Evaluation of *Caulobacter crescentus* strain fitness at the genomic scale during growth in natural freshwater

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ABSTRACT

Bacterial genomes are the products of selection in fluctuating, spatially heterogeneous, and often nutrient-poor environments. Thus bacterial gene function is best understood in this natural context, but replicating such conditions in the lab is challenging. Here we used a transposon sequencing approach to globally measure the fitness consequences of gene disruption in the free-living freshwater bacterium *Caulobacter crescentus*, cultivated in complex peptone broth, a defined mineral medium (M2-xylose), or in littoral waters of Lake Michigan. Transposon insertions in genes involved in amino acid and nucleotide biosynthesis and in transport resulted in large fitness defects in both lake water and M2-xylose relative to a complex peptone broth, though defects were more extreme in M2-xylose in most cases. In lake water, strain fitness was increased by insertions in genes required for flagellum biosynthesis and reduced by insertions in genes involved in holdfast biosynthesis. We further uncovered numerous hypothetical and uncharacterized genes for which disruption resulted in reduced fitness in either lake water, M2-xylose, or both. At the genomic scale, the fitness profile of the strain pool cultivated in lake water was more similar to that in complex peptone broth than in M2-xylose. Individual gene and strain fitness scores were significantly more variable in lake water than in M2-xylose, presumably owing to variability in water conditions collected on different days. This study advances our understanding of the genetic determinants of *Caulobacter* growth in a complex natural environment, and provides a new avenue to study gene function in a free-living freshwater bacterium.

IMPORTANCE

Bacteria live in complex environments that are variable over time and space. Bacterial genomes encode the molecular machinery that allows the cell to interact with its environment and with other organisms. Much of this machinery remains uncharacterized, in part because it is difficult to simulate natural conditions in the laboratory. Using the model bacterium *Caulobacter crescentus*, we developed an

approach to study bacterial gene function in conditions mimicking the organism's natural freshwater habitat. We identified dozens of genes that are beneficial or detrimental in this natural lake water environment compared to typical laboratory conditions. Our approach will help illuminate the functions of many genes that are missed using standard cultivation approaches, and is broadly applicable to diverse organisms and environments.

INTRODUCTION

Microbial cells interact with their environment on the microscale, which has enormous physicochemical complexity. This complexity arises in part from spatial heterogeneity, which is well recognized in biofilms, soils, and host-associated habitats (1-3). Free-living aquatic bacteria also encounter strong chemical gradients that can appear as ephemeral patches, arising from algal exudates, sinking particles, or lysis events (4, 5) and they may have to cope with prolonged periods of nutrient scarcity. In addition, bacteria in natural environments face interspecies interactions, protistan predators, and viruses, as well as physical gradients such as temperature and light. These biotic and abiotic factors, acting together in complex combinations, have driven myriad bacterial adaptations that enable survival and reproduction in heterogeneous natural environments.

Despite the complexity faced by bacterial cells in situ, studies on microbial physiology and gene function have relied on simplified experimental conditions. Hence, it is not surprising that a large fraction of bacterial genomes remain uncharacterized. However, recently developed methods that combine transposon mutagenesis with next-generation DNA sequencing technologies now enable the phenotypic assessment of thousands to millions of distinct mutant strains. Such transposon sequencing (Tn-Seq) approaches (6) have been used to interrogate bacterial gene function in defined in vitro conditions or in animal models of infection, and discover new genes involved in specific biological processes, including secretion, sporulation, and conjugation (7). More recently, transposon mutagenesis approaches in which each transposon carries a unique 20-bp barcode sequence have been developed (8); each insertion site is associated with a short barcode, and the abundance of all the mutant strains in the pool can be assessed by a simple amplification and sequencing of the barcode.

Here, we used a barcoded Tn-Seq approach to identify genes affecting fitness in a freshwater oligotrophic bacterium, *Caulobacter crescentus* strain CB15 (hereafter referred to as *Caulobacter*), cultivated in filtered and unfiltered freshwater of Lake Michigan, Illinois, USA. As a well-

characterized and genetically tractable freshwater oligotroph that was originally isolated from a freshwater pond in California, USA, in 1960 (9), *Caulobacter* is uniquely suited for this investigation. However, *Caulobacter* is typically grown in a complex medium consisting of dilute peptone and yeast extract (PYE) or in a defined medium consisting of mineral salts and a single carbon source (M2X) (10), neither of which adequately represents natural freshwater. PYE is replete with peptides, amino acids, and a range of carbon sources, and the defined medium contains abundant macronutrients and enables dense culture growth, but requires that *Caulobacter* synthesizes all cellular building blocks from salts and a simple sugar. Natural freshwaters, by contrast, contain an undefined, complex mixture of organic and inorganic nutrient sources. Labile compounds such as amino acids and simple carbohydrates are turned over rapidly and thus never accumulate to high concentrations. We predicted that genes that are dispensable in PYE or M2X medium would provide important functions when cells are subjected to the physicochemical and biological complexity of natural freshwater. A previous Tn-Seq study has examined the genes required for *Caulobacter* growth in PYE (11), providing a reference point for comparison to natural freshwater (see Supplemental Material).

