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Giner-Lamia, J

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Identification of the direct regulon of NtcA during early acclimation to nitrogen starvation in the cyanobacterium *Synechocystis* sp. PCC 6803

Joaquín Giner-Lamia¹,²,* Rocío Robles-Rengel³, Miguel A. Hernández-Prieto¹,⁴, M. Isabel Muro-Pastor³, Francisco J. Florencio³ and Matthias E. Futschik¹,⁵,⁶,*

¹Systems Biology and Bioinformatics Laboratory, CBMR, University of Algarve, 8005-139 Faro, Portugal, ²Laboratory of Intracellular Bacterial Pathogens, Department of Microbial Biotechnology, Centro Nacional de Biotecnología-Consejo Superior de Investigaciones Científicas (CNB-CSIC), 28049 Madrid, Spain, ³Instituto de Bioquímica Vegetal y Fotosíntesis. Universidad de Sevilla-CSIC, Av. Américo Vespucio 49, E-41092 Seville, Spain, ⁴ARC Centre of Excellence for Translational Photosynthesis and School of Life and Environmental Sciences, University of Sydney, NSW 2006, Australia, ⁵Centre of Marine Sciences (CCMAR), University of Algarve, 8005-139 Faro, Portugal and ⁶School of Biomedical & Healthcare Sciences, Plymouth University Peninsula Schools of Medicine and Dentistry, Plymouth PL6 8BU, UK

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ABSTRACT

In cyanobacteria, nitrogen homeostasis is maintained by an intricate regulatory network around transcription factor NtcA. Although mechanisms controlling NtcA activity appear to be well understood, its regulon remains poorly defined. To determine the NtcA regulon during the early stages of nitrogen starvation for the model cyanobacterium *Synechocystis* sp. PCC 6803, we performed chromatin immunoprecipitation, followed by sequencing (ChIP-seq), in parallel with transcriptome analysis (RNA-seq). Through combining these methods, we determined 51 genes activated and 28 repressed directly by NtcA. In addition to genes associated with nitrogen and carbon metabolism, a considerable number of genes without current functional annotation were among direct targets providing a rich reservoir for further studies. The NtcA regulon also included eight non-coding RNAs, of which Ncr1071, Syr6 and NsiR7 were experimentally validated, and their putative targets were computationally predicted. Surprisingly, we found substantial NtcA binding associated with delayed expression changes indicating that NtcA can reside in a poised state controlled by other factors. Indeed, a role of PipX as modulating factor in nitrogen regulation was confirmed for selected NtcA-targets. We suggest that the indicated poised state of NtcA enables a more differentiated response to nitrogen limitation and can be advantageous in native habitats of *Synechocystis*.

INTRODUCTION

Cyanobacteria perform oxygenic photosynthesis and play key roles in the global carbon and nitrogen cycles (1,2). They are continuously exposed to environmental fluctuations, such as changes in nutrient availability, light conditions or temperature, and have developed sophisticated mechanisms to sense and respond to these fluctuations to maintain their metabolic homeostasis. This is also the case for nitrogen, an essential element necessary for the synthesis of molecular building blocks, such as amino acids and nucleotides. Its deficiency results in a gradual decrease in transcripts encoding for components of photosynthesis, e.g. the tricarboxylic acid cycle (TCA), the Calvin–Benson cycle, and protein synthesis (3–5). To counteract nitrogen limitation, systems for high-affinity nitrogen uptake and sugar catabolic genes are induced, including those involved in the pentose phosphate pathway (OPP) or glycolgen metabolism (3,4). Cyanobacteria prefer ammonium as a nitrogen source, although they can also use nitrate, nitrite, urea and some amino acids. In addition, many cyanobacteria are able to fix N2 (2). Nitrogen compounds acquired by cyanobacteria are converted to ammonium, which is then incorporated into the carbon skeleton of 2-oxoglutarate (2-OG) through the glutamine synthetase (GS)-glutamine oxoglutarate aminotransferase (GOGAT) cycle. Low intracellular ammonium levels during nitrogen starvation limit the turnover of the GS-GOGAT cycle resulting in increased lev-

*To whom correspondence should be addressed. Tel: +34 915 854 923; Email: jginer@cnb.csic.es

Correspondence may also be addressed to Matthias E. Futschik. Tel: +44 1752 586 848; Email: matthias.futschik@plymouth.ac.uk

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els of 2-OG, which serves as an indicator of an unbalanced C/N ratio within the cells (6).

In cyanobacteria, the global regulator for nitrogen assimilation and metabolism is NtcA, a transcription factor belonging to the CRP (cAMP receptor protein) family (7,8). NtcA is highly conserved in cyanobacteria and controls the cellular response to nitrogen availability (including nitrogen fixation in diazotrophic cyanobacteria) by binding as dimer to a consensus sequence GTAN₅TAC within the promoter of its target’s genes (8). In the absence of ammonium, NtcA activates the expression of genes for nitrogen assimilation pathways, including ureA, nirA, ntcB, and gltA (8). NtcA also acts as a transcriptional repressor of some genes, such as gifA and gifB, that encode for the GS inactivating factor IF7 and IF17, respectively (8,9). Under nitrogen depletion, the accumulation of the metabolite 2-OG stimulates DNA-binding of NtcA as well as the transcriptional modulation of targets genes by NtcA. Maximal activation of NtcA requires the subsequent binding of the coactivator, PII, interacting protein (PipX), a small monomeric protein conserved among several cyanobacteria (10). This interaction is modulated by both 2-OG levels and the signal transduction protein PII, an integrator of the nitrogen and carbon balance in bacteria and plants (11). When nitrogen is abundant, PII binds to PipX to counteract NtcA activity at low 2-OG levels. However, under conditions of low nitrogen abundance (high 2-OG levels), PII binds 2-OG in a cooperative manner with adenosine triphosphate (ATP) and is phosphorylated (1). This causes the release of the PipX, and its interaction with NtcA, stabilizing the active 2-OG-bound conformation of NtcA (12).

Previous studies based on transcriptomic and bioinformatic predictions have attempted to identify putative binding sites of NtcA in different cyanobacteria (13–15). In Synechocystis sp. PCC 6803 (hereafter Synechocystis), which serves as a model cyanobacterium and promising microbial cell factory, 48 putative binding sites were computationally predicted in an early study; but no experimental validation of these sites was carried out (13). For Anabaena sp. PCC 7120, two genome-wide studies, one based on chromatin immunoprecipitation followed by next-generation sequencing (ChIP-seq) analysis, and another based on the identification of transcriptional start sites (TSS) by RNA sequencing (RNA-seq) under nitrogen-depleted conditions, showed a great discrepancy in the number of possible NtcA-regulated genes. The RNA-seq data obtained by Mitschke et al. (15) suggested 158 TSS as potential NtcA targets, while the ChIP-seq analysis of NtcA performed by Picossi et al. (14) returned 2424 putative NtcA binding DNA regions, 865 of them ascribed to promoter regions. This striking discrepancy in the number of NtcA targets is not surprising, as separate application of RNA-Seq and ChIP-Seq provides only incomplete evidence for the regulatory activity of transcription factors. Although RNA-seq alone can faithfully detect changes in expression, it remains unclear whether these changes are related to the transcription factor of interest or reflect secondary effects caused by downstream events. In contrast, ChIP-seq alone can capture (differential) binding of transcription factors, but does not provide an indication of whether this causes activation or repression of nearby genes. A combination of these complementary high-throughput techniques, however, overcomes the limitations of individual approaches and can determine the NtcA regulon with unprecedented resolution. Through integration of differential expression and chromosomal binding location, we could identify not only in vivo functional NtcA binding sites, but also whether NtcA binding repressed or induced gene transcription during the early phase of nitrogen starvation. We identified 51 genomic regions bound by NtcA in ammonium-replete conditions, and 141 regions after 4 h of nitrogen starvation. Parallel transcriptome profiling revealed 669 genes as differentially expressed between these two conditions. Integration of NtcA binding and RNA-seq data classified 51 genes as being directly activated by NtcA and 28 as being directly repressed, including eight non-coding RNAs (ncRNAs). Direct target genes encoded mainly for proteins known to be involved in nitrogen and carbon metabolism, photosynthesis, respiration and transport, as well as various proteins without functional annotation. Interestingly, we observed significant differential expression for some genes, despite unchanged NtcA binding in their promoter regions as well as NtcA binding with only delayed expression changes of associated genes. Both observations suggest involvement of additional regulatory elements and potential different states of NtcA. A modifying role of PipX was specifically examined in selected NtcA target genes, confirming that PipX assists NtcA with nitrogen control in Synechocystis.

MATERIALS AND METHODS

Cyanobacterial strains and growth conditions

A glucose-tolerant strain of Synechocystis sp. PCC 6803 was grown in flask culture at 30°C under constant illumination (45 μmol photons m⁻² s⁻¹) on a rotatory shaker in liquid BG110C medium (16), supplemented with 10 mM NH₄Cl and 20 mM TES (BG110C–NH₄). The pipX(ssl0105)-disruptant mutant (ΔpipX) was grown under the same conditions, except that 50 μg ml⁻¹ of kanamycin was added. To induce nitrogen starvation, flask cultures of Synechocystis cells, growing in BG110C–NH₄, at linear growth phase (3–6 μg Chl/ml; Supplementary Figure S1) were collected, washed twice with BG110C and resuspended in BG110C medium under the same growth conditions for 4 h. Samples in the control treatment were also washed twice in BG110C supplemented with NH₄ and re-suspended in BG110C-NH₄ medium. For all experiments, nitrogen starvation and ammonium-cultured cells were resuspended in the same medium volume at similar cell density.

