The role of phosphorylation and dephosphorylation in the regulation of Rubisco activase

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SUMMARY

Rubisco activase (Rca) is an ATP-dependent chaperone that facilitates dissociation of inhibitory sugar phosphates from the catalytic sites of ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) during photosynthesis. In Arabidopsis, Rca is negatively regulated by dark-dependent phosphorylation of Thr78. Here we identify chloroplast localized *SHEWENELLA-LIKE PROTEIN PHOSPHATASE 1 (SLP1)* as the major phosphatase responsible for light-dependent Rca dephosphorylation. The prevalence of Thr78 in Rca was investigated across sequences from 91 plant species, finding 29 (~32%) species shared a threonine in the same position. Analysis of seven C3 species with an antibody raised against a Thr78 phospho-peptide demonstrated that this position is phosphorylated in multiple genera. However, light-dependent dephosphorylation of Thr78 was observed only in Arabidopsis. Further, phosphorylation of Thr78 could not be detected in any of the four C4 grass species examined. The results suggest that despite conservation of Thr78 in Rca from a wide range of species, a regulatory role for phosphorylation at this site may be limited. This provides a case study for how variation in post-translational regulation can amplify functional divergence across the phylogeny of plants beyond what is explained by sequence variation in a metabolically important protein.

INTRODUCTION

Photosynthesis provides energy for all forms of life involving light-driven fixation of carbon dioxide and water into carbohydrates while producing oxygen. The rate and efficiency of this system depends upon several factors. Under saturating light, or low CO_2 concentrations, the activity of Ribulose-1,5-bis-phosphate carboxylase/oxygenase (Rubisco) is commonly limiting (Stitt *et al.*, 1991; Hudson *et al.*, 1992; Stitt & Schulze, 1994; Poolman *et al.*, 2000; Zhu *et al.*, 2007). In turn, Rubisco activation state is regulated by Rubisco activase (Rca), a member of the AAA+ ATPase superfamily (Somerville et al., 1982; Salvucci et al., 1986; Jiang et al., 1994). During CO_2 fixation, five carbon sugar phosphates can bind to Rubisco active sites preventing catalysis or blocking activation, by preventing carbamylation of Lys-21 (Orr et al., 2023). Rca uses energy from ATP hydrolysis to drive conformational changes in Rubisco, facilitating the release of the inhibitory sugar phosphates from the Rubisco active site (Neuwald et al., 1999; Portis & Jr., 2003; Flecken et al., 2020). Thus, Rca is critical for regulation of Rca activity and carbon assimilation. This also makes it a target to improve photosynthetic efficiency in crop plants (Parry et al., 2013; Wijewardene et al., 2021; Qu et al., 2023; Orr et al., 2023).

Most species produce two forms of Rca, α and β which can form mixed complexes (Salvucci et al., 1985; Zhang & Portis, 1999a), with the longer α isoform possessing a 20-30 amino acid C-terminal extension (To et al., 1999). Isoforms can arise from alternate splicing(Werneke et al., 1989; Rundle & Zielinski, 1991; To et al., 1999), or from transcription of independent genes (Rundle & Zielinski, 1991; Salvucci et al., 2003). The relative expression level, thermostability and catalytic properties of Rca-α and Rca-β differ across species (Rundle & Zielinski, 1991; Crafts-Brandner et al., 1997; Carmo-Silva & Salvucci, 2013; Shivhare & Mueller-Cajar, 2017; Degen et al., 2021) and can be impacted by environmental factors (Shivhare & Mueller-Cajar, 2017; Scafaro et al., 2019; Kim et al., 2020, 2021; Degen et al., 2021). Some species have almost equal abundance of both isoforms (e.g., Arabidopsis), whereas in others Rca-β is more highly expressed (Salvucci et al., 1987). In several C4 grasses such as sorghum, only the Rca-β isoform is abundant under normal growing conditions, while Rca-α upregulated under stress (Sanchez de Jimenez et al., 1995; Crafts-Brandner & Salvucci, 2002; Ristic et al., 2009; Yin et al., 2010). In contrast in wheat one of two β isoforms is induced at elevated temperature (Degen et al., 2021).

Some forms of Rca are sensitive to inhibition by ADP (Robinson & Portis, 1989). Most of our understanding about this process comes from Arabidopsis, where the C-terminal extension of Rca-α contains two cysteine residues (Cys-451 and Cys-470), which are regulated by thioredoxin f in response to ATP/ADP ratio (Zhang & Portis, 1999b; Zhang et al., 2002). In an oxidized state, the two cysteine residues form a disulfide bridge (oxidized state, E_m ~344 mV pH 7.9), and C-terminal domain then interacts with the nucleotide binding pocket, increasing the sensitivity of Rca to inhibition by ADP (Portis et al., 2007). This downregulates Rca activity, in accordance with the redox state of the chloroplast stroma. In contrast, the activities of AtRca-β are unaffected by thioredoxin (Zhang et al., 2002). Thus Rca-α provides a mechanism to fine-tune Rubisco activation state in dynamic light environments. However, redox regulation of Rca does not appear to be essential. The sensitivity of Rca-β isoforms to inhibition by ADP varies (Carmo-Silva & Salvucci, 2013). Further, studies with transgenic Arabidopsis mutants expressing only Rca-α showed lower Rubisco activation and impaired growth (Zhang et al., 2002; Kim et al., 2020), while plants only expressing Rca-β had higher biomass accumulation under fluctuating light, where the impact of the rate of Rubisco reactivation on net carbon gain is amplified relative to non-fluctuating light (Carmo-Silva & Salvucci, 2013). Solanaceae species, such as tobacco, are reported to only express Rca-β under normal conditions (Nagarajan & Gill, 2018). Instead of redox regulation, activity of tobacco Rca-β is sensitive to the ratio of ADP/ATP, the precise mechanism behind this sensitivity is unclear, but it has been demonstrated to be caused by a substitution in one of 17 amino acid positions which vary between Arabidopsis and tobacco sequences (Carmo-Silva & Salvucci, 2013). ADP sensitivity alone may therefore explain control of Rca in species or mutants lacking an α isoform (Carmo-Silva & Salvucci, 2013).

Post-translational modification of Rca may add a supplemental layer of regulation (Amaral et al., 2024). Phosphorylation of Threonine 78 (Thr78) in Arabidopsis Rca was identified during a phospho-proteomic screen of dark-harvested leaf proteins (Reiland *et al.*, 2009). Subsequent research showed Thr78 was phosphorylated in the dark and under low light intensities, but not under high light, suggesting a regulatory role (Reiland *et al.*, 2009; Boex□Fontvieille *et al.*, 2014; Kim *et al.*, 2016). Functional support for this hypothesis came from several findings:(1) phosphorylation at Thr78 (Thr78-Rca) in Arabidopsis caused a significant decrease in plant biomass that was linked to a decreased Rubisco activation state(Kim

et al., 2019); (2) transgenic Arabidopsis expressing phospho-null mutants of Rca (T78A) had enhanced photosynthetic efficiency and plant growth; and (3) substitution of Thr78-to-Ser (T78S) resulted in hyper-phosphorylation, and the transgenic plants expressing T78S-Rca showed reduced carbon assimilation rate and slower plant growth under continuous and fluctuating-light regimes (Kim *et al.*, 2019).

cpCK2 was shown to be the major kinase responsible for dark phosphorylation of AtRca, with T-DNA insertion, loss-of-function mutant lines showing a reduction in Rca phosphorylation (Kim *et al.*, 2016) but the phosphatase that is active in the light has not been identified. In addition to the PPH/TAP3 and PBCP phosphatases that act in opposition to STN7 and STN8 to regulate the kinetics of state transitions (Samol *et al.*, 2012), several other phosphatases belonging to phosphoprotein phosphatase (PPP), protein phosphatase 2C (PP2C), and phosphotransferase gene families have been reported to be localized in chloroplast based on the presence of Chloroplast Transit Peptide (CTP)(White-Gloria *et al.*, 2018), but their function remains unclear (White-Gloria *et al.*, 2018).

