Abscisic acid (ABA) plays an important role in fruit development and ripening. Here, three NCED genes encoding 9-cis-epoxycarotenoid dioxygenase (NCED, a key enzyme in the ABA biosynthetic pathway) and three CYP707A genes encoding ABA 8′-hydroxylase (a key enzyme in the oxidative catabolism of ABA) were identified in tomato fruit by tobacco rattle virus-induced gene silencing (VIGS). Quantitative real-time PCR showed that VIGS-treated tomato fruits had significant reductions in target gene transcripts. In SINCED1-RNAi-treated fruits, ripening slowed down, and the entire fruit turned to orange instead of red as in the control. In comparison, the downregulation of SICY707A2 expression in SICY707A2-silenced fruit could promote ripening; for example, colouring was quicker than in the control. Silencing SINCED2/3 or SICY707A1/3 made no significant difference to fruit ripening comparing RNAi-treated fruits with control fruits. ABA accumulation and SINCED1 transcript levels in the SINCED1-RNAi-treated fruit were downregulated to 21% and 19% of those in control fruit, respectively, but upregulated in SICY707A2-RNAi-treated fruit. Silencing SINCED1 or SICY707A2 by VIGS significantly altered the transcripts of a set of both ABA-responsive and ripening-related genes, including ABA-signalling genes (PYL1, PP2C1, and SnRK2.2), lycopene-synthesis genes (SIByc, SIPSY1 and SIPDS), and cell wall-degrading genes (SIG1, SIEW, and SIXET) during ripening. These data indicate that SINCED1 and SICY707A2 are key genes in the regulation of ABA synthesis and catabolism, and are involved in fruit ripening as positive and negative regulators, respectively.

Key words: Abscisic acid (ABA), SINCED1, SICY707A2, tomato fruit ripening, tobacco rattle virus, virus-induced gene silencing (VIGS).
respectively. An important phase of ABA biosynthesis is initiated in plastids with the hydroxylation and epoxidation of the β-carotene to produce the all-trans xanthophylls zeaxanthin and violaxanthin. Violaxanthin is then converted into 9-cis-epoxyxanthophylls, which are oxidatively cleaved by 9-cis-epoxyxycarotenoid dioxygenase (NCED) to yield xanthoxin, the first C15 intermediate of ABA biosynthesis. Xanthoxin exits the plastid into the cytosol where it is oxidized in two further steps to form ABA (Schwartz et al., 2003; Taylor et al., 2005). In addition, the ABA metabolic pathway plays an important role in the regulation of ABA levels (Cutler and Krochko, 1999; Schwartz et al., 2003). The hydroxylation pathway is the main ABA catabolic pathway. In the hydroxylation pathway, among three different methyl groups, C8 is the predominant position for the hydroxylation reaction, which is mediated in Arabidopsis by proteins encoded by the CYP707A gene family (Saito et al., 2004; Kushiro et al., 2004). Dihydroxynaphthoic acid (DPA) may be the major metabolite of ABA (Setha et al., 2005). The 8-hydroxylation is reported to be the major regulatory step in many physiological events controlled by ABA (Kushiro et al., 2004; Saito et al., 2004). Recently, a major breakthrough in the field of ABA signalling was achieved with the identification of the PYR/PYL/RCAR protein family, the type 2C protein phosphatases (PP2Cs), and subfamily 2 of the SNF1-related kinases (SnRK2s) (Ma et al., 2009; Park et al., 2009; Melcher et al., 2009; Santiago et al., 2009). To elucidate the mechanism of ABA action, it is necessary to identify all the components involved in ABA homeostasis, including the functional components in ABA metabolic pathways, signal transduction, and transport.

In tomato (Solanum lycopersicum), three NCED genes have been isolated, and expression analysis indicated that, among them, SIND1 may regulate ABA biosynthesis in fruit (Sun et al., 2012a, b). However, the molecular evidence remains to be elucidated. To address this, a key step in ABA biosynthesis, NCED was targeted for inhibition via RNAi in tomato fruit (Ma et al., 2012). Our data showed that NCED potentially regulated the development and ripening of tomato fruit. In addition, ABA could control, at least in part, the production and effects of ethylene in climacteric tomato fruit. In recent years, tobacco rattle virus-induced gene silencing (IGS) has been used as a rapid gene function assay system in molecular biological studies of fleshy fruit (Fu et al., 2006; Hoffmann et al., 2006; Li et al., 2013). In this study, we further identify the function of three NCED and three CYP707A genes by VIGS. Results show that SIND1 and SlCYP707A2 are key genes in the regulation of ABA level during development and ripening of tomato fruit.