Construction of ΔpipX mutant Synechocystis strain

A 1639-bp DNA fragment, lacking a 211-bp internal fragment of pipX, was constructed by two-step polymerase chain reaction (PCR), using oligonucleotides pairs pipX-S'-HindIII and pipX-3'-XbaI, as well as pipX-deletion-for and pipX-deletion-rev (Supplementary Table S1). The resulting 1617-bp HindIII-XbaI restriction fragment was cloned into pBS II KS(+)+. An antibiotic resistance C.K1 cassette, which confers kanamycin resistance (Kmr), was inserted into a BamHI site in the positive transcription orientation to generate pPipX. Transformation of Synechocystis cells
with pPipX was carried out. Correct integration of the C.K1 cassette and total segregation of the mutant chromosomes into the *Synechocystis* Δ*pipX* mutant strain was confirmed by PCR (Supplementary Figure S2).

**Chromatin immunoprecipitation and sequencing procedure**

Aliquots of 250 ml of ammonium and nitrogen-starved cultures were used for chromatin immunoprecipitation. To achieve protein–DNA crosslinking, formaldehyde was added to these cultures, yielding a final concentration of 1% and incubated for 15 min at room temperature, with occasional gentle shaking. The crosslinking reaction was terminated by adding 125 mM of glycine followed by a 5-min incubation at room temperature, with occasional gentle shaking. Next, cells were filtered, washed with cold TBS (20 mM Tris–HCl, pH 7.4, 140 mM NaCl) and collected in tubes (50 ml of culture per tube). Cell lysis was carried out, as previously described (14). The lysate was sonicated (15 cycles of 10 s at 10% amplitude, with 40 s on ice between cycles) to fragment chromosomal DNA into sequences of sizes between 100 and 400 bp. Cell debris was removed by centrifugation (15 min at 10 000 × g, 4°C). Chromatin was collected before immunoprecipitation to serve as a control input sample. Immunoprecipitation of NtcA-bound chromatin by an anti-NtcA antibody (generated in our laboratory using purified NtcA protein from *Synechocystis*, injected in rabbits according to standard immunization procedures) was carried out, as described by Picossi *et al.* (14). This protocol was repeated four times, using cells from independent inductions. The resulting DNA was pooled on the same DNA purification column (miniElute; QIAGEN, Hilden, Germany) to obtain 40 and 20 ng samples from ammonium and nitrogen-depleted conditions, respectively. Prior to construction of sequencing libraries, quantitative Real Time PCR (qRT-PCR) was performed to assess the enrichment of the promoter region of *glnA* and *glnB* in the immunoprecipitated samples, compared with the control input sample. Enrichment of a promoter region in the ChIP sample was determined using the percent input method: 100×[Ct(IP-sample)−Ct(Adjusted-Input)], with the control input sample adjusted to give 100%, given that 5% of starting chromatin was used. A CFX Connect RT-PCR machine (Bio-Rad Laboratories, Inc., Hercules, CA, USA) and ssoFast EvaGreen Supermix (Bio-Rad Laboratories) were used for qRT-PCR. The sequences of the primers used for the qRT-PCR to validate ChIP are listed in Supplementary Table S2.

Illumina libraries (Illumina, San Diego, CA, USA) were prepared from 32.5 and 12.5 ng of immunoprecipitated DNA from ammonium and nitrogen-depleted samples, respectively, as well as from the two controls DNA (input samples), using the Illumina TruSeq ChIP-seq DNA sample preparation kit. DNA sequencing was performed on the Illumina HiSeq 2500 platform, using single-end 50 bp sequencing. A total of 153 894 213 reads were obtained for four samples (Supplementary Table S3). The Finnish Microarray and Sequencing Centre (FMSC, Turku, Finland) conducted all DNA-sequencing and library preparation.

**ChIP-seq peak calling analysis**

Raw reads were mapped against the *Synechocystis* genome (NCBI Reference sequences: NC_000911.1 (chromosome), NC_005229.1 (plasmid pSYSM), NC_005230.1 (plasmid pSYSA), NC_005231.1 (plasmid pSYSG) and NC_005232.1 (plasmid pSYSX)) using Bowtie2 (17). The resulting BAM files were processed using SAMTools and BEDTools (18,19). BAM files were normalized for visual inspection in the Integrative Genomics Viewer (IGV) (20), using BamCoverage from DeepTools2 (21). Peaks for NtcA were identified by two peak calling algorithms: MACS (v1.4.1) (22) and BayesPeaK (v1.22.0) (23). In both algorithms, the background noise of unspecific binding was modeled using the input data (control DNA). Surrounding genes were retrieved using the Bioconductor package ChIPseeker (v1.6.7) (24). Peaks were also visually inspected for artefacts, and false positives were removed.

**RNA preparation and differential expression analysis**

RNA from *Synechocystis* cultures was extracted using the PGTX 95 RNA extraction protocol, described in Pinto *et al.* (25). Samples for RNA-seq were taken simultaneously from the same cultures used for the chromatin immunoprecipitation experiments. The quantity and quality of total RNA were evaluated using RNA electropherograms (Agilent 2100 Bioanalyzer; Agilent Technologies, Santa Clara, CA, USA). The Ribo-Zero Magnetic Kit for Bacteria (Epicentre; Illumina) was applied to remove ribosomal RNA from each sample. Two biological replicates for each condition of RNA samples were analyzed using the Ion PGM Template Hi-Q OT2 kit and Ion Touch 2 Instrument (Thermo Fisher Scientific, Inc., Waltham, MA, USA) and subsequently sequenced on the Personal Genome Machine (Ion PGM; Thermo Fisher Scientific), with reagents from Ion Hi-Q Sequencing kit (STAB VIDA, Lda, Lisbon, Portugal), following the manufacturer’s instructions (Supplementary Table S4). Reads were aligned against the NCBI genome sequence for *Synechocystis* (NC_000911.1, NC_005229.1, NC_005230.1, NC_005231.1 and NC_005232.1), applying the Torrent Mapping Alignment Program (TMAP; available from https://github.com/ iontorrent/TMAP). Raw read counts were calculated using the HTSeq Python script from HTSeq-count (26). The Bioconductor DESeq package from R software (27) was used to detect differentially expressed genes under ammonium depletion and nitrogen starvation. An adjusted P-value of <0.1 was considered to be significant. For Gene Ontology (GO) enrichment analysis, the GSEA tool (28) and Synergy (29) (available at http://synergy.plantgenie.org), were applied. Network construction and visualisation were carried out using Cytoscape 3.2.0 (30).

Hierarchical complete-linkage clustering was performed with Cluster 3.0 (31). Clusters were visualized using Java TreeView software (32). Differential expression was displayed as heat maps, using a color range from yellow to blue. Potential target genes of NsiR7 were identified with the IntaRNA algorithm v2.0.2 (33), using default parameters and a window of 275 nt around the start codon (200 upstream and 75 downstream). A threshold P-value of <0.005 was used.
Northern blot analysis

Total RNA was isolated from 30 ml samples of *Synechocystis* cultures in the mid-exponential growth phase (3 to 4 μg chlorophyll ml\(^{-1}\)). Extractions were performed by vortexing cells in the presence of phenol–chloroform and acid-washed baked glass beads (0.25–0.3 mm diameter), as described by Garcia-Dominguez and Florencio (34). An aliquot of 5 μg of total RNA was loaded per lane, and electrophoresed in 1.2% agarose denaturing formaldehyde gels (35). For the ncRNA analysis, RNA samples (5–10 μg) were separated on 6% urea-polyacrylamide gels for 3 h at 25 mA. In both cases, migrated gels were later transferred to nylon membranes (Hybond N-Plus; GE Healthcare, Little Chalfont, UK). Prehybridization, hybridization and washes were carried out in accordance with GE Healthcare instruction manuals. Probes for northern blot hybridization were prepared by PCR, using primers shown in Supplementary Table S2. DNA probes were \(^{32}\)P-labeled, with a random-primer kit (Amersham Biosciences, GE Healthcare), using [\(\alpha-^{32}\)P]dCTP (3000 Ci/mmol). Hybridization signals were quantified with a Cyclone Plus storage phosphor scanner (PerkinElmer, Inc., Waltham, MA, USA). Each experiment was replicated at least twice.

Western blot analysis

To prepare western blot analyses, 5 μg of total proteins from soluble extracts were fractionated on sodium dodecyl sulphate-polyacrylamide gel electrophoresis (SDS/PAGE) and immunoblotted (35) with antibodies against: thioredoxin A (1:3000) (36); IF7 and IF17 (1:2000) (37); PII (1:4000) and GS III (1:20000) (34). ECL Prime (GE Healthcare) was used to detect the different antigens, with anti-rabbit secondary antibodies conjugated to horseradish peroxidase (1:25 000).

