NADPH Thioredoxin Reductase C and Thioredoxins Act Concertedly in Seedling Development[^OPEN]


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Thiol-dependent redox regulation of enzyme activity plays a central role in the rapid acclimation of chloroplast metabolism to ever-fluctuating light availability. This regulatory mechanism relies on ferredoxin reduced by the photosynthetic electron transport chain, which fuels reducing power to thioredoxins (Trxs) via a ferredoxin-dependent Trx reductase. In addition, chloroplasts harbor an NADPH-dependent Trx reductase, which has a joint Trx domain at the carboxyl terminus, termed NTRC. Thus, a relevant issue concerning chloroplast function is to establish the relationship between these two redox systems and its impact on plant development. To address this issue, we generated Arabidopsis (Arabidopsis thaliana) mutants combining the deficiency of NTRC with those of Trxs f, which participate in metabolic redox regulation, and that of Trx x, which has antioxidant function. The ntrc-trxf1/f2 and, to a lower extent, ntrc-trxx mutants showed severe growth-retarded phenotypes, decreased photosynthesis performance, and almost abolished light-dependent reduction of fructose-1,6-bisphosphatase. Moreover, the combined deficiency of both redox systems provokes aberrant chloroplast ultrastructure. Remarkably, both the ntrc-trxf1/f2 and ntrc-trxx mutants showed high mortality at the seedling stage, which was overcome by the addition of an exogenous carbon source. Based on these results, we propose that NTRC plays a pivotal role in chloroplast redox regulation, being necessary for the activity of diverse Trxs with unrelated functions. The interaction between the two thiol redox systems is indispensable to sustain photosynthesis performed by cotyledons chloroplasts, which is essential for early plant development.

Photosynthesis is a central feature of chloroplasts, allowing the use of light and water for the production of organic material, thus being the primary source of biomass and oxygen in the biosphere. Besides their essential function as factories of metabolic precursors, chloroplasts also play a relevant role in harmonizing the growth of the different organs of the plant as well as in its acclimation to changing environmental conditions. Therefore, chloroplast biogenesis and function are deeply integrated with plant growth and development (Inaba and Ito-Inaba, 2010; Jarvis and López-Juez, 2013). A classic example of this integration occurs at the seedling stage, when true leaves are generated (Waters and Langdale, 2009; Pogson et al., 2015). To fulfill these functions, chloroplast metabolism needs to adjust rapidly to unpredictable changes of light availability. In this regard, the thiol-dependent redox regulation of enzyme activity plays a relevant role (Couturier et al., 2013; Balsera et al., 2014), the disulfide reductase activity of thioredoxins (Trxs) being central for this regulatory mechanism (Meyer et al., 2012; Serrato et al., 2013).

Trx-dependent redox regulation is universally found in any kind of organism from bacteria and yeasts to plants and animals. In heterotrophic organisms and nonphotosynthetic compartments of plant cells, the reducing power for Trx reduction is provided by NADPH in a reaction catalyzed by an NADPH-dependent Trx reductase (NTR; Jacquot et al., 2009). In contrast, redox regulation in plant chloroplasts has remarkable specific features. First, these organelles harbor a rather complex set of Trxs (Meyer et al., 2012; Serrato et al., 2013), while in heterotrophic organisms, Trx and NTR are encoded by small gene families. Moreover, the source of reducing
power for Trx reduction in chloroplasts is not NADPH, as in heterotrophic organisms, but reduced ferredoxin (Fdx); hence, chloroplasts are equipped with an Fdx-dependent Trx reductase (FTR; Schürmann and Buchanan, 2008), which is specific for these organelles. Based on the function of the FTR/Trx redox system, the classic view of the redox regulation of chloroplast metabolism states that metabolic pathways such as carbon assimilation by the Calvin-Benson cycle are active during the day due to the reductive activation of enzymes of the cycle, which relies on Fdx reduced by the photosynthetic electron transport chain, thus linking metabolic regulation to light (Michelet et al., 2013; Serrato et al., 2013).

The view of chloroplast redox regulation based on the action of the Fdx-dependent FTR/Trx system was modified after the discovery of a novel type of NTR with a joint Trx domain at the C terminus, which was termed NTRC (Serrato et al., 2004). NTRC is exclusive of organisms that perform oxygenic photosynthesis and shows plastid localization in plants (Kirchsteiger et al., 2012). Moreover, biochemical analyses revealed that NTRC is able to conjugate both NTR and Trx activities to efficiently reduce the hydrogen peroxide-scavenging enzyme 2-Cys peroxiredoxin (Moon et al., 2006; Pérez-Ruiz et al., 2006; Alkhalfioui et al., 2007). Arabidopsis (Arabidopsis thaliana) NTRC knockout mutants show a characteristic phenotype of retarded growth and pale green leaves, this phenotype being more severe under short-day conditions (Pérez-Ruiz et al., 2006; Lepistö et al., 2009). Based on these results, it was initially proposed that NTRC constitutes an NADPH-dependent redox system that might have a complementary function to the Fdx-dependent FTR/Trx system. Further evidence showed the participation of NTRC in the redox regulation of enzymes that were known previously to be Trx regulated. This is the case for ADP-Glc pyrophosphorylase (AGPase), a key enzyme of starch biosynthesis (Michalska et al., 2009; Lepistö et al., 2013) and of enzymes of the chlorophyll biosynthesis pathway (Richter et al., 2013; Pérez-Ruiz et al., 2014). These results suggest that chloroplast redox regulation depends on the cross talk of both Fdx/FTR/Trx and NTRC redox systems and, hence, is more complex than anticipated previously.