Here we report that, based on global mutant fitness scores, Lake Michigan water is more similar to PYE than to M2X defined medium. Growth in M2X defined medium poses larger fitness constraints on the mutant pool than growth in either PYE or Lake Michigan water. We uncovered fitness costs and benefits for genes involved in amino acid and nucleotide biosynthesis, motility, and adhesion across the distinct cultivation conditions. Surprisingly, there were few significant differences in the fitness of mutant strains cultivated in filtered and unfiltered lake water. Though all lake water experiments were conducted within a 2-week time period, we observed day-to-day variability in strain fitness scores, which likely reflects temporal heterogeneity of the lake environment. This variability in strain fitness scores in lake water collected on separate days contrasts with low variability of fitness scores for cell in replicate defined media conditions.

RESULTS

Growth of Caulobacter *is substantive in waters from two Laurentian Great Lakes*

To identify *Caulobacter* mutants with altered fitness in a bona fide freshwater environment, it was first necessary to test whether we could measure substantive growth of *Caulobacter* in natural freshwater. Lake Michigan, one of the five Laurentian Great Lakes, represents the kind of dynamic oligotrophic freshwater ecosystem that is inhabited by *Caulobacter* spp. (12, 13). We investigated the growth dynamics of wild-type *Caulobacter* (**Fig. 1**) in water collected from the littoral zone of Lake Michigan. With no additional supplementation, filtered (0.1 μm) lake water supported *Caulobacter* growth to a maximal density of approximately 5×10^5 CFU/mL (**Fig. 1A**). From an initial inoculum of 2.5×10^4 CFU/mL, *Caulobacter* doubled 4–5 times at a rate of approximately 0.14 hr^{-1} or a doubling time of 5 hours. Similar growth rates were observed in unfiltered lake water. Supplementation with 0.1% xylose increased the maximal density by about 10-fold, while addition of 23 μm K_2HPO_4 had no effect (**Fig. 1A**), implying that carbon, but not phosphorus, limits *Caulobacter* growth in Lake Michigan water. For comparison, we also assayed *Caulobacter* growth in water collected from Lake Superior and found a similar growth yield (**Fig. 1B**). Supplementation with either 23 μm K_2HPO_4 or 0.1% xylose did not significantly enhance *Caulobacter* growth, but together 0.1% xylose and 23 μM K_2HPO_4 enhanced growth by more than 10-fold, suggesting that both carbon and phosphorus limit growth in Lake Superior. By comparison, *Caulobacter* grew to a density of 3×10^9 CFU/mL in PYE broth or in defined M2X medium (**Fig. 1C**). It is noteworthy that these high population densities attained in laboratory media are unsustainable: in both M2X and PYE, cell density decreased by 2–3 orders of magnitude after 2 days of cultivation, and long-term culture viability was more compromised in M2X than in PYE. By contrast, the lower population densities achieved in lake water were stable over the course of 1 week (**Fig. 1**). This result is consistent with a report by Poindexter describing *Caulobacter* species that tolerated prolonged nutrient scarcity with little loss of viability, a physiological feature of

the genus that has been leveraged for their enrichment from water and soil samples (14). Based on our results, we chose to carry out a genetic analysis of mutant *Caulobacter* strains carrying transposon insertions in unsupplemented water from Lake Michigan.

A genomic-scale approach identifies Caulobacter *mutants with altered growth and survival in lake water*

We sought to test whether different genes and pathways are required for *Caulobacter* growth in a natural freshwater medium compared to defined M2X or complex PYE medium. To this end, we constructed two different transposon mutant libraries using Tn5, which inserts randomly throughout the genome, and Tn-Himar, which inserts specifically in TA dinucleotides. The *Caulobacter* genome is 67% G+C, and TA dinucleotides occur on average every 82 bp. Each transposon in the pool of Himar transposons contains a unique 20-bp barcode sequence (Wetmore et al 2015). This barcode approach (BarSeq) has the benefit of requiring the sites of insertion to be mapped only once. Thereafter, the abundance of each Tn-Himar mutant strain in a complex pool can be quantified by amplifying and sequencing the barcode, which uniquely identifies the insertion site (8). Both transposon libraries were constructed by growing cells in PYE. Thus, insertions in genes essential for growth in this condition are not represented in either library. Transposon pool statistics for Tn-Himar and Tn5 are shown in **Table 1**.