Glutamine synthetase assay

GS activity was determined *in situ* by a Mn\(^{2+}\)-dependent γ-glutamyl-transferase assay in cells permeabilized with mixed alkyltrimethylammonium bromide (MTA) (38). The same assay, but without MTA, was performed in cells from the same samples in parallel. One unit of GS activity corresponds to the amount of enzyme that catalyses the synthesis of 1 μmol min\(^{-1}\) of γ-glutamylhydroxamate.

Gel retardation assays

DNA fragments used in the binding assays were obtained by PCR, with the corresponding oligonucleotides pairs (Supplementary Table S4). DNA probes, including NtcA-binding consensus sequences, were cut with NotI restriction enzyme, generating fragments of ~200 bp. These fragments were end-labeled with [\(\alpha-^{32}\)P]dCTP, using Sequenase version 2.0 enzyme. The GST-NtcA fusion protein was expressed and purified, as previously described (39). DNA radiolabeled fragments (0.5 nM) were incubated with purified NtcA (0.1–0.4 μM), and with 2-OG (0.6 mM), when indicated. The binding reaction with the corresponding DNA fragment was carried out in a final volume of 15 μl within binding buffer (12 mM HEPES-NaOH pH 8.0, 8 mM Tris–HCl pH 8.0, 10% (w/v) glycerol, 0.5 mM ethylenediaminetetraacetic acid pH 8.0, 100 mM KCl, 2 mM MgCl\(_2\), 0.05 μg/μl poly (dI–dC), 0.01 μg/μl bovine serum albumin and 1 mM dithiothreitol (DTT)). These mixtures were incubated at 25°C for 20 min, and the DNA–protein complexes were separated on non-denaturing 6% (w/v) polyacrylamide gel. Gels were dried and imaged using a Cyclone Plus storage phosphor scanner (PerkinElmer).

Quantitative real-time polymerase chain reaction analysis

The qRT-PCR was performed in an qTMT5 multicolor RT-PCR detection system (Bio-Rad), in a 10 μl reaction volume using the ssoFast EvaGreen Supermix (Bio-Rad). The sequences of primers used for the qRT-PCR for RNA-seq validation are listed in Supplementary Table S2. The efficiency of the PCR was calculated using the program LinRegPCR (40). Normalized data were calculated by dividing the average of at least three replicates of each sample from the candidate and the reference gene, *rnpB*.

RESULTS

Nitrogen starvation response of *Synechocystis*

To characterize the NtcA regulon in response to nitrogen deprivation in *Synechocystis* sp. PCC 6803, we combined the two powerful genome-wide profiling techniques, RNA-seq and ChiP-seq. Samples were taken from wild-type (WT) cells grown in a medium with ammonium (NH\(_4\)) as nitrogen source and after their incubation in a medium depleted of combined nitrogen (−N) for 4 h (Figure 1A). GS activity was measured to verify that nitrogen starvation was induced under the experimental conditions. Results obtained for GS activity were consistent with a transition from a nitrogen-rich medium to a nitrogen-depleted medium, showing higher activity after 4 h (71.92 ± 7.93 U/mg*chl*\(^{-1}\)) in the depleted medium (Figure 1B). After 24 h in a nitrogen-depleted medium, cell growth arrested and a yellow appearance (bleaching) typical of the chlorotic cultures was observed (Figure 1C), consistent with degradation of the phycobilisomes (PBS) related to prolonged nitrogen starvation.

Transcriptional profiling by RNA-seq of nitrogen starvation response

To study the transcriptional response after the transition from an NH\(_4\)-replete to a N-depleted medium, total RNA obtained under both conditions was sequenced. Samples taken after 4 h of nitrogen starvation were compared with samples taken at the zero time point (with NH\(_4\); Figure 2A). There were 1080 genes significantly regulated (adj. P < 0.1; Supplementary Table S6), of which 669 genes showed more than a 2-fold change in expression. Of these latter ones, 332 and 337 genes were up- and downregulated, respectively (Supplementary Tables S7 and 8). RNA-seq analysis also enabled detection of small open reading frames (ORFs) and ncRNAs, which were not captured by previous DNA microarray analyses (3,4). In total, 21 ncRNAs were detected as differentially expressed, including NsiR4 (Supplementary Tables S7 and 8), which has been recently identified as
Nitrogen assimilation. Adjustment of nitrogen assimilation pathways is crucial for survival under nitrogen-limited conditions. This is reflected in the expression pattern, with 24 genes involved in nitrogen uptake and assimilation being differentially expressed after nitrogen depletion (Table 1). Seven of them (glnA, urtA, antI, urtB, glnN, hgtB and hmt2) are among the 10 most-induced genes (Figure 2A). They include genes encoding the high-affinity nitrate/nitrite transporters (urtBACD), the glutamine permease (hgtA and hgtB), the urea transport system (urtADBC) and the ammonium permeases (antI and antM). Thus, after 4 h of nitrogen starvation, all scavenging nitrogen systems were activated to compensate for the loss of combined nitrogen from the media.

Nitrogen in the form of ammonium is incorporated into amino acids by sequential action of GS and glutamate synthase (GOGAT) (Figure 3). Significant upregulation was observed for glnA and glnN encoding GS type I and III, respectively (Figure 3). The upregulation of GS coincided with a strong downregulation of genes encoding the GS inactivating factors IF7 (gifA) and IF17 (gifB) (Figure 3). Both NADH-GOGAT and Ferredoxin-GOGAT convert glutamine to glutamate, with 2-OG provided by the isocitrate dehydrogenase (icd). This reaction constitutes a crossroad between nitrogen and carbon metabolism (Figure 3).

Transcripts of gifB and gifD encoding the large and the small subunits of the NADH-GOGAT were slightly induced (Figure 3 and Table 1). Remarkably, icd together with the genes encoding the phosphoenolpyruvate carboxylase (ppc) and the pyruvate kinase (pyk1) genes were also upregulated, facilitating enhanced synthesis of 2-OG in response to nitrogen starvation (Figure 3; Supplementary Tables S6 and 7). Surprisingly, expression of ntcA and pipX was not significantly affected, despite the observed differential expression of known NtcA targets (i.e. gifB, gifA glnA glnB, antI and icd). In contrast, transcripts encoding the regulatory protein Pit (glnB) were accumulated upon nitrogen depletion. Pit is involved in the regulation of central metabolism processes, integrating signals of cellular carbon, nitrogen and energy balances by binding 2-OG and ATP (42).

Photosynthesis, carbon assimilation and central carbon metabolism. We observed a major increase in the expression of genes encoding for almost all subunits of PSI and PBS. In addition, several subunits of the ATP synthase (atpI, atpC, atpH) and photosystem II (PSII), namely psoO, psoU, psoK, psoT and psoB, were upregulated (Supplementary Table S7). In contrast, CO2 fixation appeared to be diminished after nitrogen starvation, as genes encoding the bicarbonate transporter (Na+/HCO3− symport), (bicA), as well as the carbon-concentrating mechanism proteins, ccmN and ccmM, were repressed (Supplementary Table S8). Additionally, ndhF3-ndhD3-cupA encoding subunits of the NDH–1MS complex associated with high-affinity CO2 uptake were downregulated (43,44) (Supplementary Table S6). Although the expression of the genes encoding the two subunits of the ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCo) remained unaltered, expression of other genes encoding enzymes of the Calvin-Benson cycle was downregulated, especially for prk, pgk, tktA and rpiA (Figure 3 and Supplementary Table S8).

Genes involved in sugar and glycogen metabolism displayed divergent patterns. Genes encoding sugar catabolic enzymes were induced under nitrogen starvation, while genes for sugar anabolism were downregulated. In this case, increased expression of the oxidative pentose phosphate pathway (OPP) genes zwf, talB and gnd was observed, whereas expression of fbp (sho952) encoding for the fructose-1,6-bisphosphatase, which acts exclusively in the direction of the gluconeogenesis, was diminished (Figure 3; Supplementary Tables S7 and 8). Similar divergence was
Figure 2. Global response to nitrogen starvation in *Synechocystis* sp. PCC 6803. (A) MA plot: a scatterplot of log₂-fold-change (−N/NH₄) versus average expression in log₂ scale for each gene, produced using the DESeq2 package. Dots shown in red indicate differentially expressed genes with adj. P-value of < 0.1. The nine genes with the highest induction and repression are shown in blue and yellow, respectively. (B) GO enrichment analysis of differentially expressed genes under nitrogen starvation conditions. Only GO of biological processes and cellular components having a false-discovery rate of <0.1 are shown.