**Materials and methods**

**Construction of the viral vector and agroinoculation**

The pTRV1 and pTRV2 virus-induced gene silencing vectors (described by Liu et al., 2002) were kindly provided by YL Liu (School of Life Science, Tsinghua University, Beijing, China). A 456-bp cDNA fragment of an NCED or CYP707A gene was amplified using primers (Table 1). The amplified fragment was cloned into EcoRI/Sacl-digested pTRV2. Agrobacterium tumefaciens strain GV3101 containing pTRV1, pTRV2, and the pTRV2-derivative pTRV2-NCED/CYP707A were used for RNAi. Thirty fruits from ten independent plants grown in the greenhouse were sampled for inoculation, and each basal pedicel or one side of fruit was injected with the NCED/CYP707A-RNAi TRV vector at the maturation green stage. The fruits were evaluated 3–12 days after treatment.

**Plant materials**

Tomatoes (Solanum lycopersicum L. cv. JiaBao) were grown under standard greenhouse conditions (25 ± 5°C and 70% humidity under a 14h/10h light/dark regime). Fruit ripening stages were divided according to the days after flowering (DAF) and fruit colour: immature green (IM), 15 DAF; mature green (MG), 30 DAF; breaker 0 (B0), 34 DAF; breaker 1 (B1), 35 DAF; breaker 2 (B2), 36 DAF; turning 0 (T0), 37 DAF; turning 3 (T3), 40 DAF; red ripe (R), 42 DAF; and over ripe (OR), 45 DAF. Ten fruits were harvested at each stage and immediately frozen in liquid nitrogen. They were then powdered, mixed, and stored at −80°C until further use. ‘Tom’ tomatoes were also grown in the same greenhouse.

**Dehydration treatment of fruits**

In order to evaluate the effect of dehydration stress, 60 fruits were harvested at the MG stage and divided evenly into two groups. The first group (control) was stored at 20°C under high relative humidity (RH) (95%) which included 10 control fruits, 10 SIND1-RNAi-treated fruits, and 10 SlCYP707A2-RNAi-treated fruits. The second group (dehydration stress) was stored at the same temperature and subjected to the same treatments, but under low RH (55%, dehydrated fruits). The ABA content and expression of related genes in the pulp were determined 0, 3, 5, and 7 d after the treatment of fruits and 0, 1, and 2 d after the treatment of sepals. Every single fruit was weighed immediately after harvest and then weighed again before sampling for calculation of water loss rate. Water loss rate is calculated as the ratio of the decreased fruit weight to the initial fruit weight.

**ABA or NDGA treatment**

Sixty fruits harvested at the MG stage were divided into two groups (n = 30 for each group), and immediately soaked in 100 μM ABA (Sigma, A1049, USA) (group I) or distilled water (group II, control) for 10 min under low vacuum. The fruits were then placed in a tissue culture room at 25°C and 95% RH. After 0, 1, and 3d, the fruits were sampled, frozen with liquid nitrogen, powdered, mixed, and stored at −80°C for further use. Different treatments with

### Table 1. Specific primers used for VIGS in this study

| Target gene | Oligonucleotides (5’-3’) |
|-------------|-------------------------|
| SIND1 F-v   | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
| SIND1 R-v   | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
| SIND2 F-v   | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
| SIND2 R-v   | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
| SIND3 F-v   | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
| SIND3 R-v   | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
| SlCYP707A1 F-v | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
| SlCYP707A1 R-v | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
| SlCYP707A2 F-v | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
| SlCYP707A2 R-v | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
| SlCYP707A3 F-v | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
| SlCYP707A3 R-v | CGGGAATTCATCGACCTGCACTGTTTCTAAGTCTGAG |
nordihydroguaiaretic acid (NDGA) were the same as with ABA; NDGA concentration was 200 μM.