It was reported recently that a double mutant of Arabidopsis devoid of NTRC and Trx f1, which is the most abundant f-type Trx, shows a very severe growth inhibition phenotype and an almost complete abolishment of light activation of Fru-1,6-bisphosphatase (FBPase), a redox-regulated enzyme of the Calvin-Benson cycle (Thormählen et al., 2015). Furthermore, the Arabidopsis double mutant deficient in NTRC and FTR displays a lethal phenotype under autotrophic growth conditions (Yoshida and Hisabori, 2016), suggesting that NTRC and the Fdx/FTR/Trx systems act in concert in the redox regulation of common target genes in plants. Bifluorescence complementation assays showing that NTRC interacts in vivo with well-established Trx-regulated enzymes (Nikkonen et al., 2016), further supporting this notion. The question arising is whether the effect of NTRC is exerted only on Trxs such as those of the f type, which participate in the redox regulation of metabolic pathways, or also affects the activity of other types of Trxs. To address this issue, we analyzed the genetic interaction of NTRC with two functionally unrelated chloroplast Trxs: f type, as representative of Trxs involved in the redox regulation of metabolic pathways (Michelet et al., 2013), and x type, as representative of Trxs involved in antioxidant defense (Collin et al., 2003). The Arabidopsis ntrc-trxf1 f2 triple mutant and the ntrc-trxf1 f2 triple mutant were generated. While the Trx-deficient parental lines, trxf1 f2 and trxx, showed a visible phenotype similar to the wild-type plants when grown under long-day conditions, these deficiencies caused a severe growth inhibition phenotype when combined with the lack of NTRC. Moreover, the ntrc-trxx mutant and, to a higher extent, the ntrc-trxf1 f2 mutant showed a massive mortality at the seedling stage. These results reveal that NTRC is essential for the activity of unrelated Trxs, thus playing a pivotal role in chloroplast redox regulation, which is critical during early stages of plant development.

RESULTS

The Combined Deficiencies of NTRC and f- or x-Type Trxs Cause a Severe Growth Inhibition Phenotype and the Impairment of Light-Dependent Regulation of FBPase

In our attempt to establish the function of NTRC in chloroplast redox regulation, we studied the genetic interaction of NTRC with functionally divergent chloroplast Trxs, such as Trx f and Trx x. Previous results suggesting the concerted action of NTRC and Trx f1 were based on the severe growth-retarded phenotype of the Arabidopsis ntrc-trxf1 double mutant (Thormählen et al., 2015). However, this mutant still contains Trx f2, which constitutes approximately 10% of the total content of f-type Trxs in wild-type plants (Thormählen et al., 2013). To avoid any effect of the residual Trx f2 in its relationship with NTRC, we generated the triple mutant ntrc-trxf1 f2 devoid of NTRC and Trx f. In addition, the ntrc mutant was crossed with the trxx single mutant (Pulido et al., 2010) and the ntrc-trxx double mutant was obtained. These lines were effectively knockout mutants, as shown by the lack of transcripts of the corresponding genes in each of the mutants as determined by real-time quantitative PCR (RT-qPCR) analyses (Fig. 1A). As reported previously, the Trx-deficient lines trxf1 f2 (Naranjo et al., 2016a) and trxx (Pulido et al., 2010) showed a visible phenotype very similar to that of wild-type plants when grown under a long-day photoperiod (Fig. 1, B and C), while the ntrc mutant showed a growth-retarded and pale-green phenotype (Fig. 1, B and C), in agreement with previous results (Serrato et al., 2004; Lepistö et al., 2009). In contrast, the ntrc-trxx mutant, combining the deficiencies of NTRC and Trx x, showed a very severe growth-retarded phenotype, which was even more severe in the case of the ntrc-trxf1 f2 triple mutant (Fig. 1B). In line with their phenotypes, the ntrc-trxf1 f2 and ntrc-trxx mutants showed significantly
lower content of chlorophyll than their respective parent lines (Fig. 1C). It should be noted that, despite their severe growth inhibition, both the ntrc-trxx and ntrc-trxf1f2 mutants were able to produce flowers and viable seeds when grown under a long-day photoperiod. Therefore, while the lack of Trxs f or Trx x has little effect on plant phenotype, when these deficiencies are combined with that of NTRC, the effects become very severe.