We cultivated the *Caulobacter* Tn5 pool in PYE and filtered lake water (0.1 µm). Though Tn5 is capable of insertion at almost every position in the genome, our Tn5 library had lower site saturation than our Tn-Himar library, which limited the statistical power to identify significant fitness effects (15, 16). We calculated mutant fitness and gene essentiality for all genes (**Table S3**) and identified 55 genes for which Tn5 disruption significantly diminished or enhanced growth in lake water relative to PYE (adjusted p-value cutoff < 0.01) (**Table S4**). Given the limited statistical power of the Tn5 dataset, we primarily focused our analyses on the Tn-Himar dataset, with the Tn5 data providing useful

validation.

The *Caulobacter* Tn-Himar mutant pool was cultivated in the following conditions: 1) complex PYE medium, 2) defined M2X medium, 3) filtered lake water, and 4) unfiltered lake water. Replicate lake water treatments were performed using water collected from Lake Michigan on 4 different days in December 2016 at Promontory Point, Hyde Park, Chicago, Illinois, USA (**Table 2**). The Tn-Himar library contained an estimated 2×10^6 strains, of which 7×10^4 passed the criteria for barcode mapping (8). To capture the diversity of our mutant pool, we initiated the selections with the same total number of cells (2.5×10^7) in each treatment and aimed for 4–5 doublings in late exponential growth. Given that the maximum density of *Caulobacter* cultivated in Lake Michigan water is approximately 10^6 cells/mL (**Fig. 1**), volumes of 2.5 L were required for lake water treatments. Cells were harvested by filtration after 64 h of growth. For PYE and M2X treatments, cells were grown in 1.5 mL volumes for 10 and 20 h, respectively, and harvested by centrifugation after approximately five doublings. Initial and final cell densities of replicate experiments are shown in **Fig. S1**.

After harvest, barcodes were amplified by PCR and sequenced. Sequences were analyzed using the approach outlined by Wetmore and colleagues to quantify the consequences on fitness of disrupting each gene under each cultivation condition relative to cultivation in complex PYE medium. Strain fitness can be viewed as the $\log_2$ of the ratio of barcode abundance in lake water (or M2X) to barcode abundance in the 'control' PYE condition (8). Given the average 20–30-fold increase in cell number during growth of the mutant pool, a Tn-Himar insertion strain that did not grow at all would be expected to have a fitness score in the range of -4 to -5. More extreme (lower) fitness scores may be expected for strains that did not survive cultivation. The observed fitness scores in this experiment are consistent with these expectations (**Fig. 2**). The complete list of Tn-Himar BarSeq gene fitness values is presented in **Table S2.**

To evaluate the validity of the BarSeq analysis approach, we examined fitness scores for strains with insertions in xylose utilization genes after cultivation in M2X. Genes in the *xylXABCD* operon are

required for xylose utilization (17, 18). As expected, insertions in these genes generated fitness scores of -3.6 to -6.6 when the pool was cultivated in M2X (**Fig. 3A, Table S2**). Disruption of *xylR*, which functions as a transcriptional repressor of the xylose operon (17), resulted in a positive fitness score in M2X relative to PYE, consistent with the idea that derepression of the xylose utilization genes is advantageous when xylose is the sole carbon source. Disruption of the *xylXABCD* genes had little to no consequence on fitness in lake water, which contains a range of carbon sources beyond xylose; disruption of *xylR* resulted in a modest fitness decrease in lake water relative to PYE (**Fig. 3A)**.

Variability in strain fitness across replicates is higher in lake water than in defined medium

M2X medium has a relatively stable, defined composition. Lake water, by contrast, is heterogeneous over time and, particularly in the case of unfiltered water, in space (because of variations in e.g. dissolved solutes, particles or grazers). We collected water on four separate occasions within a 2-week period for the four biological replicates and observed greater variability in strain fitness scores across the four lake water replicates than in M2X (**Fig. 2A & 3C, and Table S5**). This variability may reflect changing environmental conditions, as differences in temperature, precipitation, and wind-driven mixing could influence nutrient availability and microbial community composition, which could in turn alter the functional importance of particular genes. For example, more similar fitness profiles were obtained using water collected Nov 30 and Dec 9 (replicates 1 and 3) compared to Dec 6 and Dec 12 (replicates 2 and 4) (**Fig. 3B**). Significant snowfall events preceded both Dec 6 and Dec 12 water collections, but not the Nov 30 and Dec 9 collections, suggesting a possible weather-related driver of lake water strain fitness variability. The fitness of individual mutants could, therefore, help discriminate genes whose functions are consistently important from genes that are exploited under transient conditions.