Quantitative real-time PCR analysis

Total RNA was isolated from tomato samples using the hot borate method (Wan and Wilkins, 1994). Genomic DNA was eliminated using an RNase-free DNase I kit (Takara, China) according to the manufacturer’s recommendations. For every RNA sample, quality and quantity were assessed by agarose gel electrophoresis. cDNA was synthesized from total RNA using the PrimeScript™ RT reagent kit (Takara) according to the manufacturer’s recommendations. Primers used for real-time PCR are listed in Supplementary Table S1 and were designed using Primer 5 software (http://www.premierbiosoft.com/). SAND was used as an internal control gene, and the stability of its expression was tested in preliminary studies (Sun et al., 2011). All primer pairs were tested by PCR. The presence of a single product of the correct size for each gene was confirmed by agarose gel electrophoresis and double-strand sequencing (Invitrogen). The amplified fragment of each gene was subcloned into the pMD18-T vector (Takara), and used to generate standard curves through real-time PCR (Ex Taq™ primer mixture (containing 4 μM of each forward and reverse primer), 1.5 μl cDNA template, 10 μl SYBR Premix Ex Taq™ (2X) mixer, and 7.7 μl water). Reactions were performed under the following conditions: 95°C for 30 s (one cycle), 95°C for 15 s, 60°C for 20 s, and 72°C for 15 s (40 cycles). The changes of relative fold expression were calculated using the relative two standard curves method with Rotor-Gene 6.1.81 software (Invitrogen).

Determination of ABA content

For ABA extraction, 1.0 g of pulp was ground in a mortar and homogenized in the extraction solution (80% v/v methanol). Extracts were centrifuged at 10 000g for 20 min. The supernatant was eluted through a Sep-Pak C18 cartridge (Waters, www.waters.com) to remove polar compounds, and then were stored at 20°C for ELISA. The stepwise procedure for indirect ELISA of ABA was as follows: each well of a microtitre plate was pre-coated with ABA-BSA conjugate diluted in coating buffer according to the instructions of the manufacturer (ELISA kit for ABA, College of Agronomy and Biotechnology, China Agricultural University). Then, to each well, was added 50 μl standard or sample in assay buffer (8.0 g NaCl, 0.2 g KH2PO4, 2.96 g Na2HPO4·12 H2O, 1.0 ml Tween 20, and 1.0 g gelatin, added to 1.000 ml water), followed by 50 μl ABA antibody (Invitrogen) diluted 1:2000 in assay buffer. The plates were incubated for 0.5 h at 37°C and then washed four times with scrubbing buffer (which contained the same ingredients as assay buffer, but without gelatin). Anti-mouse IgG coupled to alkaline phosphatase buffer (which contained the same ingredients as assay buffer, but without gelatin), added to 1.000 μl of a 1–2 mg l−1 o-phenylenediamine substrate solution and 0.04% by volume of 30% v/v hydrogen peroxide in substrate buffer (5.10 g C6H12O6·H2O, 18.43 g Na2HPO4·12 H2O, and 1.0 ml Tween 20, added to 1000 ml water) were added to each well. After 10–15 min, 50 μl of the headspace gas, and injecting it into a gas chromatograph (Agilent model 6890N) fitted with a flame ionization detector and an activated alumina column. Fresh tissues from each fruit were frozen in liquid nitrogen and stored at –80°C until use.

Determination of fruit firmness

Fruits were harvested from all of the plants in each of three replicate plantings at the different ripening stages. Flesh firmness was measured after the removal of fruit skin on three sides of each fruit using a KM-model fruit hardness tester (Fujihara). The strength of each fruit was measured three times, and the average of the maximum force was used.