To establish the impact of the combined deficiencies of NTRC and Trxs f and x on the redox regulation of chloroplast metabolic pathways, we analyzed FBPase, a well-established redox-regulated enzyme of the Calvin-Benson cycle. First, activity assays showed slightly lower FBPase activity in leaves of the ntrc, trxx, and trxf1f2 mutants than in the wild type, while the ntrc-trxx mutant showed lower activity, which was even lower in the ntrc-trxf1f2 mutant (Fig. 2A). It should be taken into account that Arabidopsis contains three isoforms of FBPase, one localized in the cytosol (Cséke and Buchanan, 1986) and two in the chloroplast (Serrato et al., 2009); hence, the FBPase activity determined here reflects the contribution of these isoforms. However, only one of the chloroplast-localized FBPase isoforms is redox regulated, and Arabidopsis mutants lacking this isoform have a more severe dwarf phenotype than mutants lacking the cytosolic isoform (Rojas-González et al., 2015). Thus, to get more insight into the function of NTRC, Trxs f, and Trx x in chloroplast redox regulation, we analyzed the light-dependent changes of the redox state of the plastid-localized FBPase isoform, which is known to be regulated by Trxs f but not by Trx x (Michelet et al., 2013). As reported previously (Thormählen et al., 2015; Naranjo et al., 2016a), thiol derivatization with the alkylating agent methyl-maleimide polyethylene glycol [MM(PEG)24] showed that FBPase was fully oxidized in leaves from dark-adapted wild-type plants and became reduced upon illumination, the level of reduction being dependent on light intensity (Fig. 2, B and C). The light-dependent FBPase reduction was partially impaired in the trxf1f2 mutant and, surprisingly, also in the trxx mutant (Fig. 2, B and C). Interestingly, the degree of FBPase photoreduction was even lower in the ntrc mutant and was almost abolished in mutants combining the deficiency of NTRC with those of Trx x or Trxs f (Fig. 2, B and C), in agreement with previous studies with ntrc-trxf1 double mutants (Thormählen et al., 2015). Illumination with higher light intensity resulted in a higher level of enzyme reduction, although the pattern of FBPase reduction of the different lines was similar to that obtained under growth light (Fig. 2, B and C).

These results are surprising, since biochemical analyses have shown that FBPase is regulated by Trxs f but not by NTRC (Yoshida and Hisabori, 2016) or Trx x (Collin et al., 2003). Thus, to analyze further the role of these thiol redox systems in the regulation of FBPase, we performed in vitro assays with the purified enzymes. While almost full reduction of FBPase was accomplished with 0.5 μM concentration of either Trx f1 or Trx f2, the concentration of Trx x needed to obtain a similar level of...
FBPase reduction was at least 10-fold higher (Fig. 3), which is in contrast with the similar level of impairment of light-dependent FBPase reduction in the trxx and trxf1f2 mutants (Fig. 2, B and C). Moreover, NTRC did not show any capacity to reduce FBPase in vitro (Fig. 3), despite the fact that the degree of light-dependent FBPase reduction was greatly decreased in the ntrc mutant (Fig. 2, B and C). The severe impairment of the light-dependent reduction of FBPase in the ntrc-trxx and ntrc-trxf1f2 mutants demonstrates the concerted action of both NTRC and f- or x-type Trxs on FBPase redox regulation, although these results suggest that NTRC affects FBPase redox regulation by an indirect mechanism.

The Combined Deficiencies of NTRC and f- or x-Type Trxs Affect Photosynthetic Performance and Chloroplast Structure

The effects of the combined deficiencies of NTRC and Trxs f or Trx x on plant growth (Fig. 1) and the activity (Fig. 2A) and redox regulation (Fig. 2, B and C) of FBPase suggest that the impairment of these redox regulatory systems affects photosynthesis performance. Previous reports have shown that the deficiency of NTRC, but not of Trxs f or Trx x, provokes enhanced nonphotochemical quenching (NPQ) at low light intensity (Naranjo et al., 2016a, 2016b), hence causing a poor efficiency in the utilization of light energy by the ntrc mutant. Thus, as a first step to determine the effect of the combined deficiencies of NTRC and Trxs f or x on photosynthetic performance, we analyzed NPQ in the different lines under study. In agreement with previous results, the ntrc mutant showed enhanced NPQ at light intensity as low as 42 \( \mu \text{mol quanta m}^{-2} \text{s}^{-1} \), while NPQ was enhanced only slightly in the trxx and trxf1f2 mutants (Fig. 4A). Similar to the ntrc mutant, ntrc-trxx and ntrc-trxf1f2 plants showed extended NPQ values during the whole illumination period; however, NPQ did not decay completely in the period of darkness as it did in ntrc plants (Fig. 4A), showing that light utilization in...
ntrc-trxx and ntrc-trxf1f2 mutants was even less efficient than in the ntrc mutant. In line with these results, the photosynthetic ETR also was impaired. In line with these results, the photosynthetic ETR also was impaired. The deficiency of NTRC affected the photosynthetic ETR more severely than the deficiency of Trxs x and f (Fig. 4B). Notably, both the ntrc-trxx and ntrc-trxf1f2 mutants showed dramatically reduced photosynthetic ETR at any of the light intensities analyzed (Fig. 4B). Moreover, the stability of PSII, determined as the ratio of variable fluorescence to maximal fluorescence ($F_v/F_m$), which was affected slightly in the ntrc and trxx mutants, also was severely affected in the mutants combining the deficiencies of NTRC with those of f-type Trxs (Table I). Finally, the net rate of CO$_2$ fixation ($A_N$) at growth light intensity ($125 \mu$E m$^{-2}$ s$^{-1}$), which was lower in the ntrc mutant but unaffected in the trxx and trxf1f2 mutants, compared with the wild type, showed negative values in the ntrc-trxx and ntrc-trxf1f2 mutants (Fig. 4C), indicating that the rates of respiration and photorespiration were higher than the rate of CO$_2$ fixation in these plants. Moreover, the severe impairment of photosynthetic performance in mutants simultaneously devoid of NTRC and f- or x-type Trxs has a wider effect on chloroplast metabolism, as shown by the content of starch, which also was severely decreased in these mutants (Table I). Therefore, these results show that the simultaneous deficiency of NTRC and Trxs f or x has a severe effect on photosynthesis performance, in line with the severe growth inhibition phenotype of these mutants.