Here, we sought to define the mechanisms controlling Thr78 phosphorylation, and prevalence of this PTM in photosynthetic organisms. This was achieved by considering the following five questions, (1) what is the enzyme response for dephosphorylation of Thr78? (2) at what stage of flowering plant evolution did Thr78 emerge? (3) how conserved is Thr78 among photosynthetic angiosperms? (4) to what extent is Thr78 phosphorylated in different species? (4) and is light-dependent de-phosphorylation of Thr78 a general mechanism of controlling of RCA activity?

MATERIAL AND METHODS

Determination of Rca isoform and photosynthetic species containing Thr78-Rca

To analyze the conservation of Thr78 in Rca protein across plant species, the sequence of Arabidopsis Rca (AtRca: AT2G39730) was retrieved from the Arabidopsis thaliana TAIR10 genome assembly (Lamesch *et al.*, 2012) on Phytozome v13 (Goodstein *et al.*, 2012). Syntelogs to AtRca (i.e., shared positional homology along chromosomes) were subsequently identified in monocots (*Setaria viridis* Rca: Sevir.8G261433) and asterids (*Mimulus guttatus* Rca: Migut.F00758), which have homology to this sequence using either synteny mapping features on CoGe (Lyons & Freeling, 2008; Lyons *et al.*, 2008). Setaria Rca was chosen as an example of a

gene that has been previously characterized (Kim et al. 2021), while Mimulus shares comparable synteny to Arabidopsis in the genomic region surrounding Rca enabling identification of syntelogs in the asterids. Working from these three representatives, additional syntelogues were locally identified based on their closest known Rca sister lineage within the Angiosperm phylogeny across other accessible plant genomes on these databases. *Amborella trichopoda* was leveraged as an outgroup for flowering plants in this case study given that this is known to be the one of the earliest diverging lineages for flowering plants (Soltis *et al.*, 2011). Additionally, homologues were surveyed, which contained threonine at position 78 phosphorylation site even if they didn't precisely fit this stringent criterion of synteny using pBLAST on NCBI (https://blast.ncbi.nlm.nih.gov/Blast.cgi) for key agronomic model systems. This ultimately resulted in 217 isoform CDS sequences being identified. Alternative splicing of the same locus in some lineages meant that these CDS sequences represented 153 unique genes from across 91 species and 50 plant families. The longer, Rca-α, sequence was preferentially retained as a taxonomic representative for each alternative splicing gene when available for phylogenetic analysis. The CDS sequence of these genes were visualized in Seaview (Gouy *et al.*, 2010) and codon-aligned using MUSCLE (Edgar, 2004). Obvious pseudogenes that were missing large portions of their AAA+ ATPase domain such as the rice sequence (LOC_Os11g47980) were removed prior to phylogenetic analysis of this DNA alignment. A maximum likelihood tree was subsequently assembled using IQTree (Nguyen *et al.*, 2015) with the Amborella Rca sequence being specified as an outgroup and 1000 bootstraps being run to generate statistical support for nodes along the tree with the automatic substitution model selection determining a SYM+R8 model was the best-fit according to Bayesian Information Criterion. The resulting treefile were then visualized either in Figtree (http://tree.bio.ed.ac.uk/software/figtree/) (Figure S3) or in R using the Phytools and Ape libraries (Paradis & Schliep, 2019; Revell, 2024). Ancestral state reconstructions were performed using the Ape function *ace* particularly for the original position 78 amino acid identity between syntelogous genes, and the manner of α/ß origin (either by alternative splicing or distinct genes) for each plant family (Figure S4).

Plant growth and stress treatment

Arabidopsis Col-0 and camelina seeds were sterilized in 1 % (v/v) bleach for 5 min, rinsed with 70 % EtOH, and dried on filter paper. The sterilized seeds were sown on MS (Murashige and

Skoog basal salt mixture powder, Phyto Technology Laboratories, M524) agar (0.8 %, w/v, Sigma-Aldrich, A1296) with 1 % (w/v) sucrose. The plates were stored at 4 °C for 2 days for cold stratification before transfer to a growth chamber. Seedlings were transferred into pots (5 cm diameter) filled with soil (Berger; PRO-MIX BX All Purpose Growing Mix) before the third true leaf emerged, which was approximately 5 to 7 days after germination (DAG). The other plants (brassica, soybean, green bean, and Medicago) were directly sown in soil after sterilization. Arabidopsis homozygous mutants of SLP1 (SALK_129247C) were ordered from ABRC, and homozygous lines were confirmed by genomic DNA PCR using LB_6313R (TCAAACAGGATTTTCGCCTGCT), SLP1_LP (GCCTGATCATCAAGTGACCTC) and SLP1_RP (CGGGAACCATGTCTGACTTAG) xfs designed using iSect tool by SALK (http://signal.salk.edu/tdnaprimers.2.html) (Alonso *et al.*, 2003). All plant species were grown at 22 °C, 16 h light and 8 h dark, 200 µmol m^{-2} s^{-1} PPFD with 2100 K 400W high pressure sodium bulbs (Ceramalux ALTO; C400S51).

Protein extraction and immunoblotting assay

Total proteins were extracted from three frozen leaf discs (1 cm in diameter) using a Qiagen Tissuelyzer for tissue grinding. The ground tissue was suspended in 0.5 mL of extraction buffer containing 62.5 mM Tris-HCl (pH 6.8), 2% SDS, 10% glycerol, 0.35 M 2-mercaptoethanol, and 0.001% protease inhibitor cocktail (Sigma-Aldrich; P9599). The suspension was heated at 95°C for 5 minutes to denature proteins and inactivate proteases, followed by centrifugation at 13,500 rpm for 30 minutes at 4°C. The supernatant was collected, and 10 µL aliquots were separated on 10% SDS-PAGE gels. Proteins from the gels were transferred electrophoretically to 0.2 µm nitrocellulose membranes (Bio-Rad) and blocked with PBS solution with 5% (w/v) non-fat milk powder (Sigma) for 1h at room temperature. For immunodetection, primary antibodies were diluted in Intercept Blocking Buffer (LI-COR; 927-70001); anti-Rca (Agrisera; AS10 700) at 1:5000 and anti-pT78 (GenScript) at 1:4000, and incubated overnight at 4°C. Modification-specific antibody was generated against the phosphopeptide antigen RGLAYDpT78DDQQDC (Arabidopsis anti-pT78). For each peptide antigen, the Cys residue at the N- or C-terminus was added for coupling to keyhole limpet hemocyanin (KLH). All custom antibodies were produced by GenScript (Piscataway, NJ, USA). Secondary detection used a fluorescent goat anti-rabbit antibody (Invitrogen; A32735) at a

1:10,000 dilution in PBS-T, incubated for 1 h at room temperature, and visualized with a LI-COR Odyssey Infrared Imaging System. All immunoblotting experiments were conducted at least twice to ensure reproducibility of results.