Table 1. Selected genes involved in nitrogen assimilation which expression is altered after 4 h of nitrogen starvation

| Gene   | Symbol | Function                        | Log₂ (ratio) | P-value       |
|--------|--------|---------------------------------|--------------|---------------|
| Regulators of nitrogen metabolism |        |                                 |              |               |
| ssl0570 | glnB   | nitrogen regulatory protein PII  | 3.83         | 2.6E-101      |
| ssl1911 | gifA   | GS inactivating factor IF7      | -4.20        | 4.3E-96       |
| ssl1315 | gifB   | GS inactivating factor IF17     | -2.32        | 4.3E-23       |
| Nitrate/Nitrite assimilation |        |                                 |              |               |
| sll1450 | nrtA   | nitrate transport               | 3.45         | 2.7E-25       |
| sll1451 | nrtB   | nitrate transport               | 2.51         | 1.5E-05       |
| sll1452 | nrtC   | nitrate transport               | 2.39         | 8.7E-19       |
| sll1453 | nrtD   | nitrate transport               | 2.16         | 2.0E-06       |
| Glutamine/glutamate assimilation |        |                                 |              |               |
| sll1756 | glnA   | glutamate–ammonia ligase GSI    | 5.38         | 9.2E-191      |
| sll0388 | glnN   | glutamate–ammonia ligase GSIII  | 4.64         | 4.5E-117      |
| sll1502 | gldB   | glutamate synthase large subunit| 0.96         | 9.4E-09       |
| sll1027 | gldD   | glutamate synthase small subunit| 0.50         | 1.4E-02       |
| sll0710 | gdhA   | glutamate dehydrogenase (NADP+) | 0.93         | 2.1E-03       |
| sll1733 | bgtA   | Component of ABC-type Bgt permease| 1.27     | 1.8E-05       |
| sll1270 | bgtB   | Component of ABC-type Bgt permease| 4.19     | 7.0E-01       |
| Ammonium assimilation |        |                                 |              |               |
| sll0108 | amtl1  | ammonium/methylammonium permease| 5.32         | 2.8E-216      |
| sll0107 | amtl2  | ammonium/methylammonium permease| 4.12         | 2.7E-15       |
| Urea assimilation |        |                                 |              |               |
| sll0447 | urtA   | Component of ABC-type urea transport system| 5.36 | 7.7E-212 |
| sll0764 | urtD   | Component of ABC-type urea transport system| 1.48 | 6.5E-09 |
| sll1200 | urtB   | Urea transport system permease protein| 5.19 | 8.1E-71 |
| sll1201 | urtC   | Urea transport system permease protein| 3.33 | 4.7E-17 |

recorded for glycogen metabolism. Both *gltX* (*sll1356*) and *gltG* (*sll1356*) involved in the catabolism of glycogen were upregulated; while *gltB* and *gltC*, which participate in the synthesis of this molecule, were down- and upregulated, respectively (Figure 3; Supplementary Tables S7 and 8).

To confirm and validate differential expression detected by RNA-seq, qRT-PCR was carried out for genes related to nitrogen and carbon metabolism (*glnA, glnB, glnN, amtl1, gifB, icd* and *rre37*). For these genes, RNA-seq and qRT-PCR data provided very consistent results (Supplementary Figure S3).

ChIP-seq analysis of NtcA binding

ChIP with anti-NtcA antibodies enabled *in vivo* genomewide detection of NtcA binding sites. For quality control, enrichment of the promoter regions of two *bona fide* NtcA targets, *glnA* and *gifB*, within the immunoprecipitated fraction was confirmed by qRT-PCR. Primers against the promoter region of the ORF, *sll1875*, which is not regulated by NtcA, served as a negative control. Our qRT-PCR results confirmed the specificity of the immunoprecipitation, as strong enrichment of the two known binding sites for
Figure 3. Changes in expression of genes involved in nitrogen assimilation and carbon metabolism. This diagram shows metabolic pathways and metabolites of the TCA and GS/glutamine oxoglutarate amidotransferase (GOGAT) cycle, glycolysis, gluconeogenesis, pentose phosphate pathway (OPP) and glycogen metabolism. These pathways were predicted from the KEGG database (www.genome.jp/kegg/pathway.html). NtcA target genes obtained from ChIP-seq analysis are shown for −N (green square) or NH₄ (red square) treatments. Genes encoding metabolic enzymes are shown below; narB, nitrate reductase; nirA, nitrite reductase, gifA, GS-inactivating factor; gifB, GS-inactivating factor; glnA, GS type I; glnN, GS type III; gltD, glutamate synthase small subunit; glnB, GOGAT, glsF, ferredoxin-dependent glutamate synthase, gdhB, glutamate dehydrogenase; icd, isocitrate dehydrogenase; acnB, aconitase hydratase; citH, malate dehydrogenase; citB, citrate synthase; citD, citrate synthase; pyk1,2, pyruvate kinase; eno, enolase; ppc, phosphoenolpyruvate (PEP) carboxylase; gpmB, phosphoglycerate mutase; pgk, phosphoglycerate kinase; gap1, glyceraldehyde-3-phosphate dehydrogenase (catabolic reaction); gap2, glyceraldehyde-3-phosphate dehydrogenase (anabolic reaction); tpi, glycogen isomylase; cbbA, fructose-bisphosphate aldolase; pgl, fructose-1,6-bisphosphatase; pgl, 6-phosphogluconolactonase; pgl, phosphoglucomutase; glnC, glucose-1-phosphate adenylyltransferase; glnA, glycogen phosphorylase; tbl, glycogen isomylase; tblB, 1,4-alpha-glucan branching enzyme; zwf, glucose-6-phosphate dehydrogenase; gnd, 6-phosphogluconate dehydrogenase; tktA, transketolase; rpiA or B, ribose-5-phosphate isomerase; rpe, pentose-5-phosphate-3-epimerase; prk, phosphoribulokinase; rbcL, ribulose bisphosphate carboxylase large subunit; rbcS, ribulose bisphosphate carboxylase small subunit.
NtcA was measured, especially after nitrogen depletion, in contrast to the negative control (Supplementary Figure S4).

For comprehensive detection of binding sites, two different peak-calling methods were applied, MACS (22) and BayesPeak (23). NtcA binding was identified, if peaks in the sequence coverage were detected by at least one of the two peak-calling algorithms and passed visual inspection. We identified 51 NtcA binding peaks in NH4 and 141 peaks after nitrogen depletion (Figure 4A and B, Supplementary Tables S9 and 10). Three-quarters of the binding regions (151/192) were shorter than 450 bp, consistent with DNA fragment sizes obtained after DNA sonication. Thirty-two regions were slightly larger in size (500–850 bp), while only one region extended over more than 1 kbp (1200 bp). Visualization of this latter peak, revealed two peaks that overlapped each other within the bidirectional-promoter region for both slr0821 and slr0822 genes. Interestingly, slr0783 gene is reported to be involved in polyhydroxybutyrate accumulation under nitrogen starvation conditions in Synechocystis (45).

The majority of chromosomal NtcA-IP peaks (73%) in the –N medium were located immediately upstream of genes coding sequences, ncRNAs and asRNAs, consistent with preferential NtcA binding to promoter regions under nitrogen-depleted conditions (Figure 4C). In contrast, only 46% of chromosomal peaks correspond to putative promoter regions in the NH4 condition, and of those 92% were also present in the –N condition (Figure 4C). Interestingly, we detected 24 peaks that were present exclusively under NH4 conditions. The vast majority of these peaks occurred within intragenic locations, with only four in promoter regions.

NtcA binding in promoter regions was assigned to transcribed genes, based on experimentally defined TSS in Synechocystis (5,46) and on gene expression data from our RNA-seq analysis. An unambiguous assignment to a single TSS was not possible for six of the NtcA binding peaks, because of the presence of nearby flanking genes. These peaks were assigned to both genes. In nine cases, we observed NtcA binding close to small RNAs, which were co-expressed with down-stream genes of the same transcriptional unit; a genetic feature that has recently been termed ‘actuon’ (47).

For these transcriptional structures, both coding genes and small RNAs were considered as NtcA-targets. Collectively, 18 ncRNAs and 5 asRNAs had an NtcA binding region within their promoter regions, with the exception of ncRNA nc0530 and the downstream gene sigD, with its peak located within the nc0530 sequence (Figure 5).

Genes identified as NtcA targets were classified into 16 functional categories (Figure 4D). About a third of the assigned genes (48) encode unknown or hypothetical proteins. The most represented functional categories were ‘amino acids biosynthesis’ and ‘transport and binding’. Both functional categories include most of the well-known NtcA-regulated genes, such as glnA, glnB, glnC, aspA, as well as several genes coding for the nitrogen uptake system (amt1, amt2, urtABCD, bgtA, bgtB, nrtABCD). Interestingly, NtcA binding sites were also found upstream of ten genes coding regulatory proteins. These included PipX (49), response regulator Rre37 (50), P1 (34) and NtcA, but also newly identified ones, i.e. the response regulators Rre8, Rre12 and SphR, and the predicted transcription factor Sll0783.

Electrophoretic mobility shift assays (EMSA) were performed to validate the capability of NtcA to bind in vitro to DNA fragments of binding regions determined by ChIP-seq (Supplementary Figure S5). As a positive control, the promoter region of glgA, which contains a verified NtcA binding site, was used (51). In contrast, a DNA fragment containing the promoter region of nrsK, which has not been described as an NtcA target, was used as the negative control. We selected seven binding regions, including those with high (sll0327, urtA, pilA4, ncl0350) and low (gltB, metX, glgP) fold enrichment, as identified by ChIP-seq analysis (for both NH4 or –N conditions; Supplementary Tables S9 and 10). A strong positive correlation between ChIP-seq fold enrichment and NtcA EMSA affinities was found, indicating that our ChIP-seq analysis produced reliable results (Supplementary Figure S5).

