumination transient increase in Chl fluorescence was determined according to the procedure described previously (Mi et al., 1995; Shikanai et al., 1998). Soybean plants were kept at 25 °C and third intact leaves were used for measurement, which were also utilized for assessment of redox changes of P700. Weak modulated irradiation (<0.1 μmol m–2 s–1) was used to determine F0. Subsequently, a saturating light (>7000 μmol m–2 s–1) flash was given to determine Fm, and then actinic light (1000 μmol m–2 s–1) was turned on. After 3 min, the actinic light was turned off and fluorescence yield changes were continuously recorded (Yang et al., 2007). Redox changes of P700 were monitored by absorbance changes at 810–830 nm, and the t1/2 of P700’ re-reduction following far-red light (>705 nm, 5.2 μmol m–2 s–1) exposure for 1 min was calculated (Klughammer and Schreiber, 1998).

**Determination of ATP content**

To determine ATP content in leaves, the third leaves were collected and 0.1 g samples were placed in 10 ml tubes, with 2 ml of Tris–HCl (pH 7.8). The tubes with samples were kept for 10 min at 100 °C in a boiling water bath for ATP extraction. Then, the samples were kept at room temperature for cooling and 10 μl of ATP extraction solution was used for analysis. The ATP standard curve was obtained using standard ATP samples in an ENLITEN ATP Assay Kit (Cat. FF2000, Promega) by a GloMax 20/20 Luminometer (Promega). The ATP content of all samples was calculated via the ATP standard curve, as determined with the weight of samples and solution concentrations. The detailed procedures were performed following the instructions in the ENLITEN ATP Assay System.

**Antibody preparation**

The full-length ndhH sequence was cloned by PCR from cDNA with the primers 5’-GGAATTCATGAAATACCTCAACTACAAGA-3’ and 5’-GTCGACTCAAGCTAATCTTCTCCCA-3’ (underlining indicates Bam and Sbf I sites, respectively). The amplified fragment was ligated into pGEX-4T-2 vector for production of glutathione S-transferase and the thrombin target at the N-terminus of NDH-H. The full-length ndhB-GGAATTGTTTGAT CTTAAAGGGGGCTT CGATAATTTCGC-3’; ndhH-5’-GGGTTTGTGCAC CAATATCT GCCATAAAAAGTCTCTAGCC-3’) are completely complementary to ndhB and ndhH, respectively.

**Quantitative real-time PCR**

RNA was extracted from three biological replicates of 25-day-old soybean plants using RNAiso Reagent (TaKaRa). cDNA was synthesized from 1 μg of DNase-treated RNA with the TaKaRa First Strand cDNA Synthesis Kit using oligo(dT) primers. Technical replicates of gene-specific products were amplified in 10 μl reactions using the Rotor-Gene SYBR Green PCR Kit on a Rotor-Gene 6000 Real-Time PCR machine fitted with a Rotor-Disc 72 (Qiagen). Primer sequences are described in Supplementary Table S2 available at JYB online. Relative transcript levels were determined by incorporating PCR efficiencies as described previously (Talke et al., 2006).

**Measurements of vacuolar H+–ATPase activity**

The V-ATPase activity was determined by the detailed method described by Tang et al. (2012). Leaf microsomal fractions were prepared from 25-day-old hydroponically grown plants treated or not with thienoyltrifluoroacetone (TTFAs). Plant materials were ground with cold homogenization buffer containing 350 mM sucrose, 70 mM Tris–HCl (pH 8.0), 3 mM Na2EDTA, 0.2% (w/v) BSA, 1.5% (w/v) polyvinylpyrrolidone (PVP)-40, 5 mM DTT, 10% (v/v) glycerol, 1 mM PMSF, and 1× protease inhibitor mixture (Roche). The homogenate was filtered through four layers of Microcloth (Calbiochem, Cat. 475855) and centrifuged at 4000 g for 20 min at 4 °C. The supernatant was filtered through Microcloth again and then centrifuged at 100 000 g for 1 h. The resulting microsomal pellet was resuspended in 350 mM sucrose, 10 mM Tris–MES (pH 7.0), 2 mM DTT, and 1× protease inhibitor mixture. The V-ATPase activity of 10 μg of microsomal membranes was determined as phosphate (P) release after 40 min incubation at 28 °C. V-ATPase activity was calculated as the value difference between the measurements in the absence and the presence of 200 mM concanamycin A plus 50 mM NaN3. The reaction was colorimetrically examined at 355 nm.
Statistical methods