Protein phosphorylation assay with phosphatase inhibitor

WT Col-0 plants were grown as described above and whole rosettes were sampled and dipped in the protein phosphatase inhibitor buffer: 1% (v/v) solution of phosphatase inhibitor cocktail 2 (Sigma: P5726) and phosphatase inhibitor cocktail 3 (Sigma: P0044), overnight under dark. For dark treatment samples, the protein extraction was done using the overnight incubated samples and for light treatment samples the rosettes were exposed to 150 µmol m^{-2} s^{-1} PPFD light for 2 h and then total protein was extracted.

Physiological analysis

For light induction analysis, the leaves of 5-week WT and *slp1* mutants were dark adapted overnight before measurement in a portable infra-red gas exchange system (LI-6800, LICOR Environmental, Lincoln, Nebraska, USA) connected to a multiphase flash fluorometer (6800-01A) with a 2 cm^2 chamber. During low light incubation the plants were managed under dark conditions to make sure that Rca remained phosphorylated in both WT and *slp1* mutants. The chamber settings were 1:1 red:blue ratio, leaf temperature of 22 °C, CO_2 level of 420 µmol mol^{-1}, and 50% relative humidity. The measurement started with a low light of 20 µmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD) for 20 min, then the PPFD was increased to high light conditions of 1000 µmol m^{-2} s^{-1} for 60 min, measurements were logged every 10 s. For CO_2 response analysis, plants were measured at the same high light conditions described above after finishing the light induction measurement. The CO_2 level was adjusted to produce a plot of net CO_2 assimilation against intercellular CO_2 concentration (A-C_i curve). The CO_2 levels were changed every 90 – 120 s in the following order: 420, 300, 200, 100, 50, 10, 420, 420, 420, 600, 800, 1200, 1800 µmol mol^{-1}. The relative comparisons and significant differences between *slp1* and WT were determined using students t-test (n = 4 to 6).

Statistical Analysis

Comparisons of rosette size and assimilation rate between *slp1* and WT were done using a two-tailed Students' t-test using data from four to six biological replicates (individual plants) in Microsoft Excel v16.88.

RESULTS

SHEWENELLA-LIKE PROTEIN PHOSPHATASE 1 (SLP1) dephosphorylates Rca in-vivo

Light-dependent dephosphorylation of AtRca suggested that an unknown protein phosphatase is operating. To test this hypothesis, the phosphorylation state of Rca was assessed under light and dark conditions in the presence and absence of a protein phosphatase inhibitor cocktail (PPIC) (Fig. 1A and B). Under dark conditions, Rca phosphorylation increased compared to the sample lacking PPIC (Fig. 1B) which is consistent with the presence of a protein phosphatase. Dephosphorylation of Rca occurred in the light (Fig. 1B), even in the presence of the PPIC, which may be because the level of dephosphorylation exceeded the ability of the PPIC to inhibit activity. To identify the gene responsible for dephosphorylation of Rca, all known chloroplast localized protein phosphatases in Arabidopsis (White-Gloria *et al.*, 2018) were screened for reported associations with Rca in the literature and co-expression databases. Out of 9 chloroplast localized protein phosphatases, AtSLP1 (AT1G07010) showed a potential association based on co-expression (Fig. 1C). We hypothesized that in the absence of *AtSLP1*, AtRca will not be dephosphorylated in the light. To test this, a homozygous T-DNA insertion mutant of *slp1* was identified (Figure S1) and assessed for the ability to dephosphorylate Rca in the dark and light. *slp1* mutants showed phosphorylation of Rca in the dark, as also observed in the case of Col-0, but in the mutant phosphorylation was also observed in the light (Fig. 1D).

We hypothesized that lack of Rca dephosphorylation in *slp1* mutants would lead to decreased photosynthesis and a growth penalty. Analysis of 5-week-old plants found *slp1* mutants have a significant reduction in rosette size relative to Col-0 under normal light conditions (Fig. 1E and F). To assess the impact of SLP1 on steady state photosynthesis, A/Ci (net CO_2 assimilation vs internal CO_2 concentration) curves were performed on Col-0 and *slp1* mutants, finding no difference between lines (p=0.05; Figure S2). As there is a tight correlation between Rubisco activation state and the rate of induction of photosynthesis during shade to sun transitions, the impact of SLP1 on the rate of photosynthetic induction after a step-increase in

photosynthetic photon flux density from 20 to 1000 µmol m^{-2} s^{-1} was assessed, again finding no significant difference compared to Col-0 (p=0.05; Fig. 1G).

Thr 78 in Rca is common

To study the conservation of Thr78 (Arabidopsis numbering) in Rca, 1893 protein sequences from 479 plants species were assessed. Among these, 203 species retained Thr78 (Table S1). Next, a more stringent synteny informed ortholog phylogeny of Rca-α and Rca-β isoforms was generated across angiosperms to address the questions: at what stage of flowering plant evolution did the putative Thr78 phosphosite emerge, and how well conserved is it among photosynthetic angiosperms? Leveraging maximum likelihood gene family phylogeny ancestral states, Thr78 distribution was estimated for each family, including deeper nodes within the tree such as the branch point of the *Amborellaceae* (Fig. 2). The presence of Thr78 was observed in most plant families (Fig. 2), while among the *Poaceae*, that includes major crop species, the presence of Isoleucine (Ile) was found to dominate at position 78 compared to Threonine (Fig. 2). The difference in the abundance of both amino acids, Thr and Ile at this site is similar at the evolutionary scale, and an estimate of the ancestral state was ambiguous. Interestingly, the *α* and *β* copies appeared polyphyletic, with multiple origins of the two isoforms arising from alternate splicing or gene duplication across the phylogeny (Fig. S4, and S5). Within the Brassicaceae *Arabidopsis thaliana* and its immediate relatives all appear to have a single copy of Rca with alpha and beta forms being the result of alternative splicing of a single transcript.

By contrast in the Fabaceae, *Glycine max* has four gene copies of Rca (two each of *α* and *β*) with the Papillionoid legumes more generally having two copies of Rca. There is no equivalent duplication event in *Cercis canadensis* that would indicate a Fabaceae-wide pattern. Therefore, this pattern of two Papillionoid copies is consistent with the whole-genome doubling (WGD) event preceding the diversification of this subfamily, and by undergoing an additional allopolyploid event, *Glycine max* has two additional copies for each of these ancestral homeologues (Gill, *et al.*, 2009; Koenen, *et al.*, 2021). Within Poaceae, *Setaria viridis* and the grasses more generally displayed two mirrored clades, which reflect the known taxonomic sorting of this family. The grass family has undergone three WGD events (τ, σ, and ρ), two of which are shared with monocots, with the p WGD unique to the Poaceae (Paterson *et al.*, 2004; Tang *et al.*, 2010; McKain *et al.*, 2016). Although superficially resembling the *ρ* WGD event,

these grass copies are physically proximal to their sister copies in the adjacent clade suggesting that this may instead be an ancient tandem duplication event.