Such a defective photosynthetic performance of the ntrc-trxx and ntrc-trxf1f2 mutants suggested as well alterations in chloroplast morphology. To test this possibility, the chloroplast structure in the different lines under study was analyzed by transmission electron microscopy. The ntrc mutant contains chloroplasts with different levels of ultrastructural alterations, as reported previously (Pérez-Ruiz et al., 2006; Lepistö et al., 2009), while chloroplasts in the trxx and trxf1f2 mutants showed similar morphology to those in the wild type (Fig. 5). In contrast, the ntrc-trxx and, to a higher extent, the ntrc-trxf1f2 mutants showed heterogenous chloroplast ultrastructure, with a number of chloroplasts showing clear alterations (Fig. 5). The most remarkable characteristic of chloroplasts from both the ntrc-trxx and ntrc-trxf1f2 mutants was the increased number and size of plastoglobules (Fig. 5), which is indicative of oxidative stress and senescence (Austin et al., 2006). As an additional approach to determine the effect of the combined deficiencies of NTRC and Trxs f or Trx x on chloroplast function, selected proteins indicative of the different chloroplast compartments were analyzed by western blot. The ntrc-trxx and ntrc-trxf1f2 mutants showed decreased levels of D1, a core component of PSII, PsAC, a core component of PSI, lhca1, a component of the

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Light-dependent NPQ, linear photosynthetic electron transport rate (ETR), and net CO$_2$ assimilation rate ($A_N$) in wild-type (WT) and mutant lines. A and B, Quantum yields of NPQ ($Y_{NPQ}$; A) and relative linear ETRs of PSII (ETR (II); B) were measured in preilluminated attached leaves of plants grown at 125 $\mu$E m$^{-2}$ s$^{-1}$ under long-day conditions. Chlorophyll fluorescence of PSII was determined using a pulse-amplitude modulation fluorimeter. Determinations were performed at least five times, and each data point is the mean ± se. White and black bars indicate light and dark periods. C, $A_N$ was measured using an open gas-exchange system in leaves of plants grown during 4 weeks under a long-day photoperiod, dark adapted, and then illuminated with a photosynthetically active radiation of 125 $\mu$E m$^{-2}$ s$^{-1}$. Six leaves were measured per line, and means ± se are represented. Letters indicate significant differences by Tukey’s test and a confidence interval of 99.9%.
The maximum PSII quantum yield was determined as \( F_{v}/F_{m} \) in dark-adapted leaves of plants grown under long-day conditions. The \( F_{v}/F_{m} \) values ± SD are averages of at least 10 measurements. The content of starch was determined from rosette leaves of plants grown under long-day conditions for 31 d and harvested after 12 h of the light period. Values represent means ± SD of three independent samples. Letters indicate significant differences by Student’s t test (\( F_{v}/F_{m} \)) or Tukey’s LSD test (starch content) and a confidence interval of 95%.

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<tr>
<th>Parameter</th>
<th>Wild Type</th>
<th>ntrc</th>
<th>Plant Line</th>
<th>trx112</th>
<th>ntrc-trxx</th>
<th>ntrc-trxf1f2</th>
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<td>( F_{v}/F_{m} )</td>
<td>0.78 ± 0.03 a</td>
<td>0.76 ± 0.02 b</td>
<td>0.75 ± 0.03 b</td>
<td>0.79 ± 0.02 a</td>
<td>0.62 ± 0.11 c</td>
<td>0.52 ± 0.10 d</td>
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<tr>
<td>Starch (( \mu g \text{mg}^{-1} \text{fresh wt} ))</td>
<td>8.11 ± 2.06 a</td>
<td>2.25 ± 0.49 c,d</td>
<td>4.36 ± 0.81 b</td>
<td>3.57 ± 1.65 b,c</td>
<td>0.82 ± 0.34 d</td>
<td>1.59 ± 0.51 d</td>
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The Combined Deficiencies of NTRC and f- or x-Type Trxs Cause High Mortality at the Seedling Stage

A remarkable feature of the ntrc-trxx and ntrc-trxf1f2 mutants was the low number of individuals that reached...
The high mortality of the ntrc-trxx and ntrc-trxf1f2 mutants at the transition from seedling to true leaves suggests that photosynthesis performed by cotyledon chloroplasts is critical for the development of vegetative organs. However, these assays were performed in soil and, thus, the nutritional conditions could not be strictly controlled. Therefore, we analyzed in more detail the contribution of photosynthesis in cotyledons to seedling development. To this end, the generation of roots as a sink organ was studied in synthetic medium supplemented or not with Suc under continuous light. Like the wild type, seedlings of the ntrc, trxx, and trxf1f2 mutants produced roots regardless of the presence of Suc in the medium (Fig. 8). In contrast, root formation was completely abolished or severely impaired in seedlings of the ntrc-trxf1f2 or ntrc-trxx mutants, respectively (Fig. 8, A and B). Root elongation was restored by the addition of external Suc, although the rate of root growth was still decreased in the ntrc-trxx and ntrc-trxf1f2 mutants, as compared with the other lines under analysis (Fig. 8, A and C). These results show the relevance of redox regulation in the photosynthetic activity of cotyledon chloroplasts for early plant development.