Results

Expression patterns of ABA metabolic genes in pulp during fruit development and in response to application of exogenous ABA and dehydration stress

Within the SINCED gene family, the expression of SINCED1 was the highest in pulp. SINCED1 decreases from 10 days after full bloom (DAFB) to the MG stage, then it increased sharply and peaked at the turning stage; after that it declined to a low level at the OR stage (Fig. 1A). The expression variation of SINCED2 was generally decreased from 10 DAFB to fruit ripening. The expression of SINCED3 was very low through fruit development and ripening. Among the SICYP7074 gene family, the expression of SICYP707A2 (Fig. 1B) exhibited a fluctuant expression pattern with four peaks during development, and then it increased rapidly during ripening. Compared to SICYP707A2, the expression of SICYP707A1 and SICYP707A3 (Fig. 1B) was very low during fruit development and ripening. In addition, expression of ABA metabolic genes in response to exogenous ABA treatment and dehydration in tomato fruits was tested. For SINCED1, expression was significantly increased by exogenous ABA and dehydration at 2 days after treatment (DAT) (Fig. 1C, E). The expression of SINCED2 and SINCED3 was also significantly increased in the water stressed and ABA-treated tomato fruits (Fig. 1C, E). For SICYP707A2, expression was downregulated in the fruits under both ABA treatment and dehydration at 1 DAT (Fig. 1D, F), and then it significantly increased at 2 DAT (Fig. 1D, F). The expression of SICYP707A1 and SICYP707A3 was significantly downregulated under both water stress and ABA treatment at 1 DAT, but upregulated at 2 DAT.

Silencing of the SINCED1 gene suppresses tomato fruit ripening

To examine the role of SINCEDs, the tobacco rattle virus (TRV) vector was used to suppress the expression of SINCEDs (Fig. 2). When the SINCED1-RNAi TRV vector was injected into the basal pedicel of 15 fruits (cv. Tom) attached to the plant at the MG stage, fruit ripening slowed down, and the entire fruit turned orange (Fig. 3D, E, F) instead of red as in the control (Fig. 3A). Ten days after the SINCED1-RNAi TRV vector was injected, the fruits did not show normal

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ripening (Fig. 3D, E, F) as in the control (Fig. 3A). Compared to \textit{SINCED1}-RNAi-treated fruits, there were no significant differences in colouring between \textit{SINCED2/3}-RNAi-treated fruits and control fruits (Fig. 3B, C) during fruit ripening and in response to dehydration stress. The \textit{SINCED1}-RNAi TRV vector was also injected into the attached fruits (cv. JiaBao) at the MG stage. 12 d after injection, control fruits turned red (Fig. 3M, N); however, for \textit{SINCED1}-RNAi-treated fruits, parts of the peel and placenta inside the fruit did not turn red as in the control (Fig. 3K, L). The water loss of the sepal in the \textit{SINCED1}-RNAi-treated fruits was quicker than in the control under the same conditions. Meanwhile, the wilting of the sepals was more serious than that of the control under the same conditions.

\textit{SINCED1}-RNAi treatment alters the expression of genes involved in ABA-responsive genes

In \textit{SINCED1}-RNAi-treated fruits, expression of \textit{SINCED1} was markedly downregulated to 19\% of the control while expression of \textit{SINCED2/3} was downregulated/upregulated (Fig. 4A, B, C). In fruits with the same treatment, the expression of \textit{SICY707A1/2} was downregulated, while the expression of \textit{SICY707A3} was upregulated (Fig. 4D, E, F). Among the ABA-signalling genes, including those of the PYR/PYL/RCAR protein family (\textit{SIPYL1}), type 2C protein phosphatases (\textit{SIPP2C1}), and subfamily 2 of SNF1-related kinases (\textit{SlSnRK2.2}) (Ma et al., 2009; Park et al., 2009), \textit{SIPYL1} and \textit{SlSnRK2.2} were downregulated.
SlNCED1 and SlCYP707A2 are key genes in ABA metabolism

and SlCYP707A2 are key genes in ABA metabolism, while SlPP2C1 was upregulated (Fig. 4G, H, I). As shown in Fig. 5A, in SlNCED1-RNAi-treated fruits, the ABA content was 21% of the control at the turning stage (7 d after MG); moreover, fruits couldn’t become fully red and this incomplete colouring couldn’t be rescued by the application of exogenous ABA (although ABA contents were increased by application of exogenous ABA) (Fig. 5A). Expression of SlPYL1 and SlSnRK2.2 in SlNCED1-RNAi-treated fruits couldn’t be increased by application of exogenous ABA (Fig. 5B).
SINCE1-RNAi treatment alters the expression of genes involved in ripening-related genes