Light-dependent dephosphorylation of Thr78 in Rca is unique to Arabidopsis

Previous reports showed that both AtRca isoforms phosphorylate in the dark and are dephosphorylated as plants are exposed to light. To test whether Thr78 phosphorylation status is light-sensitive in species other than Arabidopsis, we screened three C3 plants from the *Brassicaceae* for dark-dependent phosphorylation of Thr78, using a pT78 antibody (Kim et al., 2019) (Fig. 3A). As in Arabidopsis, Rca-α and Rca-β isoforms arise from alternate splicing in *Brassicaceae* and the Thr78 site is conserved in all proteins (Fig. 3B). However, unlike Arabidopsis, Rca in *Camelina sativa* (*Cs*), *Brassica oleraceae* (*Bo*) and *Brassica napus* (*Bn*) phosphorylated in dark but lacked light-induced dephosphorylation (Fig. 3A). These data suggest that although Thr78 is phosphorylated in multiple species, light-dependent regulation may be specific to Arabidopsis.

To broaden the analysis, we performed the dephosphorylation assay on several legumes: *Glycine max* (*Gm*), *Phaseolus vulgaris* (*Pv*), and *Medicago truncatula* (*Mt*). The Rca isoforms in these species are derived from individual genes of *Rca-α* and *Rca-β*, unlike the situation in the *Brassicaceae*. The Rca-α isoforms retain Thr78, whereas the β isoforms have Ile78 in *Gm* and *Mt*, and Val78 in *Pv* (Fig. 3B). Publicly available data suggest the transcription level of Rca-α is low relative to β in both *Gm* and *Pv*, and moderately expressed in *Mt* (Table S2). The light/dark assay on legume plants showed that both the isoforms were expressed, and phosphorylated in the dark, but as with the Brassicaceae, did not dephosphorylate in the light (Fig. 3A). The reason why the antibody was able to detect phosphorylation of β forms, which lack Thr78, is unclear. It is possible that there is relaxed selectively, but we consider these results with caution.

To study the impact of phosphorylation in C4 plants, we analyzed Rca phosphorylation in four species of C4 grass: *Sorghum bicolor* (*Sb*), *Miscanthus* (*Ms*), *Saccharum officinarum* (*Su*), and *Setaria viridis* (*Sv*) (Fig. 4A). Each of these species possess two separate genes for the alternative Rca isoforms, with Rca-α containing Thr78, but with it lacking from Rca-β (Fig. 4B, C). In accordance with previous reports (Kim *et al.*, 2021), only the Rca-β isoform could be detected under normal growth conditions (Fig. 4A and C). An unspecific cross-reaction was present in C4 grass samples probed with pT78, but the detected protein was too large to be Rca-

β, subsequently no phosphorylation of Rca-β was detected (Fig. 4A). To test whether a C4 Rca-α isoform could be phosphorylated, sorghum plants were exposed to heat induce Rca-α isoform expression (Fig. 4C). Plants accumulated SbRca-α after 24 h heat treatment, but no bands of the correct size could be detected using the pT78 antibody (Fig. 4C). To rule out the possibility that a lack of detectable Thr78 phosphorylation was due to high protein phosphatase activity, the assay was repeated in the presence of a protein phosphatase inhibitor cocktail (PPIC), but again protein phosphorylation was not observed under any condition (Fig. 5). This result suggests that SbRca-α T78 is not phosphorylated by cpCK2 as it is in Arabidopsis even though the gene for cpCK2 is present in sorghum.

DISCUSSION

Rca is subject to multiple levels of regulation to adjust carbon fixation in response to environmental conditions (Amaral *et al.*, 2024). Differences in gene expression, biochemical properties of isoforms, redox status, and post-translational modification have been topics of investigation (Boex□Fontvieille *et al.*, 2014; Kim *et al.*, 2016, 2019). Dark dependent phosphorylation of Thr78 is proposed to downregulate Rca activity leading to reduced assimilation (Kim et al. 2019). cpCK2 is described as the major kinase responsible for phosphorylation of AtRca Thr78 based on dramatically reduced phosphorylation in *cpcpk2* T-DNA insertion lines (Kim *et al.*, 2016). Here we identified Shewanella-like protein phosphatase 1 (SLP1) as the second component of this regulatory mechanism, acting to dephosphorylate AtRca Thr78 in the light (Fig. 1). SLP1 is a highly conserved protein phosphatase reported to be blue light responsive in Arabidopsis (Depuydt & Vandepoele, 2021) and belongs to a protein family consisting of two members, of which, SLP1 is the only chloroplast localized isoform (Uhrig & Moorhead, 2011). A role for mitochondrial targeted SLP2 has been described in negative regulation of gibberellic acid related seed germination (Uhrig *et al.*, 2017), but the physiological role and targets of SLP1 have not previously been explored.

If phosphorylation of Rca has a dominant impact on activity, plants lacking SLP1 would be predicted to see an increase Thr78 phosphorylation in the light, leading to lower Rubisco activity, and lower Anet. an impact on photosynthesis, with no difference observed in assimilation rates between WT and knockout lines during light induction or CO_2 response (Fig. 1G and Fig. S2). These findings are in keeping with observations by Kim *et al.* (2016), who

reported no change in assimilation rates when Thr78 phosphorylation state was reduced in *cpck2* mutants. These results were attributed to redundancy in Rca regulation between protein phosphorylation and control by thioredoxin (Kim *et al.*, 2016) and the same rationale may apply here. Support for a functional role for phosphorylation of Thr78 in Arabidopsis has only been shown in Rca variant lines lacking the redox sensitive C-terminal extension (Kim *et al.*, 2019). Our analysis, conducted on lines containing the C-terminal extension, are therefore consistent with the hypothesis that Rca possesses multiple redundant mechanisms in Arabidopsis, which operate to regulate activity in response to variable light environments. The impact of SLP1 on photosynthesis may only be apparent in the absence of redox regulation.

Despite the absence of impact on Anet, the *slp1* mutant showed reduced growth (Fig. 1). Given that the *cpck2* mutant, which also showed altered phosphorylation of Rca, did not have a growth phenotype, we attribute this to an unrelated impact on chloroplast physiology. As a largely uncharacterized protein, the specificity and targets of SLP1 are unknown. Phosphatases have traditionally been considered promiscuous, with specificity dictated by regulatory subunits (ref). SLP1 is not known to have regulatory subunits, it is therefore conceivable there are other targets within the chloroplast that are impacted in the mutant leading to the observed growth phenotype.