All assays described above were repeated at least three times on three biological replicates. For multiple comparisons, the data first were examined by one-way ANOVA to check the equality of variance (Levene test), and then Tukey’s multiple comparison tests were used to determine the significant difference ($P<0.05$) of means with the SAS 8.0 statistical software package (SAS Institute, Inc., Cary, NC, 2000; He et al., 2014).

Results

Effect of salt stress on phenotype and the accumulation of Na$^+$ in mesophyll cells

To compare the salt resistance of different genotypes, S111-9 and Melrose soybean plants were cultured in nutrient solution with 150 mM NaCl. After 2 d of salt stress, chlorosis and necrotic lesions appeared in the leaves of Melrose but not of S111-9 (Fig. 1A; see red asterisks). Melrose plants also lost more water than did S111-9 (Supplementary Fig. S1 at JXB online) and showed visible wilting after salt stress. Staining with CoroNa Green, an indicator of Na$^+$ concentration, showed that although the fluorescence signal intensity increased significantly in both varieties upon salt stress (Fig. 1B), there was no obvious different between both varieties. Together, the above results provided further evidence that S111-9 had higher tolerance to salt stress than Melrose.

Changes in the concentration and distribution of Na$^+$, K$^+$, and Ca$^{2+}$ in the whole plant

The concentrations of Na$^+$, K$^+$, and Ca$^{2+}$ were measured by ICP-MS. After 4 h salt stress, the Na$^+$ concentration increased in roots from ~0.05 mmol g$^{-1}$ DW to 0.4 mmol g$^{-1}$ DW in both varieties (Fig. 2C). Although the S111-9 roots had a significantly lower Na$^+$ concentration than the Melrose roots at 4 h and at 1 d salt stress, the two varieties showed no difference after 2 d salt stress. The concentrations of Na$^+$ in leaves and stems also increased significantly in both varieties after 1 d salt stress. Although the Na$^+$ concentration of Melrose leaves was significantly higher than that in S111-9, the difference in absolute values became smaller after 2 d treatment. However, stems showed the opposite tendency, with S111-9 showing a larger increase than Melrose (Fig. 2A, B), to 1.13 mmol g$^{-1}$ DW and 1.06 mmol g$^{-1}$ DW in the stems of S111-9 and Melrose, respectively (Fig. 2B) after 2 d stress. After 2 d salt stress, the leaf K$^+$ concentration in Melrose decreased significantly compared with that in S111-9, and the leaf K$^+$ concentration in S111-9
Electron flow, \( \text{Na}^+ \) sequestration, and salt stress

returned to the level observed at 4h salt stress (Fig. 2D). This change in \( K^+ \) concentration affected the \( K^+/Na^+ \) ratio (Supplementary Fig. S2 at JXB online) and might thus affect \( Na^+ \) transport and accumulation in vacuoles of mesophyll cells. The \( K^+ \) concentration in stems and leaves of both varieties showed the same trends, but, after salt treatment, Melrose roots had a much higher \( K^+ \) concentration than did S111-9 roots. The \( Ca^{2+} \) concentration in leaves (Fig. 2G) also significantly increased in both varieties after salt treatment, but it decreased in stems and roots (Fig. 2H, I) after 1 d or 2 d salt stress. Regression analysis showed a significant negative correlation between \( Na^+ \) and \( K^+ \) in leaf and stem of Melrose, in roots of S111-9, and between \( Na^+ \) and \( Ca^{2+} \) in stems and roots of Melrose and in stems of S111-9 (Supplementary Table S1).

Effect of salt stress on NDH activity and ATP contents

NDH activity was measured in vivo by measuring the post-illumination transient increase in Chl fluorescence after turning off actinic light, an increase that is due to NDH-dependent reduction of the plastoquinone pool in darkness (Munekage et al., 2004). The results showed no difference in the increase in Chl fluorescence between the two varieties before salt stress (Fig. 3A, B). However, the increase rapidly became greater in both S111-9 and Melrose after salt stress. Compared with the unstressed plants, the increase of Chl fluorescence was ~6-fold more in S111-9, but only 2-fold more in Melrose after 2 d salt stress. These results indicated that under salt stress, NDH-dependent CEF activity increased faster in salt-resistant S111-9 plants than in salt-sensitive Melrose plants.