Several ripening-related physiological parameters were measured, including fruit firmness, solid soluble content, and lycopene content. As shown in Fig. 6, in SINCE1-RNAi fruits, the trends were for a decrease in solid soluble content and lycopene content, but an increase in fruit firmness. To clarify the role of SINCE1 in the regulation of tomato fruit ripening, several ripening-related genes were examined in both SINCE1-RNAi-treated fruits and control fruits. SlBcyc, SlPSY1 and SlPDS encode lycopene β-cyclase, phytoene synthetase, and phytoene dehydrogenase, respectively. Relative quantitative real-time PCR analysis showed that the expression of all these genes was downregulated (Fig. 7H, I) except for SlBcyc, which was upregulated (Fig. 7J). In addition, we examined the expression of genes encoding cell-wall hydrolases. In SINCE1-RNAi fruit, genes encoding polygalacturonase (SlPG1), expansin (SlEXP1), and xyloglucan endotransglycosylase (SlXET16) were all significantly downregulated during fruit ripening compared to the control (Fig. 7E, F, G). Relative expression analysis showed that the expressions of SlACS2 [encoding 1-aminocyclopropane-1-carboxylic acid (ACC) synthase], SlACO1 (encoding ACC oxidase), and SlETR3 (involved in the ethylene response), were upregulated in the SINCE1-RNAi fruits (Fig. 7A, B, C). The expression of SlERF2 was significantly downregulated in SINCE1-RNAi fruits (Fig. 7D). Ethylene release was upregulated at turning stage, but downregulated at harvest red stage compared to the control (Fig. 7K).

Silencing of the SINP707A2 gene promotes tomato fruit colouring

To clarify the role of SINP707A2 in the regulation of ABA levels during fruit ripening, ABA levels and ABA-responsive genes were examined in both RNAi-treated and control fruits. When the SINP707A2-RNAi TRV vector was injected into the 15 fruits attached to the plant at the MG stage, the fruits could become red quicker (Fig. 8F), and ripening was also faster than in the control (Fig. 8G). In SINP707A1/2/3-RNAi-treated Tom fruits (Fig. 8B, C, D), fruit ripening was the same as with control fruit (Fig. 8A) at harvest stage. In SINP707A2-RNAi-treated fruits, the ABA content was higher than the control at 5 and 7 d after MG, and fruit ripening couldn’t be inhibited by the application of NDGA, which delayed the control fruit ripening (Fig. 9J).

SINP707A2-RNAi treatment alters the expression of genes involved in ABA-responsive genes

In the SINP707A2-RNAi-treated fruits, expression of SINP707A1 was downregulated, but SINP707A3...
was upregulated; however, SICY707A2 was markedly downregulated to 18% of the control (Fig. 9D, E, F). The expression of SINCED1 was upregulated, while SINCED2 was downregulated in SICY707A2-RNAi fruits (Fig. 9A, B, C). The expression of SIPYL1 and SISnRK2.2 in ABA signalling was upregulated, while SIPP2C1 expression was downregulated in SICY707A2-RNAi fruit (Fig. 9G, H, I).

SICY707A2-RNAi treatment alters the expression of genes involved in ripening-related genes

As shown in Fig. 6, fruit firmness was lower than that of the control in SICY707A2-RNAi fruits, while the soluble solid content and lycopene content did not show significant differences compared to the control fruits. In SICY707A2-RNAi fruits, genes encoding polygalacturonase (SIPG), expansin (SIXYP) and xyloglucan endotransglycosylase (SIXET16) were upregulated at breaker and turning stages; however, there were no significant changes compared to the control fruits at the harvest stage (Fig. 10E, F, G). In the lycopene synthesis pathway, compared with the control, the relative expression levels of SIPSY1 and SIPDS were higher, but SIBcyc was lower, at breaker and turning stages (Fig. 10H, I, J). With respect to ethylene, relative expression analysis showed that the expression of SIACS2 [encoding (ACC) synthase], SIALCO1 (encoding ACC oxidase), and SIET3 (involved in the ethylene response), which were consistent with ethylene release (Fig. 10K) in the SICY707A2-RNAi fruits, were upregulated at breaker and turning stages; however, there was no significant difference at harvest stage compared to control fruits (Fig. 10I). The expression of the SIERF2 was upregulated at the T and HR stages.
SlCYP707A2-RNAi-treated fruits during the harvest stage were unusual, with uneven colouring in pulp compared to control fruits.