Parallel differential profiling of transcriptome and NtcA binding sites

Occupancy of transcription factor binding sites alone gives only a weak indication of their regulatory potential. Therefore, we used parallel profiling of changes in both NtcA binding and transcription in response to nitrogen depletion. To define the NtcA regulon and to determine its dynamics, we intersected potential direct targets of NtcA, with their observed differential expression. This approach identified genes for which changes in NtcA binding were indicative of changes in transcriptional activity. We detected 79 genes (including ncRNAs and asRNAs) that fulfilled this criterion; they define the direct NtcA regulon in early phase of nitrogen starvation. Fifty-one of these genes were up-regulated and 28 were downregulated, after 4 h of nitrogen depletion (Figure 4B and Table 2). Read coverage from RNA-Seq and ChIP-seq is shown for representative genes in Figure 5. The direct NtcA regulon (Figure 6) included eight enzymes involved in amino acid biosynthesis (glnA, glnN, nirA, argG, glnB, hisC, icd, aspA), six nitrogen compound transporter-related genes (urtA, urtB, amt1, amt2, bgtA, bgtB) and four regulators of nitrogen metabolism (gif4, gifB, glnB, rr37). Genes coding for proteins involved in the synthesis of the two main nitrogen storage pools in cyanobacteria, cphA and cpcB for cyanophycin and phycocyanin, respectively, were also targeted and regulated by NtcA, as previously described in Anabaena sp. PCC 7120 (14,52). Additionally, several genes that encode proteins related to carbon metabolism displayed NtcA-dependent regulation: transketolase (iktA; Figures 3 and 5), glycolate oxidase subunit (gltP), carbon dioxide concentrating mechanism protein (ccmK2). Sll0783 protein required for accumulation of polyhydroxybutyrate in Synechocystis (45), and glycogen phosphorylase (glgP; Figures 3 and 6). In particular, glgP contains an intragenic NtcA-binding peak under NH4-replete condition suggesting a repressive role of NtcA, triggered by binding to an intragenic region and blocking transcription in nitrogen-rich media. This correlates well with the observed diminished expression of glgP in NH4, compared with the –N conditions (Figure 5). Similar potential NtcA-regulation by intragenic binding was observed.
Figure 4. Genome-wide NtcA DNA binding analysis. (A) NtcA binding across the genome was compared for NH$_4$ (blue track) or −N (red track) conditions. The x-axis indicates the genomic position of the ChIP-seq peaks, while the y-axis indicates the read count after each dataset was normalized using BamCoverage (Ramirez, F. 2016). Names of genes assigned to peaks with high read count are also shown. B. Venn diagram showing overlap of genes with significant binding by NtcA in +NH$_4$ versus −N conditions. Overlap of genes differentially expressed (P-value < 0.1 and fold change > 2) after nitrogen depletion versus genes with significant binding by NtcA are also shown. (C) Distribution of NtcA binding peaks for NH$_4$ and −N conditions. NtcA peaks were classified into four categories: intragenic region (green), gene promoter (blue), ncRNA promoter (yellow) and antisense promoter (purple). (D) Genes with NtcA binding peaks assigned to NH$_4$ or −N conditions, were grouped into functional categories according to the CyanoBase classification. FPS: Fatty acid, phospholipid and sterol metabolism; PPNN: Purines, pyrimidines, nucleosides and nucleotides; DNA_RRMRR: DNA replication, restriction, modification, recombination and repair.
Figure 5. Read coverage of potential NtcA targets detected by parallel differential profiling. The ChIP-seq and RNA-seq density profiles are shown in blue for NH₄ and in red for −N treatments. Examples of genes included in the NtcA regulon are displayed: NtcA activated (glnA) or repressed (tktA) genes, long transcripts containing ncRNA and downstream protein-coding genes that are transcribed by read-through over the ncRNA terminator (ncl0530-sigD); and genes with internal peaks (metX, glgB and pilA4). Values on the x-axis are the genomic coordinates. Arrows indicate transcriptional start sites (TSS) obtained from Mitschke et al. (46).

for genes, such as pilA4 in NH₄ or metX (Figure 5) and secA under −N conditions. We were particularly interested in identifying new NtcA-regulated genes. Our study reveals that NtcA coordinates a wide range of functions to cope with the early acclimation of nitrogen starvation, given that NtcA targets included genes coding for porins (apqZ and slr1841), the periplasmic protein involved in phosphate uptake (pstS), and the photomixotrophic growth protein A (pmgA). Furthermore, the NtcA regulon comprises 26 genes encoding hypothetical or unknown proteins, as well as asRNA slr1802-as and eight ncRNAs (Figure 6).

Sequence analysis of NtcA-bound promoters

The NtcA consensus binding sequence GTAN₈TAC was first described in the NtcA-regulated promoters of Synechococcus (53). Promoters activated by NtcA tend to contain a consensus sequence, centered close to position −41 with respect to the TSS, although actuating NtcA binding in positions further upstream has been reported in some cases (53). Conversely, NtcA-mediated repression is thought to be caused by NtcA binding at positions incompatible with correct assembly and positioning of the RNA polymerase. This model is supported by a promoter analysis of the NtcA regulon for Synechocystis. Promoters of the 10 most-induced genes of the NtcA regulon showed a highly conserved GTAN₈TAC motif, centered close to position −41.5. Notably, GTA at positions 1–3 was strictly conserved, and only little variation was observed for TAC at positions 12–14 (Figure 7A). In the case of the top ten repressed genes, the potential NtcA binding sites displayed greater derivation from the consensus sequence, and were widely distributed along the promoter (Figure 7B). These patterns were also found, when we examined NtcA binding positions for the entire regulon. While 71% of binding sites of induced genes were concentrated at positions −41 and −44, binding for repressed genes ranged from −69 to +83, with respect to the TSS, with slight accumulation around −30 (Figure 7C). This finding confirms previous observations that the distance between the NtcA binding site and the TSS determines the regulatory mode of NtcA (53).

In addition to examining the positioning of the established consensus binding sequence, studying the NtcA regulon provides the opportunity to refine the NtcA binding mo-
| Treatment | Regulated gene | Symbol | Peak start | Peak end | Region | log2 ratio (-N/\(\text{NH}_4\)) | Gene function | TSS located inside peak |
|-----------|---------------|--------|------------|----------|--------|-------------------------------|---------------|------------------------|
| −N        | nbl1756       | glhA   | 531291     | 531451   | promoter | 5.380                         | glutamate–ammonium ligase | 531399       |
| −N, \(\text{NH}_4\) | nbl0447     | urtA   | 2098581    | 2098991  | promoter | 5.363                         | periplasmic protein, ABC-type urea transport system substrate-binding protein | 2098760      |
| −N        | nbl0108       | amtl   | 2971052    | 2971551  | promoter | 5.318                         | ammonium/methylammonium permease | 2971398      |
| −N, \(\text{NH}_4\) | nbl1200     | urtB   | 881702     | 882201   | promoter | 5.185                         | urea transport system permease | 881923       |
| −N, \(\text{NH}_4\) | nbl0327     | glnN   | 2389552    | 2390401  | promoter | 5.141                         | glutamate–ammonium ligase | 2390100c     |
| −N        | nbl0288       | glnB   | 2128602    | 2128851  | promoter | 4.643                         | periplasmic substrate-binding and integral membrane protein of the ABC-type Bgt permease | 2128736      |
| −N        | nbl1270       | gntB   | 1115933    | 1116332  | promoter | 4.195                         | ammonium/methylammonium permease | 1116162c     |
| −N        | nbl0117       | amtl2  | 401952     | 402201   | promoter | 4.123                         | ammonium/methylammonium permease | 402151       |
| −N        | nbl0944       | glhB   | 2267152    | 2267301  | promoter | 4.094                         | nitrogen regulatory protein Pj1 | 2267292      |
| −N        | nbl0707       | icsB   | 2152602    | 2152751  | promoter | 3.826                         | hypothetical protein | 2152741      |
| −N        | nbl1119       | cphA   | 874502     | 874651   | promoter | 3.823                         | hypothetical protein | 874644       |
| −N, \(\text{NH}_4\) | nbl2002     | icd    | 1447927    | 1448046  | promoter | 3.121                         | cyanophycin synthetase | 1448016      |
| −N, \(\text{NH}_4\) | nbl0909     | irdC   | 285874     | 283225   | promoter | 3.043                         | isocitrate dehydrogenase (NADP+) | 283033       |
| −N, \(\text{NH}_4\) | nbl1912     | slrA   | 278536     | 278560   | intragenic | 2.874                       | unknown protein |                       |
| −N, \(\text{NH}_4\) | nbl0530/sll1698 | NaiR4/2 | 1289152 | 1289451 | promoter | 2.861 | hypothetical protein | 1255935 |
| −N, \(\text{NH}_4\) | nbl0763     | NaiR4/2 | 3419302   | 3419651 | promoter | 2.783 | unknown protein | 341527 |
| −N, \(\text{NH}_4\) | nbl1164     | Rec37  | 3295152    | 3295451  | promoter | 2.704 | two-component system response regulator OmpR subfamily | 3295334      |
| NH4       | nbl1142      | sll1831 | 801102     | 801851   | promoter | 2.657 | hypothetical protein | 801482 |
| NH4       | nbl0142      | sll1831 | 801102     | 801851   | promoter | 2.657 | Acmatin | 801420 |
| NH4       | nbl0763      | icd    | 1447927    | 1448046  | promoter | 3.121 | cyanophycin synthetase | 1448016 |
| NH4       | nbl1164      | Rec37  | 3295152    | 3295451  | promoter | 2.704 | two-component system response regulator OmpR subfamily | 3295334 |
| NH4       | nbl1164      | Rec37  | 3295152    | 3295451  | promoter | 2.704 | two-component system response regulator OmpR subfamily | 3295334 |

Table 2. The NtcA regulon
tif for *Synechocystis*. Using the WebLogo application (54), we obtained an approximately palindromic motif of length 14 nt, with a high prevalence of G, T and C at positions 1, 2 and 14; and medium prevalence of A, T and A at positions 3, 12 and 13 (Figure 7D). In most of the remaining positions (4–11), a weak tendency towards A or T was noticed. Subsequently, we extended this analysis to include all NtcA binding regions, determined in our ChIP-seq analysis. For this enlarged set, the information content of the motif deteriorated, although it still resembled the consensus sequence GTAN\_TAC (Figure 7E). Interestingly, the prevalence of the flanking nucleotides (G at 1, C at 14) increased, demonstrating their importance for NtcA dimer binding, even when other nucleotides were less conserved.