Substitution of Thr78 with Serine lead to a relative increase in phosphorylation at the site, in Arabidopsis resulted in smaller plants with decreased photosynthesis (Kim *et al.*, 2019). Altering a single amino acid, Thr78, was proposed as a means of generating plants with better photosynthesis. However, the prevalence of Thr78 across species, the frequency of post-translational modification and functionality were unclear. To begin to address these questions we expanded previous searches of genomic databases, which assessed the evolution of Rca copy number across the green lineage (Nagarajan & Gill, 2018; Kim *et al.*, 2019), to use a synteny based approach. Nagarajan and Gill (2018) placed the emergence of the Rca-α CTE and alternate splicing mechanisms in the charophytes, before the divergence of land plants and there is only one reported example of a species only having evidence for expression of Rca α (Nagarajan & Gill, 2018). Here, despite α and β forms (bearing or lacking a c-terminus respectively) occurring within each model system, these α and β forms appear to represent repeated cases of evolutionary convergence on these two isoforms (Figure S5) through distinct means within each clade: subfunctionalization (Birchler & Yang, 2022), following tandem duplication in the grasses

as previously described (Nagarajan & Gill, 2018), WGD in the legumes, or alternative splicing of a single coding sequence into alternative isoforms in Brassicaceae. This may suggest that Rca isoforms can be quite plastic in the way they arise within distinct plant families where α and β forms may not necessarily reflect true homology within Rubisco activase isoforms.

Previous assessment of a smaller number of Rca sequences failed to identify any with Thr78 replaced by Serine, leading to speculation that the configuration with the attendant hyper phosphorylation observed in Arabidopsis has been selected against (Kim *et al.*, 2019). In the initial set of Rca sequences identified by BLAST search, we identified gene models from at least seven species (Table S3) which do have Ser78, although these were not considered orthologs in the synteny analysis. Of the 25 species found to contain Rca sequences with Thr78, it remains to be seen how many undergo phosphorylation. Our data are consistent with it occurring in at least the Brassicaceae, while phosphorylation of an equivalent Thr residue has been reported in tomato, suggesting this modification may occur more widely (Marques et al., 2021).

We found no evidence for phosphorylation of Thr78 in monocot species, including Sorghum, Setaria, sugarcane and Miscanthus. The peptide fragment used for antibody generation is highly conserved, with 100% identity between Arabidopsis Rca and Sorghum Rca-α "RGLAYDTSDDQQDC" and should therefore have been able to detect phosphorylation if present under the conditions tested. There are several potential explanations for this finding, including an absence of the kinase, differences in localization or expression profiles of the kinase, or regulation of the kinase. In Arabidopsis, Rca is phosphorylated by cpCK2 (Kim et al., 2016). A homologous gene has been characterized in rice (LOC_Os03g55490) (Lu et al., 2015)and syntenic sequences can be found in C4 grasses including Sorghum (Sobic.001G07970) (Carvalho et al., 2020). As Sorghum operates two-celled C4 photosynthesis for an interaction to occur between Rca and cpCK2 both must be expressed in the same cell type. Transcriptomics suggests that cpCK2 is expressed in both mesophyll and bundle sheath cells in maize (Chang et al., 2012), Setaria (John et al., 2014)and Sorghum (Döring et al., 2016), albeit with ~2-fold mesophyll enrichment in maize and Setaria whereas Rca is localized in the bundle sheath. Even so, it appears that the orthologous cpCK2 is present in the same compartment as Rca (i.e., the bundle sheath cell chloroplast). However, in the monocot species tested Rca-β, which lacks Thr78, is the predominate isoform under normal conditions and Rca-α, which possess Thr78, is induced during stress (Shivhare & Mueller-Cajar, 2017; Scafaro et al., 2019; Kim et al., 2020,

2021). Whether C4 monocot cpCK2 retains the ability to phosphorylate Thr78 in Rca-α, or if the bundle sheath stromal environment is permissive for phosphorylation remains unclear (Kim et al., 2016). CK2 exists as a multigene family, composed of catalytic α subunits and regulatory beta subunits (Salinas et al., 2006; Schweer et al., 2010), which form hetero-tetramers that can differ in substrate specificity (Domańska et al., 2005). Intriguingly there appears to be a lack of regulatory β subunits in the chloroplast (Salinas et al., 2006), so differences in regulatory subunits impacting specificity appears unlikely, although multiple chloroplast CK2 containing complexes have been detected (Baginsky et al., 1997) suggesting the protein does not act alone. However, further research is required to characterize the regulation of monocot cpCK2 and whether it can phosphorylate Rca.

Conservation of phosphorylation of Thr78 in some C3 plants is not evidence of a conserved regulatory role. Indeed, in the species examined, strong evidence for light-dependent dephosphorylation of Thr78 was only found for Arabidopsis, with phosphorylation of Rca detected in both the light and dark in other C3 species (Fig. 3). These data may suggest a limited scope for phosphorylation as a means of regulation, with most species depending on other mechanisms, such as changes in redox state, catalytic properties or expression. It may be that alternate post-translational modifications of Rca have greater importance in other species and several different ones have been described (Amaral et al., 2024). Interestingly, there are several reports of phosphorylation of S79 in Arabidopsis (Willems et al., 2019), and this modification was also observed in a Brachypodium, Chlamydomonas and maize (Willems et al., 2019, 2024). Further phosphoproteomics of maize during a diurnal cycle suggests that rather than Thr78, Ser79 undergoes dark-dependent phosphorylation (Gao et al., 2023). However, the prevalence of S79 phosphorylation is also likely to vary, as seen by a failure to detected in protein samples from *Glycine max* (soybean-S86) (Soleh et al., 2017) .Therefore, the prevalence and function of Ser79 phosphorylation is unclear, and whether it can play a similar role to Thr78 warrants further investigation.

Taken together our results suggest that Thr78 can be found in Rca sequences across the green lineage, although the prevalence varies, and degree to which it undergoes phosphorylation is inconsistent. Our data provides support for a mechanism whereby Thr78 is phosphorylated in the dark by cpCK2 and dephosphorylated in the light by SLP1 in Arabidopsis. The lack of impact on photosynthesis when cpCK2 or SLP1 are knocked out suggest that phosphorylation of

Thr78 acts redundantly with redox regulation. More widely, it is likely that regulation of Rca can occur through multiple mechanisms, including redox, sensitivity to ADP and gene expression and the relative importance of each varies.

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Competing interests

The authors report no conflict of interest

Authors contributions

Conceptualization (SK, NB, SJB, DO), Investigation (NB, SC, MS, JH, SK), Formal Analysis (NB), Project administration (NB, SJB, DO), Supervision (AL, SJB, DO), Visualization (NB), Writing - original draft (NB, JH, SC, DO, SJB), Writing – review and editing (NB, JH, DO, AL, SJB).

FIGURE LEGENDS

Figure 1: SLP1 dephosphorylates Rca in Arabidopsis. Protein phosphatase assay with PPIC (+P) and without PPIC (-P) isoforms, comparing total abundance (A) to phosphorylation (B) of Rca by immunoblot. (C) Putative protein-protein interactions between Rca and chloroplast localized protein phosphatases. (D) Immunoblot analysis of light dependent dephosphorylation of Rca in WT (Col-0) and *slp1* mutants. (E) Image of 5-week-old rosettes comparing WT (Col-0) and slp1 plants. (F) Comparison of rosette size between WT (Col-0) and slp1 plants (n=20). (G) Photosynthetic induction curves of WT (Col-0) and *slp1* mutant plants (n=5 to 6).