DISCUSSION

NTRC Acts in Concert with Different Types of Trxs to Sustain Chloroplast Function

Chloroplasts play important roles in plant metabolism and development. A key component of the rapid adjustment of chloroplast metabolism to ever-fluctuating light conditions is the redox regulation of enzyme activity, which relies on two thiol redox systems, the NAPDH-dependent NTRC and the Fdx-dependent FTR/Trx pathways (Spinola et al., 2008; Cejudo et al., 2012). Thus, a central issue in understanding chloroplast redox regulation is to establish the functional relationship between these two redox systems and the relevance of chloroplast redox regulation to plant development. In this work, we addressed this issue by performing a comparative analysis of Arabidopsis mutants combining the deficiency of NTRC with that of two Trxs proposed previously to have unrelated functions, such as Trx f, which participate in the redox regulation of metabolic pathways (Michelet et al., 2013), and Trx x, which was proposed to have antioxidant function (Collin et al., 2003). Based on our results, we propose that NTRC exerts a pivotal role in chloroplast redox regulation. Moreover, the high mortality of ntrc-trxx and, to a higher extent, ntrc-trxf1f2 seedlings uncovers the essential function of cotyledon chloroplast redox regulation for early stages of plant development.

Chloroplasts harbor a complex set of different Trxs (Meyer et al., 2012; Balsera et al., 2014). Based on extensive biochemical analyses, it was established that Trxs of types m and f are relevant in the redox regulation of metabolic pathways (Buchanan and Balmer, 2005; Michelet et al., 2013; Okegawa and Motohashi, 2015), while those of types x and y were proposed to perform antioxidant

Figure 6. Levels of representative chloroplast proteins in wild-type (WT) and mutant plants. Western-blot analysis is shown for the content of representative components of photosynthetic electron transport (D1, Lhcb1, Psac, and Lhca1), ATP synthesis (α-ATPase and γ-ATPase), and carbon assimilation (RBC-L) in the lines under study. Chloroplasts of the indicated lines were isolated from 5-week-old long-day-grown plants and fractionated into thylakoid and stromal fractions as described in “Materials and Methods.” Protein samples corresponding to thylakoids (0.5 μg of chlorophyll) or stroma (1 μg of protein) were subjected to SDS-PAGE under reducing conditions, transferred to nitrocellulose filters, and probed with antibodies against thylakoid (D1, Lhcb1, Psac, Lhca1, α-ATPase, and γ-ATPase) and stromal (RBC-L) proteins. Additional amounts (3× and 1/4×) of wild-type extracts were loaded for comparison. The experiment was performed twice with similar results.

Chloroplasts harbor a complex set of different Trxs (Meyer et al., 2012; Balsera et al., 2014). Based on extensive biochemical analyses, it was established that Trxs of types m and f are relevant in the redox regulation of metabolic pathways (Buchanan and Balmer, 2005; Michelet et al., 2013; Okegawa and Motohashi, 2015), while those of types x and y were proposed to perform antioxidant
activity (Collin et al., 2003, 2004). However, despite the major function proposed for Trxs f in the redox regulation of central metabolic pathways, such as the Calvin-Benson cycle, Arabidopsis mutants devoid of Trx f1 (Thormählen et al., 2013) or Trx f1 and f2 (Yoshida et al., 2015; Naranjo et al., 2016a) show a visible phenotype very similar to that of the wild type, as does an Arabidopsis mutant devoid of Trx x (Pulido et al., 2010). These results indicate that alternative redox systems, either additional chloroplast Trxs or NTRC, might compensate for the deficiency of these Trxs. In contrast, when the deficiency of Trx f1 (Thormählen et al., 2015), Trxs f1 and f2, or Trx x is combined with the deficiency of NTRC, a dramatic effect on plant phenotype is produced (Fig. 1, B and C). As reported previously (Thormählen et al., 2015; Naranjo et al., 2016a, 2016b), the deficiency of NTRC causes more severe impairment on photosynthesis performance than the deficiency of type-f Trxs, as shown by the extensive NPQ at low light intensity, the lower photosynthetic ETR, and the rate of carbon fixation (Fig. 4) in the ntrc mutant. Remarkably, these parameters were affected dramatically in both the ntrc-trxx and ntrc-trxf1f2 mutants, thus showing the poor efficiency of light energy utilization by these mutants, which has a wide effect on chloroplast metabolism, as indicated by the lower content of starch in these mutants (Table I).