### Noncoding RNAs regulated by NtcA

Several NtcA binding peaks were assigned to promoter regions of ncRNAs and asRNAs. In total, 18 ncRNAs and 5 asRNAs with assigned NtcA binding were identified in our ChIP-seq analysis (Supplementary Tables S9 and 10). Eight of these ncRNAs were also differentially regulated; thus, we added these to the defined NtcA regulon. These included NsiR4, which has been previously reported to be involved in nitrogen assimilation control by targeting the nitratetransportproteinNrtB, *slr2136* (also called *Syr6*); Figure 8A). Specifically, *ncr1071* codes for a predicted 1057-nt long ncRNA, while *ncr0210* (also called *Syr6*) and *ncr0210* (also called *NsiR7*) have been reported to belong to the 33 most abundant ncRNAs in *Synechocystis* (5,47). Since these ncRNAs were transcribed from their own transcriptional units, they are unlikely to be by-products of the expression of other genes; thus, we decided to analyze them further.

The RNA-seq data showed the accumulation of NsiR7 transcripts after 4 h of nitrogen depletion, having an NtcA binding site upstream at position −43 from the TSS, consistent with activation by NtcA (Figure 8A and Supplementary Table S10). In contrast, both *ncr1071* and *syr6* were downregulated and their NtcA binding sites were found at positions +3 and +16, respectively (Figure 8A and Supplementary Table S9). To experimentally validate the NtcA binding peaks detected by ChIP-Seq, we performed EMSA experiments, which clearly showed NtcA binding to promoter sequences of these selected ncRNAs (Figure 8B). We also carried out northern blot experiments to examine the expression levels of these ncRNAs over a prolonged period of nitrogen starvation. For this purpose, *Synechocystis* cultures grown in NH\(_4\) were shifted to nitrogen-depleted media, and samples were collected after 4, 12 and 24 h. Both *ncr1071* and *syr6* were strongly repressed after 4 h of nitrogen starvation; although in the case of *syr6*, repression was not complete and residual transcription was still observed (Figure 8C). *nsiR7* showed a weak induction that was detected by northern blot, after only 12 h.

To predict potential targets of these three ncRNAs, we used two RNA target predictions programs: CopraRNA (55) and IntaRNA (33). CopraRNA has better accuracy than IntaRNA since it uses phylogenetic conservation in its scoring system (56), but this implies that presence of homologous sRNA sequence from distinct organisms is necessary. For both *ncr1071* and *syr6* homologous where found in other cyanobacteria but not for *nsiR7* that is only present in *Synechocystis*. Thus CopraRNA was applied for *Ncr1071* and Syr6, while IntaRNA was only used for *NsiR7*. Assuming repression as the dominant mode of regulation by ncRNAs, we expected that genes under the control of repressed ncRNAs after nitrogen depletion (*Ncr1071* and *Syr6*) would show increased expression in our RNA-seq data; while those under the control of induced *NsiR7* would show decreased expression. In the case of *Ncr1071*, four predicted targets were significantly induced: *ssl1451* encoding the nitrate transport protein NrtB, *slr2136* encoding the GpE protein homolog involved in the terpenoid biosynthesis and *sh0151* and *ssl1219* encoding the hypothetical proteins *Slr0151* and *Sll1219*, respectively (Supplementary Table S11). Alternatively, it may act as an asRNA to *ssl1864* coding for a chloride channel protein. In the case of *Syr6*, also four of the predicted targets displayed increased expression: *ssl2598* (*psbH*) encoding the photosystem II reaction center protein H, *sh0079* encoding the general secre-
induced Repressed

5.39 -4.20
0.41 -0.67

Amino acids biosynthesis

GinA

GinN

UrtA

UrtB

Arg1

GlnA

GlnB

Amino acids biosynthesis

GlnC

GlnD

MetX

GluC

GluD

AspA

SecA

Cell envelope

FgfA

FgfB

GlnN

PstS

glgP

icd

glcF

gltB

hisC

gifB

gifA

amt1

argG

amt2

GntA regulatory network and its transcriptional dynamics for the early stages of nitrogen depletion. Target genes are represented by nodes that are colored based on gene expression after 4 h of nitrogen depletion: yellow for upregulated genes, and blue for downregulated genes. Node sizes correspond to the magnitudes of expression changes as a log2 expression ratio (−N/−NH4). Genes are grouped according to the functional categories obtained from CyanoBase. PPNN: purines, pyrimidines, nucleosides and nucleotides.

Role of PipX in nitrogen regulation in *Synechocystis*

For a number of NtcA binding sites, the normalized peak height was preserved during nitrogen starvation, suggesting a similar NtcA binding affinity under both conditions. Surprisingly, the clearest example was observed in the promoter region of IF7 coding gene *gifA*. Despite significant expression change in *gifA* (−4.2 log FC; Supplementary Tables S8 and 12), following transition to a nitrogen-free medium, its NtcA peak height remained almost identical, with less 1% differential fold enrichment (DFE) between both conditions (Figure 9A). This contrasts with *gifB* encoding IF17 (Figure 9A), for which its downregulation (−2.3 log fold change, FC; Supplementary Table S8) was correlated with an NtcA binding peak present only under nitrogen starvation. Given that promoters of both GS inactivation factors contain NtcA binding sites at positions considered repressive for transcription (9), the persistence of NtcA binding under nitrogen-replete conditions, when *gifA* is highly induced, is remarkable. Intriguingly, we found several other NtcA targets (some of them well established) with unexpectedly small changes in their NtcA binding, considering their large expression changes. These included *rre37* (23% DFE, 2.7 log FC), *urtA* (24% DFE, 5.3 log FC; Figure 9A) and *urtB* (<38% DFE, 5.1 log FC). Collectively, eight genes having more than a two log FC in expression showed less than 40% DFE (Supplementary Table S12).
Figure 7. Sequence analysis of NtcA binding sites. (A and B) Promoter regions having NtcA binding sites for ten most strongly induced and repressed genes, respectively. Nucleotides confirming the putative NtcA consensus-binding sequence are indicated in blue, potential −10 promoter elements in red and transcriptional start sites (TSS) in orange. An alternative NtcA binding site for the gifA promoter at position −45 is underlined in red. (C) Distribution of positions of NtcA binding sites identified for genes of the NtcA regulon. The location of NtcA binding was determined by matching the NtcA consensus sequence. The relative position was defined as the distance of the seventh nucleotide of a putative NtcA binding site to the TSS. Blue and red bars indicate the frequency of these positions for induced and repressed genes, respectively. (D) NtcA binding motif defined by target genes of the NtcA regulon. (E) Binding motif found using all the putative NtcA binding sites identified by ChIP-seq analysis. (Representation by WebLogo 3.0) (54).

It has previously been demonstrated that high cytoplasmic concentrations of NtcA alone are not sufficient to promote activation of selected target genes (57). In fact, activation of several NtcA-dependent genes, including the amt1 or nir operon, has been directly stimulated by 2-OG in Synechococcus elongatus PCC 7942 (58). Later studies revealed that 2-OG enhances complex formation between NtcA and PipX, which is crucial for activation of NtcA target genes in Synechocystis PCC 7942 and Anabaena sp. PCC 7120 under nitrogen-depleted conditions (49, 59). Whether this is the case for Synechocystis remains unclear, as the role of PipX in nitrogen control in this cyanobacterial model has not been fully established.