The dark re-reduction of \( P700^+ \) is often used as another indicator of CEF (Burrows et al., 1998; Nakamura et al., 2013). The dark re-reduction of \( P700^+ \) was measured and the \( t_{1/2} \) of \( P700^+ \) re-reduction was calculated in both varieties after treatment with 150 mM \( NaCl \) in the absence and the presence of 100 \( \mu M \) TTFA (an inhibitor of NDH-mediated plastoquinone reduction in cyanobacteria and \( Chlamydomonas reinhardtii \) (Godde, 1982; Mi et al., 1994) (Fig. 3C, D). Under salt stress, there was a greater decrease in the \( t_{1/2} \) of \( P700^+ \) re-reduction in S111-9 (going from 2.17 s without salt stress to 1.10 s with salt stress) than in Melrose (going from 2.07 s to 1.73 s) in the absence of 100 \( \mu M \) TTFA (Fig. 3C), and there was a significant difference between the varieties. Although there was still a difference between the varieties in the presence of 100 \( \mu M \) TTFA, the difference (going from 2.22 s to 1.70 s in S111-9 and from 2.32 s to 1.90 s in Melrose) was obviously smaller than that in the absence of 100 \( \mu M \) TTFA, which implied that the CEF was attenuated by TTFA. This provided more evidence that salt stress stimulated CEF much more in S111-9 than in Melrose, and TTFA could partly inhibit the CEF activity.
To investigate whether enhanced CEF could promote ATP production, ATP contents were measured in the light, which reflects ATP produced by both photosynthetic and oxidative phosphorylation, and in darkness, which mainly reports ATP produced by oxidative phosphorylation. Therefore, the difference between the light and dark ATP production represents the ATP accumulation from photophosphorylation. In light conditions, S111-9 showed significantly higher ATP contents than Melrose after salt stress (Fig. 4A). ATP production remained stable in S111-9 (~12 nmol g⁻¹ FW), and decreased significantly in Melrose after 1 d and 2 d salt stress (Fig. 4A). The difference in ATP accumulation in light compared with in darkness was much greater in S111-9 than in Melrose (Fig. 4B). Moreover, the light-mediated portion of the ATP content of S111-9 rose markedly to 8.7 nmol g⁻¹ FW after 2 d salt stress, whereas it significantly decreased in Melrose (Fig. 4B) after salt stress. Additionally, in the presence of 100 μM TTFA, ATP content in the light and light-related ATP content were decreased by ~15–25% (Fig. 4C, D). All of these findings indicated that the increased ATP content in the light might be produced by cyclic photophosphorylation via enhanced CEF in S111-9.

Effect of salt stress on the protein and mRNA abundance of NDH-B and NDH-H

It was further investigated whether the increased ATP content in S111-9 under salt stress could be attributed to enhanced CEF caused by increased accumulation of the NDH complex. The amounts of NDH-B and NDH-H are often used to monitor the accumulation of the NDH complex (Hashimoto et al., 2003; Munshi et al., 2005). Accordingly immunoblotting was performed with antibodies raised against NDH-B and NDH-H to estimate the amount of NDH complex in S111-9 and Melrose. As shown in Fig. 5A, the constitutive levels of NDH-B and NDH-H proteins were much higher in S111-9 than in Melrose. Both NDH-B and NDH-H protein levels were induced by salt stress in Melrose. In S111-9, a salt-mediated increase was observed only in NDH-H (Fig. 5A). During the 2 d salt treatment, NDH-B and NDH-H protein levels were generally higher in S111-9 than in Melrose. Moreover, the results of immunogold labelling for NDH-B and NDH-H protein (Fig. 5C, D) are in accordance with the above immunoblotting analyses. Furthermore, the relative mRNA abundance of ndhB and ndhH was higher in S111-9 than in Melrose, both before and after salt stress (Fig. 5B), especially for ndhH, consistent with the results of immunoblotting. The mRNA levels of ndhB and ndhH were up-regulated by salt stress in both Melrose and S111-9. These findings implied that in S111-9, the higher abundance of the NDH complex might result in faster CEF and more ATP accumulation in the light.