Figure 7. Redox regulation impairment provokes high mortality at the seedling stage. A, Seeds of wild-type (WT) and mutant lines, as indicated, were allowed to germinate on soil, and representative seedlings at 5, 8, and 11 d after germination (dag) are shown. Bars = 0.5 cm. B and C, For each line, the percentage of seedlings with emerging true leaves (B) and the percentage of seedlings that remained alive (C) at the indicated days after germination were determined and represented. The experiment was performed twice, and mean values ± ss from three replicates of each experiment are represented.
The results discussed above provide an explanation for the severe growth inhibition phenotype of the ntrc-trxx and ntrc-trxf1f2 mutants and suggest the concerted action of both systems in the redox regulation of common targets in vivo, a notion further supported by the finding that NTRC interacts with well-established Trx targets (Nikkanen et al., 2016). Indeed, NTRC has been shown to participate in the regulation of enzymes such as AGPase (Michalska et al., 2009) and different enzymes of the pathway of tetrapyrrole synthesis (Richter et al., 2013; Pérez-Ruiz et al., 2014; Yoshida and Hisabori, 2016), which were identified previously as Trx regulated (Ballicora et al., 2000; Geigenberger et al., 2005; Ikegami et al., 2007). Here, we addressed this issue by analyzing FBPase, a well-established redox-regulated enzyme of the Calvin-Benson cycle. The impairment of redox regulation caused by the combined deficiencies of NTRC and Trxs affected FBPase, as shown by the lower level of activity of this enzyme in leaves of the ntrc-trxx and ntrc-trxf1f2 mutants (Fig. 2A). Interestingly, the in vivo level of FBPase reduction in response to light was lower in the ntrc mutant than in the trxf1f2 and trxx mutants (Fig. 2B). However, in vitro assays showed that Trxs f1 and f2 are more efficient reductants of FBPase than Trx x, while NTRC is unable to reduce the enzyme (Fig. 3). These results strongly support the notion that the in vivo effect of NTRC on the redox regulation of FBPase is indirect. The deficiency of NTRC may cause an imbalance of the redox state of the chloroplast, which, in turn, affects the regulatory function of Trxs f with respect to its targets.

Trxs f and x interact with different targets (Collin et al., 2003; Yoshida et al., 2015) and, hence, are considered to have different functions in chloroplast redox regulation (Meyer et al., 2012). Thus, an additional issue addressed in this work was to establish whether NTRC is required specifically for the activity of Trxs involved in the regulation of metabolic pathways, such as Trxs f, or is also required for Trxs involved in antioxidant defense, such as Trx x. The trxx mutant shows a phenotype indistinguishable from the wild-type plants (Pulido et al., 2010), whereas the ntrc-trxx double mutant shows a severe growth-retarded phenotype (Fig. 1, B and C) and impairment of photosynthetic performance (Fig. 4; Table I), thus indicating that the function of Trx x is dispensable in plants containing NTRC but is not properly exerted in the absence of NTRC. It should be noted that the level of light-dependent FBPase reduction was affected similarly in the trxx and trxf1f2 mutants (Fig. 2, B and C). However, Trxs f, which are
about 4-fold more abundant than Trx x in Arabidopsis chloroplasts (Okégawa and Motohashi, 2015), are more efficient reductants of FBPase in vitro than Trx x (Fig. 3). The phenotype of the ntrc-trxf1f2 mutant is more severe than that of the ntrc-trxx mutant at the stage of adult plant (Fig. 1B), seed germination capacity (Supplemental Fig. S1), or seedling viability (Fig. 7), suggesting that the functions of Trxs f are more relevant for plant growth than those of Trx x.

The deficiency of the redox regulatory network in the ntrc-trxx and ntrc-trxf1f2 mutants has a dramatic impact on photosynthetic performance, as shown by the high levels of NPQ at low light intensities (Fig. 4A), the corresponding decrease of the photosynthetic ETR (Fig. 4B), PSII activity based on the Fv/Fm (Table I), and the rate of net photosynthesis (Fig. 4C). Previous reports have shown that the deficiency of NTRC causes the impairment of light utilization and slightly affects the redox state of the γ-subunit of ATPase, hence affecting the qE component of NPQ (Carrillo et al., 2016; Naranjo et al., 2016b). Therefore, the combined deficiency of NTRC and f- or x-type Trxs affects the redox regulation of chloroplast metabolic pathways such as the Calvin-Benson cycle but also the efficiency of light utilization, which ultimately might be the reason for the severe growth-retarded phenotype shown by the ntrc-trxx and ntrc-trxf1f2 mutants. These results reveal the pivotal role of NTRC in the thiol redox network of the chloroplast stroma, integrating the feedback control of photochemical reactions and the regulation of metabolic pathways. Moreover, a combined deficiency in NADPH- and Fdx-dependent chloroplast redox networks has severe effects on the structure of these organelles, as shown by the presence of chloroplasts with aberrant ultrastructure in both the ntrc-trxx and ntrc-trxf1f2 mutants (Fig. 5) and the lower content of representative components of PSI, PSII, and ATPase (Fig. 6).

Therefore, the severe growth phenotype of the ntrc-trxx and ntrc-trxf1f2 mutants is the result of the effect of these mutations on a wide variety of chloroplast processes from photochemical reactions to carbon metabolism. Our results indicate that the regulation of these processes is coordinated and that NTRC exerts a central function in this coordination. The question arising is the mechanistic basis of this central function of NTRC in chloroplast redox regulation. A possibility is that the lower efficiency of light energy utilization caused by the lack of NTRC (Fig. 4) affects the availability of reducing equivalents for Trxs, hence impairing the light-dependent redox regulation of Calvin-Benson enzymes such as FBPase. This would provide an explanation for the lower level of reduction of FBPase in NTRC-deficient plants (Fig. 2), despite the fact that NTRC is unable to reduce FBPase in vitro (Fig. 3). An additional aspect to be taken into account is that the deficiency of NTRC may perturb chloroplast redox balance affecting the Trx activity. In this regard, it should be noted that the chloroplasts of the ntrc-trxx and ntrc-trxf1f2 mutants show higher number and size of plastoglobules (Fig. 5), which are indicative of oxidative stress (Austin et al., 2006), hence suggesting that the severe alteration of the redox regulatory network in these mutants also has important effects on the antioxidant machinery of the chloroplast. Indeed, NTRC is an efficient reductant of the peroxide-scavenging enzyme 2-Cys peroxiredoxin (Pérez-Ruiz et al., 2006; Pulido et al., 2010).