Figure 2: Phylogenetic representation of the amino acid present at the phosphorylation site (peptide position 78) within extant Rca gene models. Ancestral states for families, and when available deeper orders of Angiosperms, are denoted at their corresponding nodes as pie charts. The nodes depicting the presence of Thr78 is colored green and the ones with Ile78 is colored navy blue. Less abundant amino acids at the peptide position 78 are depicted as varying shades of blue and purple. The detailed confirmation of bootstrap values is mentioned in Figure S3.

Figure 3: Light dependent dephosphorylation of Thr78 in Rca is specific to Arabidopsis. (A) Immunoblot analysis comparing protein phosphorylation and total abundance of Rca under light (L) and dark (D) conditions (At: *Arabidopsis thaliana*, Cs: *Camelina sativa*, Bn: *Brassica napus*, Bo: *Brassica oleraceae*, Gm: *Glycine max*, Pv: *Phaseolus vulgaris*, Mt: *Medicago truncatula*). The upper panel shows the total Rca protein extracted from plant samples and the middle panel shows the phosphorylated Rca protein. α and β denote the 2 isoforms of Rca protein. CBB (Coomassie Brilliant Blue) depicts the loading control. (B) Sequence alignment depicting the conservation of Thr78 amino acid in C3 species. The amino acid lacking color codes depicts the change in the Thr78 site to Isoleucine (*I*) in *Glycine max* and *Medicago truncatula*, and Valine (*V*) in Phaseolus vulgaris. The letter “A” and “B” at the end of the species labelling denotes the Rca-α and Rca-β isoforms. (C) The phylogenetic tree depicts the division of C3 Brassicaceae family and legumes based on Rca isoforms arising from protein splicing in Brassicaceae as compared to different genes in legumes and presence and absence of Thr78 amino acid in the Rca-β isoform. The blue boxes depict the presence of Thr78 amino acid whereas the red depicts the lack of Thr78. The yellow box depicts the experimental confirmation of protein phosphorylation at Thr78 phosphosite.

Figure 4: Phosphorylation of Rca is not observed in selected C4 moncots. (A) Protein phosphorylation assay depicting four C4 plant samples in light and dark conditions (At: *Arabidopsis thaliana*, Sv: *Setaria viridis*, Sb: *Sorghum bicolor*, Su: *Saccharum officinarum*, Ms: *Miscanthus*). The upper panel shows the accumulation of Rca protein quantified with Anti-Rca antibody and middle panel shows the phosphorylated Rca protein quantified with Anti-pT78 antibody. α and β denote the 2 isoforms of Rca protein. CBB denotes the loading control. (B) Sequence alignment of motif comparing Arabidopsis and select C4 plants. (C) Immunoblot analysis comparing Rca phosphorylation under heat for 24 h in WT sorghum. The numbers denote the time in hours after the heat stress. CBB denotes the loading control.

Figure 5: Sorghum lacks phosphorylation of Thr78 with or without PPIC treatment. (A) Immunoblot analysis comparing sorghum WT samples collected after heat stress at 42°C under light and dark treatment. The control samples were collected at 28°C. The + and – sign denotes presence and absence of treatment, respectively. The left panel shows Rca protein accumulation and right panel depicts analysis using anti-pT78 antibody.

Figure S1: The genomic DNA (gDNA) PCR with primer combinations of LB, LP and RP showed that LB primer T-DNA insertion was confirmed in homozygous lines whereas WT showed no bands (upper panel). The SLP1 gene primers showed gDNA bands in the WT and not in the *slp1* mutants (lower panel).

Figure S2: The *ACi* curve showed that both WT (Col-0) and slp1 mutants overlap suggesting that both the genotypes have no difference in the photosynthetic efficiency. Error bars denote standard error. Green dots are *slp1* mutants and black dots are WT (Col-0).

Figure S3: The conservative phylogeny structure of Rca orthologs where all nodes with bootstrap support (blue numbers) greater than 80% being retained whereas other lower support nodes were collapsed into polytomies.

Figure S4: Rca α (white) and β (black) isoforms on extant gene models as well as alternatively spliced gene models which produce both Rca α and β (grey). Ancestral states for families, and when available deeper orders of Angiosperms, are denoted at their corresponding nodes as pie charts.

Figure S5: The likely pattern that could result in the polytomies of *α* and *β* isoforms ancestry states that Angiosperms initially beginning as Rca *α* lineages out of which *β* isoforms repeatedly arise independently following either subfunctionalization of duplicate gene copies or alternative

splicing of α gene models to β isoforms as well. Within certain lineages where α isoforms are lost all the Rca copies become canalized into a β isoform state thereafter.