Differences in the distribution of Na⁺

To understand whether differences in the distribution of Na⁺ in mesophyll cell organelles affect salt tolerance in the two varieties, CoroNa Green was used to reveal the distribution of Na⁺ in mesophyll cells. FM4-64 was used to show vacuolar membranes, as it specifically stains vacuolar membranes (Kutsuna and Hasezawa, 2002). It was found that Na⁺, as measured by
CoroNa fluorescence intensity, increased remarkably with salt stress, and enhanced Na\(^+\) was mainly concentrated in vacuoles after 1 d and 2 d salt stress (Fig. 6; Supplementary Fig. S3 at JXB online). After 2 d salt stress, the Melrose mesophyll cells showed little recognizable vacuolar membrane staining, indicating that the membrane was damaged. These results, combined with Na\(^+\) and Chl fluorescence data, further indicated that most of the Na\(^+\) was concentrated in vacuoles. However, co-fluorescence of Na\(^+\) and chloroplasts was observed in mesophyll cells of Melrose leaves (Fig. 7D), in comparison with S111-9, which showed little or no co-fluorescence (Fig. 7H). These observations indicate that the entry of Na\(^+\) into chloroplasts was more common in Melrose than in S111-9.

**Effect of salt stress on vacuolar H\(^+\)-ATPase activity**

To elucidate whether the increased ATP content in S111-9 via enhanced CEF was used to sequester Na\(^+\) in the vacuole, V-ATPase activity was determined in the absence and the presence of 100 μM TTFA. As shown in Fig. 8A, the V-ATPase activity was increased significantly under salt stress in both varieties (Fig. 8A). Meanwhile, the expression of V-ATPase subunit A and B genes was increased significantly after salt stress (Supplementary Fig. S4 at JXB online). Additionally, in the presence of 100 μM TTFA, the V-ATPase activity was decreased compared with that in the absence of 100 μM TTFA (Fig. 8B). All of these findings supported that the increased ATP content via enhanced CEF might be associated with the sequestering of Na\(^+\) in the vacuole.

**Changes in expression of genes related to Na\(^+\), K\(^+\), and Ca\(^{2+}\) transport in mesophyll cells**

To assess which Na\(^+\), K\(^+\), and Ca\(^{2+}\) transport-related genes would respond to salt stress, transcript levels were measured by reverse transcription and quantitative PCR (RT-qPCR) for a series of Na\(^+\), K\(^+\), and Ca\(^{2+}\) transport-related genes. Among these genes, *CBL4* (calcineurin B-like protein 4), *CIPK24* (CBL-interacting protein kinase 24), and *NHX* (Na\(^+\)/H\(^+\) antiporter) were significantly up-regulated in response to salt stress in S111-9, but they were unchanged and even down-regulated in Melrose (Fig. 9A–C). Transcript levels of *AKT* (Arabidopsis K\(^+\) transporter), *KAT2* (K\(^+\) channel in Arabidopsis thaliana 2), *KEA* (K efflux antiporter), and *SOS1* (salt overly sensitive 1) in S111-9 were also significantly higher than those in Melrose after 2 d salt stress (Fig. 9D–G). Therefore, these genes might be partly positively regulated by salt stress. Transcript levels of *CIPK24* and *NHX* were ~4- and 3-fold higher, respectively, in S111-9 than in Melrose (Fig. 9B, C), which further indicated that *CIPK24*, which is involved in Ca\(^{2+}\) transport, and *NHX*, which is involved in Na\(^+\) transport and accumulation in vacuoles, could directly respond to salt stress in S111-9. In addition, transcript levels of *CBL3* (calcineurin B-like protein 3), *CBL10* (calcineurin B-like protein 10), and *CIPK23* (CBL-interacting protein kinase 23) increased significantly in both varieties after salt stress, but their transcript levels were significantly higher in Melrose than in S111-9 (Fig. 9H–J). Collectively, these results revealed a greater difference between two varieties in transcription of key genes related to Na\(^+\), K\(^+\), and Ca\(^{2+}\) transport, which could be a response to salt stress.