The Concerted Action of f- and x-Type Trxs and NTRC

Most studies on chloroplast redox regulation have been performed at the adult plant stage, hence when leaves are fully developed. However, besides the severe growth inhibition of the ntrc-trxx and ntrc-trxf1f2 mutants (Fig. 1, B and C), a remarkable feature of the phenotype of these mutants was the low number of individuals that reached the adult phase (Fig. 7), suggesting that the photosynthetic function becomes critical at earlier stages of plant development. It is known that embryonic photosynthesis affects seed vigor (Allore et al., 2015); thus, the lower germination capacity of seeds of the ntrc-trxf1f2 mutant (Supplemental Fig. S1) suggests the relevance of plastid redox regulation in seed germination. It should be noted that the ntrc-trxx mutant shows germination capacity similar to that of the wild type (Supplemental Fig. S1), which is in line with the other phenotypic parameters analyzed here, most of them being more affected in the ntrc-trxf1f2 mutant than in the ntrc-trxx mutant.

A critical stage in the plant life cycle occurs after seed germination, when the growing seedling depends on the heterotrophic use of seed storage compounds until autotrophic growth is possible (Kircher and Schofer, 2012). Once germinated, the cotyledons of the ntrc-trxx and ntrc-trxf1f2 mutants were slightly smaller and showed yellowish green color, compared with cotyledons from the wild type or the ntrc, trxx, and trxf1f2 mutants (Fig. 7A). This indicates that the developmental program of photomorphogenesis is not compromised by the impairment of chloroplast redox regulation at this early stage of development. This notion was further supported by growth tests in synthetic medium supplemented or not with Suc (Fig. 8A). In contrast with the wild type and the ntrc, trxx, and trxf1f2 mutants, which produced roots in the absence of Suc, root production was severely defective in the ntrc-trxx mutant and abolished completely in the ntrc-trxf1f2 mutant unless Suc was added to the medium to compensate for decreased photosynthesis (Fig. 8). These results provide further evidence that the impairment of redox regulation caused by the combined deficiency in NTRC and Trxs f or Trx x severely affects the photosynthetic performance of cotyledon chloroplasts. However, while in adult plants this failure causes growth retardation but is not lethal, in the case of cotyledons it produces a delay in the generation of new organs such as roots and true leaves, which provokes increased seedling mortality (Fig. 7). Photomorphogenesis, the reprogramming of seedling growth promoted by light, has received much attention,

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and a complex set of light perception and signaling components has been identified (Huang et al., 2014; Wu, 2014; Pogson et al., 2015). Less attention has been given to the contribution of photosynthesis to this developmental process. The reduced viability of the ntrc-trxx and, to a higher extent, the ntrc-trxf1f2 seedlings uncovers the essential function of the redox regulation of photosynthesis at this developmental stage.

MATERIALS AND METHODS

Biological Material and Growth Conditions

Arabidopsis (Arabidopsis thaliana) wild-type (ecotype Columbia) and mutant plants were routinely grown in soil in growth chambers under long-day conditions (16 h of light/8 h of darkness) at 22°C during the dark periods and a light intensity of 125 μE m⁻² s⁻¹. In vitro culture experiments, seeds were surface sterilized using chlorine gas for 16 h, plated on MS medium (Duchefa), pH 5.8, containing 0.35% (w/v) Gelrite (Duchefa) in the presence or absence of 0.5% (w/v) Suc, and stratified at 4°C for 2 to 3 d. Mutant plants ntrc, trxx, and trxf1f2 were described previously (Serrato et al., 2004; Pulido et al., 2010; Naranjo et al., 2016a; Supplemental Table S1). The single ntrc mutant was crossed manually with the single trxx mutant and the double trxf1f2 mutant. Seeds resulting from these crosses were checked for heterozygosity of the T-DNA insertions in the mutant. Seeds resulting from these crosses were checked for heterozygosity of the T-DNA insertions in the mutant and the double trxf1f2 mutant. Plants were then self-pollinized, and the ntrc-trxx and ntrc-trxf1f2 mutants were identified in the progeny by PCR analysis of genomic DNA. Primer sequences for PCR are listed in Supplemental Table S2.

RNA Extraction and RT-qPCR Analysis

Total RNA was extracted using Trizol reagent (Invitrogen). cDNA synthesis was performed with 2 μg of total RNA using the Maxima first-strand cDNA synthesis kit (Fermentas) according to the manufacturer’s instructions. RT-qPCR was performed using an IQ5 real-time PCR detection system (Bio-Rad). A standard thermal profile (95°C for 3 min, followed by 40 cycles of 95°C for 10 s and 60°C for 30 s) was used for all reactions. After the PCR, a melting-curve analysis (95°C for 1 s, 60°C for 30 s, and 98°C for 1 s) was performed to confirm the specificity of the amplicon and to exclude primers-dimers or nonspecific amplification. Oligonucleotides used for the RT-qPCR analyses are listed in Supplemental Table S3. Expression levels were normalized using two reference genes: ACTIN and AT5G25760 (Czechowski et al., 2005).