Dehydration of SlNCED1/SlCYP707A2-RNAi-treated fruits

Both control and SlNCED1/SlCYP707A2-RNAi-treated fruits were harvested 6 d after the SlNCED1/SlCYP707A2-RNAi treatments (Fig. 11). The fruits were then incubated in the laboratory (20°C, 50% relative humidity). As shown in Fig. 11, the weight loss rate in SlNCED1-RNAi fruits was higher than the control fruit 3–6 d after dehydration. However, there was not a large difference in the rate of water loss comparing control and SlCYP707A2-RNAi fruit (Fig. 11A). The water loss of the sepal in the SlNCED1/SlCYP707A2-RNAi treated fruit was also similar to that of fruit under the same conditions (Fig. 11B).

Discussion

NCED and CYP707A are generally encoded by a small gene families, respectively (Krochko et al., 1998; Burbidge et al., 1999; Zhang et al., 2009a). Among the three NCED genes in tomato, SlNCED1 may play a primary role in regulating ABA biosynthesis during fruit ripening (Fig. 1A) in response to ABA application (Fig. 1E) and dehydration (Fig. 1C). Besides biosynthesis, catabolism of ABA is also an important way of regulating ABA levels (Kushiro et al., 2004; Li et al., 2011; Ren et al., 2011). A similar result to the reports of Ren et al. (2010) and Wang et al. (2013) was obtained in this work: the expression of SlCYP707A2 was higher than SlCYP707A1 and SlCYP707A3, and was opposite to the change of ABA content during development (Fig. 1B) in response to ABA treatment (Fig. 1F) and dehydration (Fig. 1D). Previously, to suppress SlNCED1 specifically in tomato fruits, we used an RNA interference
construct driven by the fruit-specific E8 promoter. ABA accumulation and SINCED1 transcript levels in transgenic fruit were downregulated to between 20 and 50% of the levels measured in control fruit. This significant reduction in NCED activity led to a downregulation in the transcription of genes encoding major cell wall-degrading enzymes, specifically polygalacturonase (SIpG), pectin methyl esterase (SIpME), and expansin (SIExp). This led to a significant extension of the shelf life to 15 to 29 d compared with a shelf life of only 7 d for the control fruit (Sun et al., 2012a). Fruits of RNAi lines displayed deep red colouration compared with the pink colour of control fruit. The decrease in endogenous ABA in these transgenic lines resulted in an increase in ethylene. These results indicate that, at least in part, ABA potentially regulated fruit ripening, and ethylene production and action, in climacteric tomato fruit (Sun et al., 2012b).

In the present study, we used VIGS to further verify the function of genes related to ABA metabolism in tomato fruit. The SINCED1-RNAi-treated fruits showed various chimeric symptoms similar to those reported by Fu et al. (2006) and Hoffmann et al. (2006), and fruit ripening was inhibited such that fruit couldn’t become fully red or softened. Transcript levels of the SINCED1 gene decreased after the inoculation (RNAi), concomitant with the decrease of ABA concentration, indicating that SINCED1 directly affects ABA biosynthesis in tomato fruit. In addition to the SINCED1 gene (downregulated by 81%), most of the ABA-responsive genes were downregulated in SINCED1-RNAi fruits (Fig. 4). Moreover, exogenous ABA could not rescue the uncoupled phenotype of these SINCED1-RNAi-treated fruits (Fig. 5A). The ABA content was significantly upregulated in SINCED1-RNAi fruit treated by exogenously applied ABA at 5 and 7 DAT (Fig. 5A). As high as the ABA content is in RNAi fruit, they still cannot complete full reddening, suggesting that may be attributed to the repressed effect on the numbers of ABA signal molecules when the SINCED1 is repressed by RNAi (Fig. 4). Real-time PCR analysis of the mRNA expression levels of PYL1 and SnRK2.2 showed that transcripts of these genes were significantly downregulated while PP2C1 was upregulated in RNAi fruits compared with control fruits (Fig. 4). A recent report shows that in the presence of ABA, the PYR1 receptor proteins can disrupt the interaction between the SnRK2s and PP2Cs, thus preventing the PP2C-mediated dephosphorylation of SnRK2s. This results in the activation of the SnRK2 kinases, turning on downstream factors of ABA signals, such as AREB/ABF, and finally leads to ABA-responsive physiological events (Fujii et al., 2009). In this study, PYL1 and SnRK2.2 genes were downregulated in RNAi fruit (Fig. 4) and could not be rescued by exogenous ABA treatment (Fig. 5B), which may lead to the suppression of ABA responses and, in turn, destroy ABA-responsive physiological events, such as fruit reddening and ripening.