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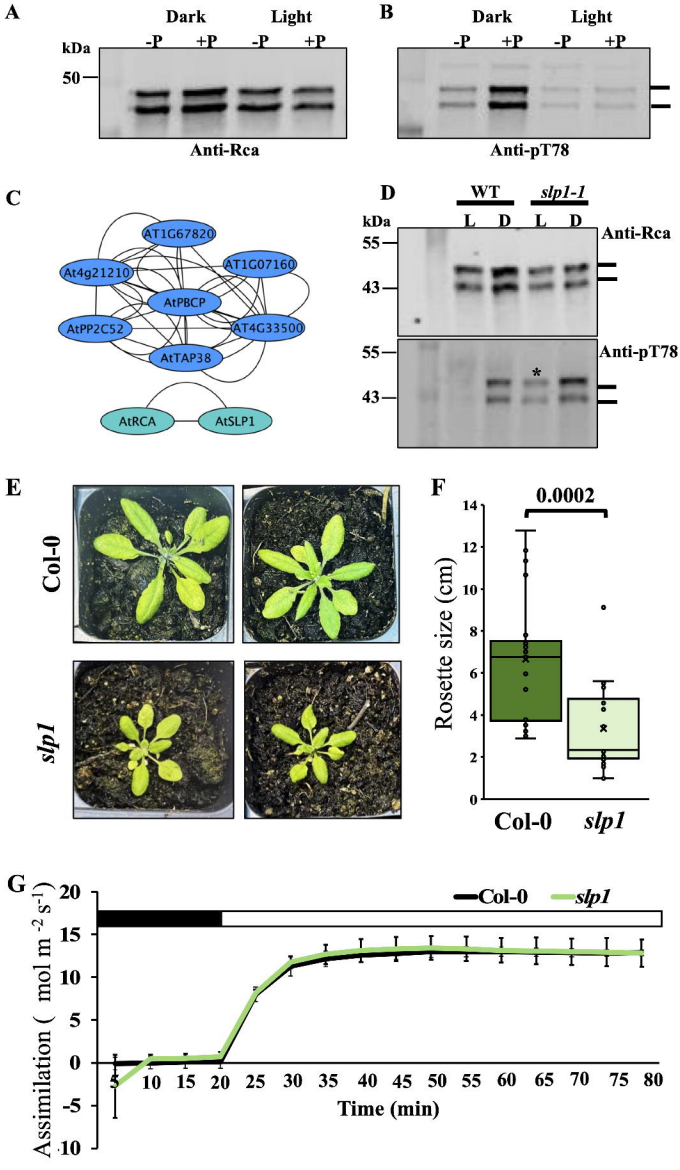
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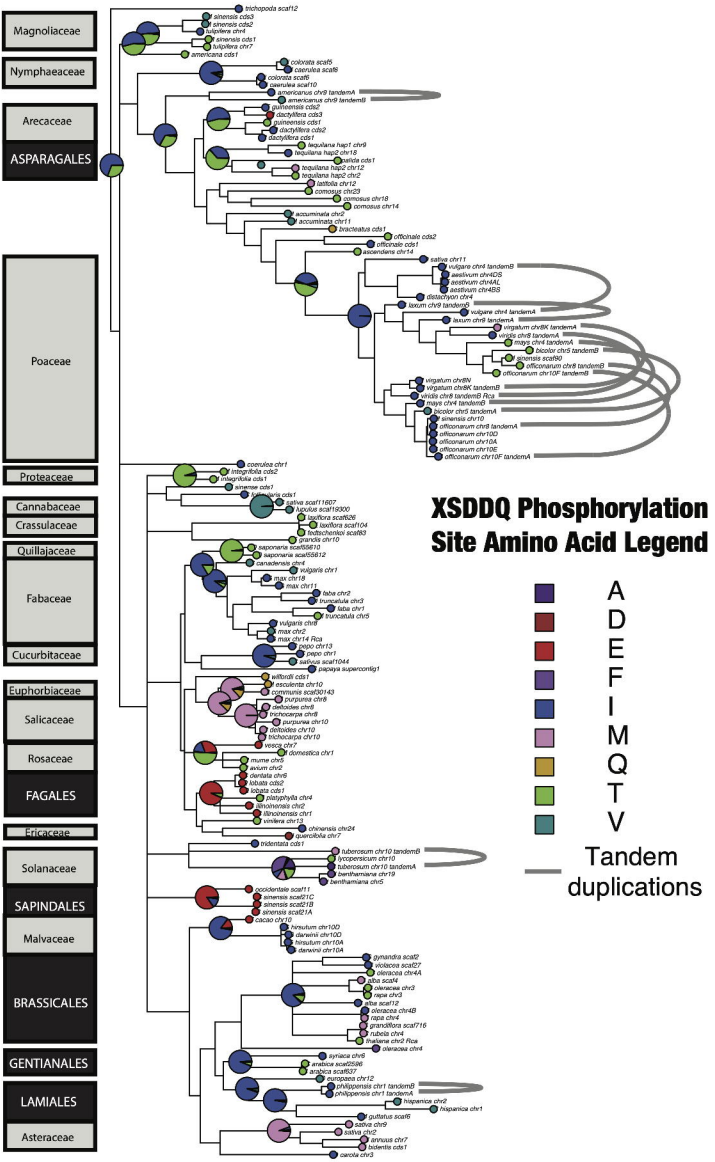
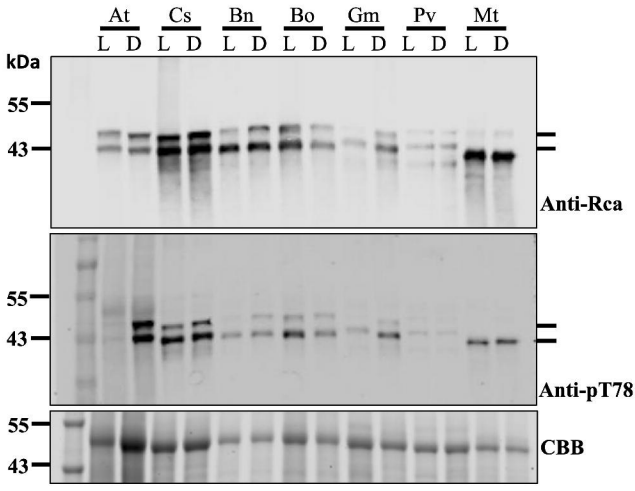
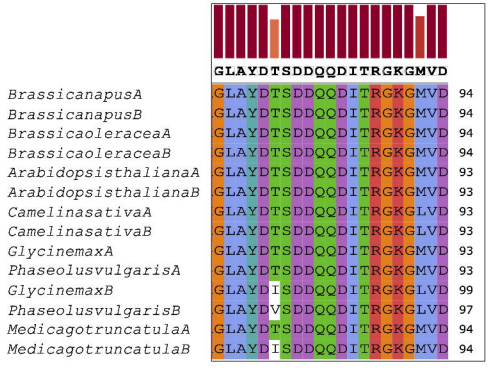
80
Time (min)