Protein Extraction, FBPs, Activity, Alkylation Assays, and Western-Blot Analysis

Plant tissues were ground with a mortar and pestle in liquid nitrogen. FBPs activity was determined as reported previously (Rojas-González et al., 2015) from leaves of plants grown for 4 weeks under long-day conditions for 4 weeks using an open gas-exchange system (Li-6400) equipped with the chamber head (Li-6400-40). Leaves were dark adapted and then illuminated with photosynthetically active radiation of 125 μE m⁻² s⁻¹ until the rate of CO2 assimilation was stabilized. Six leaves were measured per line. Measurements were performed by the Service for Photosynthesis, Instituto de Recursos Naturales y Agrobiología, Sevilla, Spain.

Determination of Chlorophylls, Starch, and FBPs Activity

Leaf discs were weighed and frozen in liquid nitrogen. After extraction in 1 mL of methanol at 4°C, chlorophyll levels were measured spectrophotometrically, as described by Porra et al. (1989), and normalized to fresh weight. Starch contents were determined as reported previously (Rojas-González et al., 2015) from rosette leaves of plants grown for 4 weeks under a long-day photoperiod and harvested at 12 h of the day period.

Measurements of Chlorophyll a Fluorescence and A\textsubscript{N}

Room temperature chlorophyll fluorescence was measured using a pulse-amplitude modulation fluorometer (DUAL-PAM-100; Walz). The maximum quantum yield of PSII was assayed after incubation of plants in the dark for 30 min by calculating F\textsubscript{V}/F\textsubscript{M}. Induction-recovery curves were performed using red (635 nm) actinic light at 42 μE m⁻² s⁻¹ for 8 min. Saturating pulses of red light at 10,000 μE m⁻² s⁻¹ intensity and 0.6-s duration were applied every 60 s, and recovery in darkness was recorded for up to 10 min. The parameters Y(I) and Y(NPQ), corresponding to the respective quantum yields of PSII photochemistry and NPQ, were calculated by the DUAL-PAM-100 software according to the equations of Kramer et al. (2004). Relative linear ETs were measured in leaves of preilluminated plants by applying stepwise increasing actinic light intensities up to 2,000 μE m⁻² s⁻¹. A\textsubscript{N} was measured in leaves from wild-type and mutant plants grown under long-day conditions for 4 weeks using an open gas-exchange system (Li-6400) equipped with the chamber head (Li-6400-40). Leaves were dark adapted and then illuminated with photosynthetically active radiation of 125 μE m⁻² s⁻¹ until the rate of CO2 assimilation was stabilized. Six leaves were measured per line. Measurements were performed by the Service for Photosynthesis, Instituto de Recursos Naturales y Agrobiología, Sevilla, Spain.

Determination of Seedling Development and Survival

The growth and development of the lines under study were monitored based on two parameters: the formation of true (postembryonic) leaves and seedling mortality. For each line, three sets of at least 60 seeds were sown on soil and grown during 28 d under long-day conditions. Seedling survival and true leaf generation were scored at 3- to 4-d intervals. Seedlings that were still green/greenish, considered as survivors, were quantified to calculate the survival rate. Seedlings that exhibited true leaves were quantified to determine the rate of seedlings reaching the true leaf stage.

Root Growth and Germination Capacity Measurements

For root growth assays, at least 30 seedlings were grown for 7 d on vertically oriented MS plates in the presence or absence of 0.5% (w/v) Suc. Root elongation was scored at 1-d intervals from day 3 until day 7.

For germination studies, five sets of at least 100 seeds were sown on horizontally oriented MS plates, and the percentage of germinated seeds was recorded at day 2 and day 7.

Transmission Electron Microscopy Analysis

Fully expanded leaves from plants cultured under a long-day photoperiod were collected at bolting time, after approximately 28 d of growth, just when the first floral bud was visible. Since the growth of ntrc-trxx and ntrc-trxf1f2 plants is delayed, the leaves of these mutants were collected after approximately 60 d of growth. Small pieces (2 mm²) of leaves were cut with a razor blade and immediately fixed in 4% glutaraldehyde in 0.1 M sodium-cacodylate buffer, pH 7.4 (3 h at 4°C, under vacuum). After fixation, samples were rinsed three times for 30 min at 4°C with the same buffer. Samples were postfixed in 1% (w/v) osmium tetroxide in cacodylate buffer (0.1 M, pH 7.4) for 1 h at 4°C. After washing, samples were immersed in 2% (w/v) uranyl acetate, dehydrated through a gradient acetone series (50%, 70%, 90%, and 100%), and embedded in Spurr’s resin. Semithin sections (300 nm thickness) were obtained with a glass
Supplemental Data

The following supplemental materials are available.

Supplemental Figure S1. Effect of the deficiency in NTRC and x- or f-type Trxs on germination capacity.

Supplemental Table S1. Arabidopsis mutants used in this study.

Supplemental Table S2. Oligonucleotides used for the determination of Arabidopsis mutant genes.

Supplemental Table S3. Oligonucleotides used for RT-qPCR analyses.

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LITERATURE CITED