In contrast, CYP707A1, encoding 8'-hydroxylase, can alter the dynamic balance of ABA level (Saito et al., 2004; Ren et al., 2011). The role of three CYP707A genes (SICYP707A1-3) was verified by VIGS, and the ABA level in fruit was mainly regulated by SICYP707A2 at the transcriptional level (Fig. 1B). SICYP707A2-RNAi caused an increase of ABA content at breaker and turning stages, and accelerated fruit colouring and softening compared to control fruits (Figs 8 and 9). This result is similar to the overexpression of
NCED genes, which could cause the increase of ABA level (Qin and Zeevaart 2002; Wan and Li, 2006; Zhang et al. 2008; Hwang et al., 2010). Thus, SlCYP707A2 is a key gene in the ABA catabolic pathway in tomato fruit. SlCYP707A1/2/3 can be upregulated by the application of exogenous ABA, suggesting that ABA might regulate its own accumulation in fruits (Sun et al., 2012a; Wang et al., 2013). Our results also suggest that appropriate ABA contents are required for fruit ripening; too much or too little could lead to abnormal ripening.

Water deficit in fruit is a direct response caused by osmotic stress, including drought and salinity. In this study, SINCED1-RNAi treatment could decrease the tolerance of fruit under dehydration stress, concurrent with the decrease of ABA accumulation and increased water loss (Fig.11). Interestingly, the effect of silencing SlCYP707A2 in tomato fruits was different from previous findings in Arabidopsis. Loss of function of CYP707A was reported to enhance drought tolerance in Arabidopsis (Umezawa et al., 2006). In contrast, SlCYP707A2-silenced tomato fruits did not show any improvements in terms of rate of weight loss of silenced fruits compared to control fruits under water stress, and this result was similar in wheat (Manmathan et al., 2013). The differences in response to dehydration stress may be due to differences in stress adaptation pathways in tomato and Arabidopsis. Another possible reason for the observed difference may have to do with the structure of the CYP707A gene family in different species (Kushiro et al., 2004; Manmathan et al., 2013). In tomato fruits, the expression of SIERF2,
encoding an ERF (ethylene response factor) protein and belonging to the ERF gene family, increases during fruit ripening (Fig. 7D). Individual members of the ERF family have been shown to be either positive or negative regulators of transcription (Fujimoto et al., 2000; Ohta et al., 2000, 2001). In SiNCED1-RNAi-treated fruits, SIERF2 expression was markedly downregulated: therefore, a decrease of ethylene release at the HR stage may be influenced by SIERF2 transcript (Fig. 7D,K).

In conclusion, six major genes including three SiNCEDs and three SiCYP707As involved in ABA biosynthesis and catabolism were identified by VIGS. VIGS-treated tomato fruits had significant reductions in target gene transcripts. The SiNCED1-RNAi-treated fruits did not undergo normal ripening compared to control fruits. In comparison, the SiCYP707A2-RNAi treatment could promote ripening; for example, colouring was quicker than the control. Silencing SiNCED1 or SiCYP707A2 by VIGS significantly altered the transcripts of a set of both ABA-responsive and ripening-related genes during ripening. These data indicate that SiNCED1 and SiCYP707A2 are key genes in the regulation of ABA synthesis and catabolism, and are involved in fruit ripening as a positive and a negative regulator, respectively.
Specific primer sequences used on 28 July 2018 and alters leaf morphology. Ectopic expression of rice OsNCED3 in Arabidopsis increases ABA level and alters leaf morphology. Plant Science 178, 12–22.

Supplementary material
Supplementary data can be found at JXB online. Supplementary Table S1. Specific primer sequences used for real-time quantitative PCR.

Funding
This work was partly supported by the 973 Programme 2012CB113900 to Yang-Dong Guo.

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