**Discussion**

Salt stress induces an increase in NDH complex levels and CEF activity

The role of the NDH complex in adaptation to salt stress was reported in studies of an ndhB-inactivated mutant of the cyanobacterium *Synechocystis* sp. PCC 6803 (Tanaka et al., 1997), which showed that enhanced CEF from the cytosol to PSI via NDH is essential for the adaptation of
cyanobacteria to salt stress. A previous study demonstrated that salt stress could induce significant up-regulation of CEF in soybean (Yang et al., 2007). In addition, the hcef1 crr2-2 double mutant, which is deficient in thylakoid NDH complex and FBPase, is highly sensitive to light and lacks elevated CEF1, further suggesting that NDH might play a direct role in catalysing or regulating CEF (Livingston et al., 2010a, b). The reduction of P700⁺ has been taken as a good indicator

Fig. 5. Effect of salt stress on the protein and mRNA abundance of ndhB and ndhH. (A) Changes in NDH-H and NDH-B content were analysed using immunoblotting in the leaves of Melrose and S111-9 treated with 150 mM NaCl for 0h, 4h, 1d, and 2 d. Equal loading is shown by Coomassie-stained gels below each blot. (B) Effect of salt stress on the mRNA expression of ndhB and ndhH. RNA gel blotting hybridization analysis of ndhB and ndhH was performed using the total RNA from Melrose and S111-9 treated with 150 mM NaCl stress for 0h, 4h, 1d, and 2 d. The RNA samples loaded were visualized by ethidium bromide staining of 28S rRNA (lower panel). (C and D) Immunogold labelling of NDH-B and NDH-H in the chloroplast organelles of the mature leaves of soybean (Glycine max) under 150 mM salt stress. Seven to eight individual cells of palisade and spongy layers were examined in several immunolabelled sections. Numbers of gold particles per unit area (μm²) are given as mean ±SD. (C) Effect of salt stress on label density of NDH-B (μm²). (D) Effect of salt stress on label density of NDH-H (μm²). Different letters indicate significantly different values (P<0.05) by Tukey’s test.

Fig. 6. Distribution and accumulation of Na⁺ in soybean leaves. Comparison of the distribution and accumulation of Na⁺ in the leaves of Melrose and S111-9 treated with 150 mM salt for 0h, 4h, 1d, and 2 d. Confocal images of leaf sections stained with CoroNa Green (green) and FM4-64 (red) are shown. CoroNa Green fluorescence intensity indicates the Na⁺ content. FM4-64 is an endocytic marker dye that is internalized to the tonoplast via the endosomal compartment, and red fluorescence indicates the location of the vacuole. All sections were observed at ×63 magnification. Scale bars=20 μm.
The results show that salt stress induced increases in NDH-H at the mRNA and protein levels under from 4 h to 1 d salt stress in both varieties (Fig. 5). NDH-B protein levels in Melrose markedly decreased on the second day after salt treatment, while NDH-B protein levels remained high in S111-9. The change of NDH-H expression corresponds to the rise in the transient increase in Chl fluorescence after turning off actinic light and the dark re-reduction of P700⁺ in both varieties, implying that NDH-H may play an important role in regulation of CEF under salt stress. Many studies have demonstrated that NDH-B is essential for stabilizing other subunits (Hashimoto et al., 2003; Munshi et al., 2005) and that NDH-H is unstable without other subunits (Hashimoto et al., 2003; Kotera et al., 2005; Rumeau et al., 2007). Additionally, Takabayashi et al. (2009) reported that in ndf (NDH-dependent CEF) mutants, the amount of NDH-H subunit was greatly decreased and the loss of NDH activity was caused by a defect in accumulation of NDH complex. This further supports the idea that accumulation of both NDH-B and NDH-H can enhance the accumulation and activity of the NDH complex under salt stress. Together, all of these findings suggest that salt stress induces an increase in the amount of the NDH complex, which contributes to enhanced NDH-dependent CEF activity.