To investigate the role of PipX in the regulation of the NtcA-controlled genes in Synechocystis, especially those having promoters with similar affinity to NtcA under both conditions (NH₄ and −N), a pipX-deficient mutant (ΔpipX) was generated (see ‘Materials and Methods’ section and Supplementary Figure S2). Cells of Synechocystis WT and ΔpipX cultivated in BG11C medium supplemented with ammonium were shifted to a nitrogen-free BG11C medium and cultivated for an additional 48 h. Although the growth kinetics for both strains did not show significant differences during this nitrogen-starvation treatment, chlorosis of the cells in the ΔpipX strain was slightly delayed, compared with WT (Figure 9B and C). A similar observation was made for a pipX-deficient mutant of S. elongatus PCC 7942 (10). Subsequently, we analyzed the transcript and protein accumulation of several genes involved in nitrogen assimilation, including IF7 and IF17, GSHI, PII and
the urea transport protein UrtA. Consistent with a role of PipX as an NtcA enhancer, both transcriptional activation and repression of the selected NtcA targets were delayed in the ΔpipX strain. This delay was also reflected in their corresponding protein levels (Figure 9D and E). Furthermore, transcriptional induction of glhN, glhB and urtA was weaker in the ΔpipX strain, suggesting that PipX enables faster and more efficient adaptation to nitrogen starvation. Such a function might be especially important, given that transcription of ntcA remained unaltered in both strains during our treatment with only a small increase in protein levels after 24 h, in agreement with previous report (3). Remarkably, we did not find any differences in the transcriptional expression of gifA between both strains under nitrogen-replete condition, indicating that PipX is not acting as a coactivator of NtcA for gifA transcription. A possible explanation for the persistent NtcA binding peak within the promoter of gifA in NH₄-replete media might be the presence of a degenerate NtcA consensus sequence GTAAATTTTTGTTT at position −45. At this position, NtcA could bind and enhance transcription of gifA (Figure 7). Stimulated by 2-OG or other factors, NtcA could slide to the binding site at position −33, acting as a repressor, when nitrogen is limited.

**DISCUSSION**

To understand how cyanobacteria respond to varying conditions in the environment, it is important to have comprehensive models of their underlying transcriptional regulation. Here, we present the first genome-wide analysis of a transcription factor regulon for *Synechocystis*, based on both ChiP-seq and RNA-seq techniques. Combining these two high-throughput approaches permitted us not only to identify the regulon of NtcA, but also to capture the activity of this key transcriptional regulator of nitrogen. We were able to identify 48 and 121 NtcA-bound regions in the *Synechocystis* genome under nitrogen-replete conditions and after 4 h of nitrogen step-down, respectively. In parallel, we obtained transcriptional profiles of *Synechocystis* under...
Figure 9. The role of PipX in the NtcA-regulated genes. (A) Read coverage of NtcA-binding peaks assigned to gifA, gifB and urtA. Their ChIP-seq and RNA-seq density profiles are shown in blue for NH4 and in red for −N conditions. (B) Growth of Synechocystis WT and ∆pipX strains after nitrogen step-down. Cells of WT and ∆pipX strains cultivated to their midlog growth phase in BG11C medium supplemented with NH4 were transferred to nitrogen-free BG11C medium. Their growth was measured at OD750 for 48 h. (C) Images of cyanobacterial cell suspensions of Synechocystis WT and ∆pipX obtained during growth curve analysis (panel B) at indicated times. (D) Northern blot analysis of expression of gifA, gifB, glnB, glnN, urtA and ntcA in response to nitrogen starvation. Total RNA was isolated from WT cells transferred from BG11C supplemented with ammonium to nitrogen-free BG11C medium for 24 h. The filters were hybridized with gifA, gifB, glnB, glnN, urtA and ntcA probes and subsequently stripped and rehybridized with rnpB probe as a control. (E) Western blot analysis of IF7, IF17, PII, GSIII and NtcA in response to nitrogen starvation. Cells were grown in BG11C supplemented with ammonium to midlog growth phase and then transferred to nitrogen-free BG11C medium and cultivated for 24 h. Samples of 10 μg of total proteins from soluble extracts were separated by 15% SDS/PAGE and analyzed by western blots to detect IF7, IF17, PII, GSIII, NtcA and TrxA.

The RNA-seq analysis revealed that transcription of genes involved in transcription and translation, biosynthetic process and protein synthesis were downregulated, indicating a reduction of overall protein synthesis, as previously reported.
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ported for nitrogen deprivation (3–4,60). Major changes in transcript levels were observed for genes involved in nitrogen uptake and metabolism (Table 1 and Figure 2), including many NtcA targets; glnA, glnB, amt1, urtA, g6fA and g6fB. However, genes coding for both NtcA and the nitrogen coactivator PipX were not affected (Figure 9). Absence of induction of NtcA under nitrogen starvation condition has been previously observed (3); suggesting that post-transcriptional regulation of NtcA plays a more important role than the amount of NtcA per se. Surprisingly, expression of the PSI- and PBS-related genes was induced. This finding is consistent with a previously reported transcriptome profiling after 6 h of nitrogen starvation by Krasikov et al. (3), in which PSI- and PBS-related genes were transiently activated, while cells proliferated at a normal growth rate. In contrast, Osanai et al. observed in their microarray study of nitrogen starvation that photosynthetic genes were repressed (4). The discrepancies between these studies might be related to differences in culture conditions prior or during nitrogen starvation or in a strain-specific genetic background. For example, illumination intensity used by Osanai (70 µmol photons−2 s−1) was 55 and 40% greater than used in our experiment (45 µmol photons−2 s−1) or by Krasikov et al. (50 µmol photons−2 s−1), respectively. In any case, the observed transient upregulation of PBS- and PSI-related genes may indicate increased cyclic electron transport around PSI as early stress response. This hypothesis is reinforced by the induction of ndhD1 (srl0331), which codes for a component of the NADH dehydrogenase complex involved in PSI cyclic electron flow, and some subunits of ATPase synthase (atpI, atpC and atpH; Supplementary Table S6). Increased cyclic electron flow could enhance ATP synthesis to provide the necessary energy required for nitrogen assimilation pathways. However, this phase is only transitional to a more severe response to nitrogen starvation, in which growth decreases and degradation of the PBS leads to a yellow appearance of cyanobacterial cultures. This acclimation process, known as chlorosis or bleaching, requires the expression of the cotranscribed nblA genes (nblA1 and nblA2) (5). In fact, expression of nblA2 (srl0453) after 4 h of nitrogen starvation was observed, suggesting that a transcriptional response towards PBS degradation and long-term acclimation had already started.

Nitrogen depletion in cyanobacteria leads to downregulation of genes related to carbon fixation and induction of sugar catabolic genes (3–4,60,48). Here, we observed the induction of genes involved in the oxidative pentose phosphate (zwf, talB and gnd), as well as catabolism (g6gX and g6gP) and anabolism (g6gC) of glycogen (Figure 3). Expression of genes for glycogen degradation, which are likely not to be active during nitrogen starvation, is in agreement with an anticipatory state of chlorotic Synechocystis cells described recently by Klitz et al. (61). Cells anticipate future recovery from nitrogen starvation by preparing proteins necessary for fast resuscitation without having to synthesize the corresponding enzymes de novo.

Strikingly, 33 genes involved in regulatory functions responded to nitrogen step-down, suggesting that acclimation to nitrogen depletion is a process that requires extensive transcriptional reprogramming. This is corroborated by our observation that several genes coding for two-component systems were affected by nitrogen deprivation. Two-component systems enable cells to respond to both environmental and intracellular changes. Six histidine kinases and six response regulators were upregulated, including rre37, which is involved in the activation of sugar catabolism under nitrogen starvation (62,63). The complexity of the nitrogen starvation response is highlighted by the large number of genes involved in heavy metal and oxidative stress, which altered their expression in response to nitrogen depletion. These included genes encoding the copper sensing system CopRS (sll0789, sll0790 and their respective copies in the plasmid pSYSX: srl6040 and srl6041), the ferric uptake regulator Fur (sll0367), the peroxide stress response transcriptional regulator PerR (srl1738), and the LexA repressor (sll1636). Furthermore, many genes coding for metal importer systems were downregulated, such as the ATPases for copper (ctaA and pacS), cobalt (coaT) and zinc (ziaA), as well as iron import protes FutA1 (futA1) and FutA2 (futA2). Such widespread adjustment of metal uptake could be the consequence of diminished protein synthesis following nitrogen deprivation. Given that up to a third of the total microbe proteome contains metal cofactors (64), reduction in metal uptake could be an important response to avoid build-up of excess free metals in the cytosol that would lead to detrimental reactions.

The asymmetric distribution of the NtcA binding peaks in NH4 and –N media points to condition-dependent modus operandi of NtcA

Comparative ChIP-seq analysis enabled us to characterize changes in the binding behavior of NtcA. It revealed that NtcA binds to 141 DNA regions (121 in the chromosome and 20 in the plasmids) after 4 h of nitrogen step-down, but also to a large number of regions (51 with 48 in the chromosome and 3 in the plasmids) in nitrogen-replete medium.

Its unexpected binding in vivo under nitrogen-replete conditions supports in vitro measurements showing that 2-OH is not absolutely required for NtcA binding to DNA (12). The 169 binding sites identified and assigned to 157 genes, included the vast majority of currently known NtcA target genes for Synechocystis, indicating the high sensitivity of our ChIP-Seq experiment. Further support of its reliability was provided by validation of NtcA binding to target regions with different features (intragenic or promoter binding region, different peak enrichment, etc.; Supplementary Figure S5).