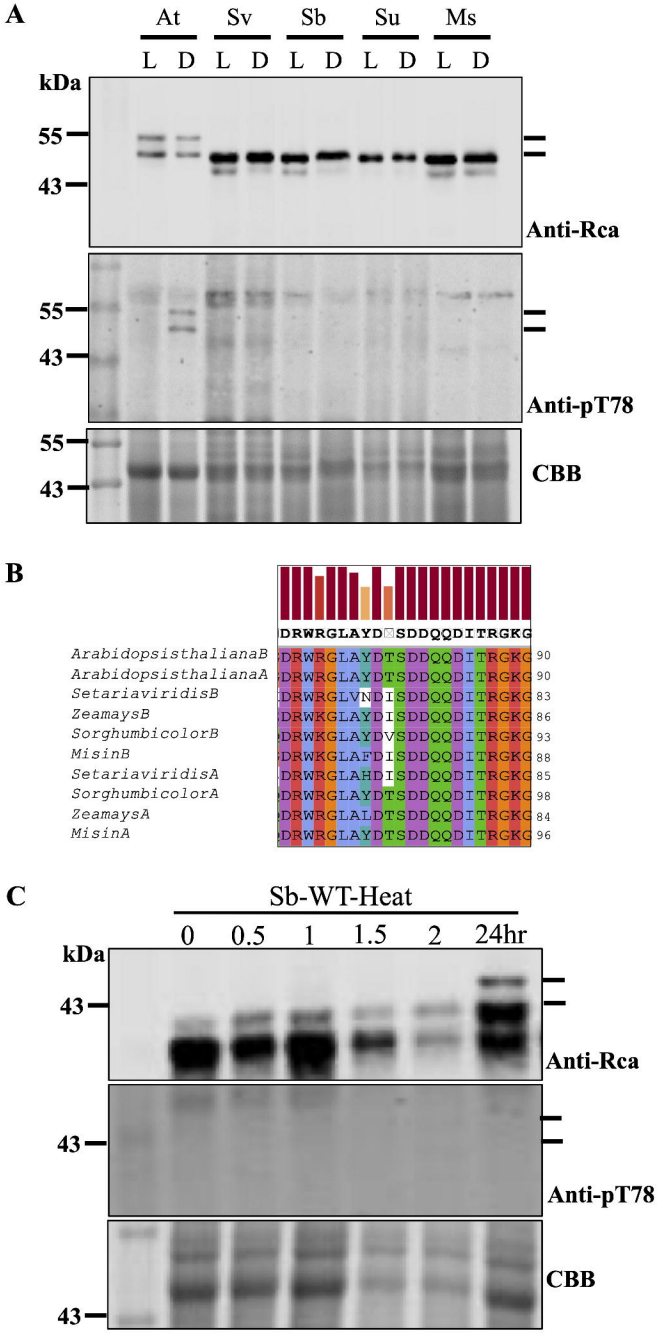

Magnoliaceae
Nymphaeaceae
Arecaceae
ASPARAGALES
Poaceae
Proteaceae
Cannabaceae
Crassulaceae
Quillajaceae
Fabaceae
Cucurbitaceae
Euphorbiaceae
Salicaceae
Rosaceae
FAGALES
Ericaceae
Solanaceae
SAPINDALES
Malvaceae
BRASSICALES
GENTIANALES
LAMIALES
Asteraceae
XSDDQ Phosphorylation Site Amino Acid Legend
A
D
E
F
I
M
Q
T
V
Tandem duplications

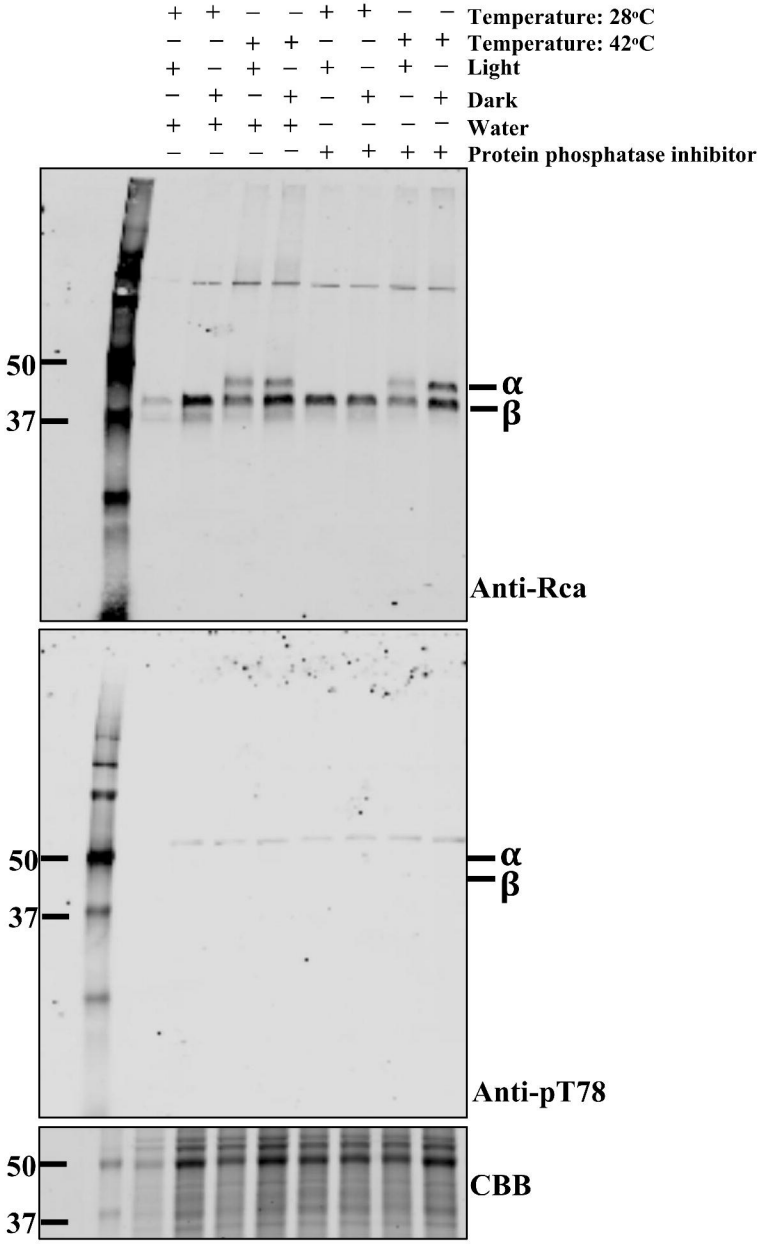
A


At
Cs
Bn
Bo
Gm
Pv
Mt
L D L D L D L D L D L D L D
kDa
55
43
Anti-Rca
55
43
Anti-pT78
55
43
CBB

B


GLAYDTSDDQQDITRGKGMVD
BrassicanapusA GLAYDTSDDQQDITRGKGMVD 94
BrassicanapusB GLAYDTSDDQQDITRGKGMVD 94
BrassicaoleraceaA GLAYDTSDDQQDITRGKGMVD 94
BrassicaoleraceaB GLAYDTSDDQQDITRGKGMVD 94
ArabidopsisthalianaA GLAYDTSDDQQDITRGKGMVD 93
ArabidopsisthalianaB GLAYDTSDDQQDITRGKGMVD 93
CamelinasativaA GLAYDTSDDQQDITRGKGLVD 93
CamelinasativaB GLAYDTSDDQQDITRGKGLVD 93
GlycinemaxA GLAYDTSDDQQDITRGKGMVD 93
PhaseolusvulgarisA GLAYDTSDDQQDITRGKGMVD 93
GlycinemaxB GLAYDISDDQQDITRGKGLVD 99
PhaseolusvulgarisB GLAYDVSDDQQDITRGKGLVD 97
MedicagotruncatulaA GLAYDTSDDQQDITRGKGMVD 94
MedicagotruncatulaB GLAYDISDDQQDITRGKGMVD 94


A
At
Sv
Sb
Su
Ms
L D L D L D L D L D
kDa
55
43
Anti-Rca
55
43
Anti-pT78
55
43
CBB
B
DRWRGLAYD SDDQQDITRGKG
ArabidopsisthalianaB DRWRGLAYDTSDDQQDITRGKG 90
ArabidopsisthalianaA DRWRGLAYDTSDDQQDITRGKG 90
SetariaviridisB DRWRGLVNDISDDQQDITRGKG 83
ZeamaysB DRWKGLAYDISDDQQDITRGKG 86
SorghumbicolorB DRWKGLAYDVSDDQQDITRGKG 93
MisinB DRWKGLAFDISDDQQDITRGKG 88
SetariaviridisA DRWRGLAHDISDDQQDITRGKG 85
SorghumbicolorA DRWRGLAYDTSDDQQDITRGKG 98
ZeamaysA DRWRGLALDTSDDQQDITRGKG 84
MisinA DRWRGLAYDTSDDQQDITRGKG 96
C
Sb-WT-Heat
0 0.5 1 1.5 2 24hr
kDa
43
Anti-Rca
43
Anti-pT78
CBB
43


+ + − − + + − − Temperature: 28°C
− − + + − − + + Temperature: 42°C
+ − + − + − + − Light
− + − + − + − + Dark
+ + + + − − − − Water
− − − − + + + + Protein phosphatase inhibitor
50
37
α
β
Anti-Rca
50
37
α
β
Anti-pT78
50
37
CBB