Enhanced NDH-dependent CEF promotes increased ATP contents

Leaf ATP content in light is balanced between ATP production and ATP consumption. Salt stress results in a much greater decrease of the net photosynthetic rate in salt-sensitive Melrose than in salt-tolerant S111-9 plants (Yang et al., 2007; He et al., 2014), indicating that ATP consumption for carbon assimilation should be lower in Melrose than in S111-9 upon light illumination. However, ATP accumulation in S111-9 was much higher than in Melrose (Fig. 4B), suggesting that there is a supplementary pathway producing more ATP in S111-9 than in Melrose under light conditions. The present results showed a greater increase in Chl fluorescence after turning off actinic light (Fig 3A, B) and faster P700⁺ re-reduction (Fig. 3C), reflecting enhanced CEF activity, in S111-9 compared with Melrose under salt stress. Phosphorylation of light-harvesting complex II induced by NaCl and light in salt-tolerant soybean (Lu et al., 2008) supports the idea that the increased absorbed light energy is distributed to PSI and enhances CEF activity. In addition, in the presence of TTFA, the reduction in t½ of P700⁺ re-reduction suggested that CEF activity was decreased, which further resulted in the decrease in ATP accumulation (Figs 3D, 4D). Therefore, the increased CEF activity in light is likely to be the main source of the increased accumulation of ATP in S111-9 compared with Melrose. Although the increase in Chl fluorescence and faster P700⁺ re-reduction also occurred in Melrose upon illumination under salt stress, ATP accumulation decreased as salt stress continued (Figs 3, 4). This may be partly explained by damage to the chloroplasts (He et al., 2014). Moreover, some studies have reported that expression of mitochondrial uncoupling proteins, which can uncouple the electrochemical
gradient from ATP biosynthesis and dissipate energy as heat, can be induced by abiotic stress and help plants adapt to abiotic stress conditions (Laloi et al., 1997; Barreto et al., 2014). Both leakage of photosynthetic membranes and activity of uncoupling proteins could reduce the production of ATP, while photosynthetic electron transport occurred normally, or even faster than usual. The co-localization of Na⁺ staining and chloroplasts showed that more chloroplasts contained Na⁺, suggesting more severe damage of photosynthetic membranes, in Melrose than in S111-9 (Fig. 7D, H), which could uncouple electron transport from photophosphorylation.

In plants, the majority of photosynthetic electron transport follows the linear (or non-cyclic) pathway passing from water through PSII, the cytochrome b6f complex, and PSI to Fd, and thereafter, for most electrons, to NADP. Linear electron flow results in the formation of ATP and reductant, while cyclic electron transport results only in the formation of ATP with no net formation of reductant (Foyer et al., 2012).

Although PGR5-dependent CEF and NDH-dependent CEF are partially redundant pathways, the PGR5 pathway might contribute to maintaining the steady state of overall photosynthesis, and the NDH pathway might play a vital role.
Increased ATP content and expression of genes relevant to Na⁺ influx or sequestering Na⁺ in vacuoles relate to the distribution of Na⁺ and salt tolerance

When plants are exposed to stress conditions such as high temperature, drought, and salt, ATP is required in a variety of processes necessary for adaptation of plant cells to stress conditions (Burrows et al., 1998; Yang et al., 2007). For example, the compartmentation in vacuoles and export from organelles and cells of toxic ions, the re-establishment of cellular homeostasis, and the uptake and/or biosynthesis of compatible solutes all utilize ATP (Hasegawa et al., 2000; Qui and Lu, 2003). Moreover, it is generally accepted that CEF makes an important contribution to the overall regulation of electron transport in response to environmental variation and metabolic cues, even though the nature of these pathways and their precise functions remain controversial (Foyer et al., 2012). It is therefore believed that switching between cyclic and non-cyclic pathways provides a degree of flexibility in the production of ATP and that plants can adjust the relative rate of ATP production to meet the demands of metabolism. Mining published data on transcriptome profiles of C₃ and C₄ leaves from plants grown under high atmospheric CO₂ compared with those grown with ambient CO₂ revealed that transition to higher photorespiratory conditions in C₃ plants enhances the expression of genes associated with NDH-dependent CEF pathways (Prins et al., 2011; Queval and Neukermans, 2012), consistent with a higher ATP requirement. Moreover, several mutants with reduced V-ATPase activity appeared to be hypersensitive to Na⁺, supporting the notion that increased V-ATPase activity is required for Na⁺ compartmentalization under salt stress (Batelli et al., 2007; Tang et al., 2012). The present results demonstrated that the increased ATP content via CEF was positively related to V-ATPase activity (Figs 4, 8), further supporting the idea that accumulated ATP was used to sequester Na⁺ in vacuoles by the hydrolysis of V-ATPase.