Under nitrogen starvation conditions, most of the binding sites were located upstream of gene coding regions (73% of peaks; Supplementary Tables S9 and 10), consistent with preferential binding of NtcA to promoter regions. Unexpectedly, this preference changed in ammonium-rich medium, with 54% of binding peaks located at intragenic positions. This highly significant change in the distribution of binding loci (P = 0.00116, Fisher’s exact test) could indicate a condition-dependent functional mode for NtcA in Synechocystis. Under nitrogen depletion, many genes involved in nitrogen metabolism and other cellular functions were induced or repressed by NtcA, supporting its established role as the master regulator of nitrogen control in cyanobacteria. In contrast, the role of NtcA in the presence...
of ammonium has remained elusive. The lower number of peaks and the high proportion of intragenic binding sites for NH₄ compared to −N treatment could simply indicate that NtcA rests in an inactive state under nitrogen-replete conditions, as previously suggested (57). However, other potential scenarios could exist, given that extensive binding of transcription factors to intragenic regions has been reported in recent years, based on genome-wide profiling. For example, substantial intragenic binding has been detected for OmpR in Salmonella enterica, GlkR in Corynebacterium glutamicum and RutR in Escherichia coli (65–67). Remarkably, a high proportion of intragenic binding sites have also been observed in a previous ChIP-seq analysis for NtcA in Anabaena sp. PCC 7120 (14). Hence, an examination of the functional relevance of intergenic binding is clearly warranted. Closer inspection of intragenic binding sites detected by our ChIP-seq experiment revealed the existence of the canonical NtcA consensus sequence, located upstream of internal TSS in some cases (i.e. ssll0377, ssll0735, ssrl1065, ssrl1864, glcF; Supplementary Tables S9 and 10). In other cases, our transcriptomic data suggest that NtcA could act as a repressor, blocking transcription elongation (Figure 5) in a similar manner to that reported for CodY in Bacillus subtilis (68). Candidates for this type of transcriptional repression by NtcA are: ssrl1852, glgP and pilA4 under nitrogen-replete conditions; or ssrl1028, ssrl0442, secA, ssll1273, mrvA and metX under nitrogen starvation (Figure 5 and Table 2). Such a regulatory mode, however, cannot be generalized, as we found other cases, such as ssll0142 in NH₄ or ssrl0909 in −N treatments, which showed increased expression and stronger intragenic NtcA binding—an observation that eludes an obvious explanation. In summary, examination of intragenic binding sites supports a model in which NtcA is not simply inactive under nitrogen-replete conditions, but in which it remains functionally important, albeit with a different modus operandi. Such a model is consistent with previous ChIP–chip and ChIP-seq studies of E. coli and Anabaena suggesting that the CRP transcriptional regulator family could work not only as a canonical transcriptional regulator, but also as a chromosome-shaping protein by binding to multiple low affinity sites (14,69).

A considerable number of NtcA targets lack current annotation. In particular, 27 genes correspond to hypothetical and unknown proteins. They are prime candidates for further experimental investigation to enhance our understanding of nitrogen control and metabolism, and to extend the functionality of the NtcA regulon. For instance, genes ssll0327 and ssr0692 showed levels of induction and repression, similar to those involved in nitrogen metabolism, suggesting related roles (Figure 6). Likewise, ssll0327 codes for a small protein containing 139 amino acids, and is a closed homolog to the amino acid transport system permease component LivM of Microcystis aeruginosa (58.1% identity; 72.1% similarity). Meanwhile, ssr0692 was reported to be highly induced under conditions of low CO₂ i.e. conditions which resemble a relative high abundance of nitrogen (70). It may be involved in the accumulation of the NDH-1 complex under low carbon/high nitrogen, given that Ssr0692 interacts with NdhH, according to yeast-two-hybrid data (71). Furthermore, the expression of both ssll0327 and ssr0692 is strongly correlated with known NtcA target genes across a large set of conditions compiled in CyanoExpress—a platform for a gene expression meta-analysis in Synechocystis (72). This is a remarkable finding, since CyanoExpress does not include expression data for nitrogen starvation. Thus, this correlation is solely based on differential expression of NtcA target genes under other conditions. Strikingly, we found that ssll0327 together with bgtB, glnA and urtB (all members of the NtcA regulon) are highly upregulated under iron limitation and downregulated under carbon limitation or oxidative stress (Supplementary Figure S6A). Conversely, ssr0692 together with gifA and gifB are downregulated under iron limitation and upregulated under carbon limitation or oxidative stress (Supplementary Figure S6B). This suggests that ssll0327 and ssr0692 have a common regulation, along with other bona fide members of the NtcA regulon. In addition, the strong correlation of NtcA targets observed in gene expression meta-analysis points to potential regulatory activity of NtcA under a wider range of environmental perturbations.

Finally, asRNAs and ncRNAs were the third most abundant class in the NtcA expression network. Although differential expression of asRNAs and ncRNAs during acclimation to different nitrogen stresses in cyanobacteria has been documented in several recent studies (15,41,61), only one ncRNA, NsiR4, has been experimentally validated to be under the control of NtcA to date (41). Our results greatly expand the repertoire of NtcA regulated ncRNAs. Eight ncRNAs were included in the NtcA regulon (Figure 6) and we have experimentally validated three of them: Ncr1071, NsiR7, Syr6 (Figure 8). Interestingly, NsiR7 is also induced under conditions of carbon limitation and was recently suggested as an NdhR-regulated sRNA (73,74). Thus, NsiR7 might play an important role in the integration of signals integration related to the intracellular carbon and nitrogen status.

**NtcA targets in nitrogen control and cellular metabolic processes**

Parallel profiling with ChIP-seq and RNA-seq techniques led to the definition of a direct target regulon for NtcA, having unprecedented resolution. In total, 79 genes were identified to have NtcA binding peaks with significantly altered expression after 4 h of nitrogen step-down (Figure 5). Analysis of their respective gene functions revealed that NtcA plays a role in the coordination of cellular processes beyond nitrogen metabolism. Indeed, various other metabolic processes (biosynthesis of cofactors, cellular processes, carbon metabolism, energy metabolism, central intermediary metabolism, photosynthesis and respiration) were dominant among these NtcA targets (Figure 6). Additionally, a small proportion of the NtcA regulon was associated with other biological functions, such as cell envelope, translation and transcription, or regulatory functions (Figure 6).
NtcA binding defines poised states of transcriptional regulation in *Synechocystis*, which are modulated by PipX and additional factors

Surprisingly, almost half of the genes having assigned NtcA binding were not transcriptionally affected after 4 h of nitrogen step-down. However, comparison with a longer time series study of nitrogen starvation (3) revealed that many of the initially unaffected genes were activated or repressed at later time points (Supplementary Figure S7). Examples are the induction of genes coding for the urease gamma subunit (*ureA*), the serine/threonine kinase (*spkD*) or repression of the PSI1 oxygen evolving complex protein (*psbP2*) after 12 h of nitrogen depletion. Even longer delays in transcriptional response were detected for the repression of *pipX* (24 h) and the induction of the ferrichrome-iron receptor coding gene *fhuA* (96 h). Importantly, late transcriptional responses are not simply the consequence of delayed NtcA accumulation, given that both NtcA transcript and protein levels remained unaltered after nitrogen step-down. Rather, these findings indicate that NtcA binding in *vivo* may not be sufficient in certain cases to evoke immediate full transcriptional control, but defines a poised regulatory state, which correlates with later changes in expression. Such poised regulation suggests the need for additional factors, as previously proposed (14,57). Further support for this model was gained through comparison of the ChIP-seq data obtained under NH4 and –N treatments. We identified 14 NtcA targets having assigned NtcA binding peaks that did not show significant changes, but were significantly differentially expressed after nitrogen depletion. Our examination of a *pipX* mutant supports the role of PipX as an NtcA modulating factor in *Synechocystis*. Transcriptional regulation of NtcA-controlled genes and their corresponding proteins levels were delayed in the *pipX* mutant strain compared to the WT strain, consistent with a role of PipX as an NtcA enhancer, as reported in other cyanobacteria (10,49,59). This mechanism could explain why several genes showed strong transcriptional change after 4 h of nitrogen starvation, without an equivalent variation in the effective affinity of NtcA to their promoters (Supplementary Table S12). This indicates that interaction of NtcA with other factors is essential to activate/repress target genes.

It is tempting to speculate on the physiological function of a poised regulatory state for NtcA. One advantage could be that it prepares the transcriptional machinery for a more extensive response, but without a full commitment. It would provide a temporal buffer, which is especially advantageous under conditions of fluctuating nitrogen availability, where premature commitment to unmitigated chlorosis might prove to be adverse. In this way, some NtcA targets, for which no differential expression was recorded after 4 h of nitrogen depletion, might constitute a ‘latent NtcA regulon’; in contrast to the NtcA regulon defined herein, which is activated during early acclimation.

In conclusion, this study provides the first genome-wide captures of the dynamics of *in vivo* NtcA binding events and the regulatory network that they define. Application of parallel differential profiling enabled us to distinguish direct from indirect regulation, extending the scope of the NtcA regulon. Finally, indications of a poised state for NtcA and of regulatory activity in a wide range of conditions beyond nitrogen limitation offer exciting avenues for further investigations.

DATA AVAILABILITY

RNA-seq and ChIP-seq datasets are available at GEO accession (GSE97291).

SUPPLEMENTARY DATA

Supplementary Data are available at NAR Online.

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