Blocking Na⁺ influx and sequestering Na⁺ in vacuoles function as important mechanisms for salt tolerance. Some studies have shown that the CBL10–CIPK24–NHX complex and the CBL4–CIPK24–SOS1 complex play vital roles in Na⁺ transport in root cells (Zhu, 2001; Kim et al., 2007). The transcript levels of genes encoding the CBL10–CIPK24–NHX complex at the vacuolar membrane and the CBL4–CIPK24–SOS1 complex at the plasma membrane were remarkably up-regulated in leaves of S111-9 after 2 d salt stress, compared with those of Melrose (Fig. 9A–C, G, I). Thus, in S111-9, the increases in the transcript abundance of genes encoding the CBL10–CIPK24–NHX complex and the CBL4–CIPK24–SOS1 complex points to an important role for these complexes in adjusting Na⁺ transport and compartmentation in mesophyll cells of soybean. The results also suggest that the CBL4–CIPK24–SOS1 complex might contribute to the retrieval of Na⁺ in S111-9 (Figs 2, 9). Furthermore, the transcript levels of ERA1 (enhanced response to abscisic acid) and PP2C (protein phosphatase 2C), which positively and negatively influence photosynthesis, respectively, were examined, and are basically consistent with the decrease in photosynthetic rate under salt stress (He et al., 2014). KEA affects chloroplast function and integrity, and is involved in regulating the plastid K⁺ content, the chloroplast osmotic potential, and stromal pH (Kunz et al., 2014). The transcript level of KEA was consistent with the likely degree of injury of chloroplasts by Na⁺ entry in both varieties (Figs 7, 9F). Overall, the enhanced abundance of transcripts encoding components of the NDH complex suggested that photosynthetic control of gene expression enhances CEF to meet the increased ATP demand of soybeans under salt stress conditions (Fig. 10). Moreover, transcripts associated with Na⁺, K⁺, and Ca²⁺ transport responded to salt stress, consistent with the expected alterations in supply and demand of ATP related to NDH-dependent CEF activity.

In conclusion, it was demonstrated that in salt-tolerant soybean, salt stress accelerates CEF by a mechanism involved in NDH expression and increased accumulation of ATP in light. The expression of genes associated with Na⁺ transport was also up-regulated. Based on the present results, a model is proposed in which more Na⁺ is sequestered into the vacuoles of mesophyll cells by those gene products, utilizing the energy from ATP, thus alleviating the damage to the photosynthetic apparatus under salt stress conditions (Fig. 10).
Supplementary data are available at JXB online.

Figure S1. Effects of salt stress on relative leaf weight.

Figure S2. Effects of salt stress on K+/Na+ ratio in leaf, stem, and root.

Figure S3. Relative fluorescence intensity in vacuoles.

Figure S4. Salt stress-induced expression of vacuolar H+-ATPase subunit genes.

Figure S5. Dark respiration rate in intact leaf.

Table S1. Linear correlation analysis of Na+, K+, and Ca2+ concentrations in Melrose and S111-9.

Table S2. Primers for RT-qPCR.

Acknowledgements

We would like to thank Professor Alex Webb and Dr Julia Davies (University of Cambridge, Department of Plant Sciences) for critical discussion and comments, and we also thank Mr. Yunrong Wu for help with soybean culture. This work was supported by the National Natural Science Foundation (31171462, 31371591, 30771302), the National Science and Technology Support Plan (2012BAD09B01), the Genetically Modified Organisms Breeding Major Projects (2009ZX08009-123B), and the Lu's Graduate Education International Exchange Fund (Zhejiang University Education Foundation).

References


The evolution of NADP-malic enzyme-type C4 photosynthesis in the genus Atriplex centralasiatica: a study of dark-starved plantlet photosynthetic responses to salinity resistance are transferred into the chloroplast envelope and their role in linking plastidial with cytosolic metabolism.