Tn-Himar strain fitness defects are more extreme in defined medium than in lake water

Transposon disruption of genes required for amino acid biosynthesis, nucleotide biosynthesis, lipopolysaccharide biosynthesis, and nucleotide sugar biosynthesis resulted in extreme (fitness score < -4) growth defects in M2X (**Fig. 3, 4, S3–S5, and Tables S2–S5**). Given that growth in M2X medium requires de novo biosynthesis of diverse monomers and intermediates, many of which are supplied exogenously in the reference PYE condition, these results were expected. In many cases, strains with severe fitness defects in M2X also had reduced growth in lake water, though the fitness costs of disruption were less severe. We controlled the number of doublings (approximately 4–5) across all conditions, so the more pronounced negative fitness scores in defined medium compared to lake water cannot be explained by differences in the number of doublings. Instead, these differences imply that lake water is more similar to PYE than M2X is to PYE, in terms of the metabolic demands it imposes on cells; this result is supported by principal component analysis across the different growth conditions (**Fig. 3A**). Indeed, we expect that the waters of Lake Michigan carry a diverse array of metabolites and carbon and nitrogen substrates for growth. In this complex milieu, genes may be dispensable if their products are supplied exogenously, or if alternative pathways exist. Growth in defined media, however, provides fewer opportunities for substrate uptake and functional substitution. Surprisingly, we did not observe large differences in strain growth between unfiltered and 0.1μm filtered lake water conditions (**Fig. 3C**). This suggests that other microorganisms present in the lake water did not have major effects on strain growth given our cultivation approach and experimental timescale.

Pathway analysis of BarSeq fitness data in lake water and defined medium

To further explore pathways conferring differential fitness between lake water and artificial media, we chose to focus on genes whose disruption induced the largest fitness effects relative to the PYE reference condition, namely fitness scores ± 3 standard deviations (± 3σ) from the mean (< -1.2 and > +1.2). Based on this criterion, we identified 83 and 82 genes in the filtered and unfiltered lake water conditions, respectively, and 213 genes in the defined M2X medium (**Table S7**). Of these 238 total

genes, 40 genes were shared across all conditions (**Table S8**). Broad functional patterns were assessed using clusters of orthologous group (COG) annotations (19) (**Fig. 4**).

The largest fitness effects were observed for genes in amino acid and nucleotide biosynthesis, and in transport; we observed similar defects in Tn5 strains harboring disruptions in select amino acid and nucleotide anabolic genes (**Tables S3, S4, S6**). Tn-Himar disruption of a set of genes encoding catabolic enzymes involved in the glycine cleavage pathway and branched amino acid degradation resulted in enhanced fitness scores in both the defined M2X medium and in lake water, relative to the PYE control (**Fig. 3C and Tables S6, S7**). This result was supported by similar fitness trends in the Tn5 dataset (**Tables S3, S4, S6**). Deletion of these catabolic genes is likely detrimental in the reference PYE condition, compared to M2X or lake water; alternatively, it is possible that the loss of particular catabolic functions is advantageous, even in natural freshwater. The former model is consistent with transcriptional data showing that select amino acid degradation pathways — including glycine cleavage, histidine, branched chain, and phenylalanine degradation — are upregulated in PYE compared with M2X (20).

We also observed strong positive effects on fitness after disruption of genes involved in motility in lake water relative to PYE (**Fig. 3 & 4**). We more carefully examined the fitness scores of genes involved in synthesis and assembly of the flagellum (**Fig. 5**). The flagellum is assembled in a regulated hierarchy of stages, which is well described in *Caulobacter* (21-23). Class II genes encode the inner components of the flagellum, including the export apparatus, and regulatory proteins that activate expression of class III and IV genes upon completed assembly of the class II structure. Class III genes encode the basal body and hook structures. Completion of the class III structures activates translation of the class IV genes, which encode the subunits of the flagellar filament. Thus, defects in each class prevent expression of subsequent classes. Within each class of flagellar genes, we observed consistent fitness effects, demonstrating the power of this method to capture even modest effects of gene disruption. Disruption of class II flagellin genes conferred an advantage that was significantly

greater in lake water than in M2X compared to PYE, (**Fig. 5B & S2**). The effect of disruption of class III genes followed similar trends with smaller magnitude effects on fitness. *Caulobacter* encodes six redundant class IV flagellin genes (24), thus it was not surprising that disruption of any of the three flagellin genes represented in our BarSeq collection had no effect on fitness. Disruption of the motor stator gene *motA* or *motB*, which results in a fully assembled but paralyzed flagellum (25, 26), did not affect fitness under our cultivation conditions. This result suggests that the fitness advantage of flagellar gene disruption is not derived from energy saved in powering the flagellum, but rather in energy saved in synthesizing and assembling the flagellum, or as a result of regulatory processes affected by incomplete assembly of the flagellum. In the lake water cultivations, we noted appreciable day-to-day variation in the fitness of each class of flagellar gene mutants (**Fig. S2**), which was particularly pronounced for class III genes. Patterns in this day-to-day variability were consistent across members of each class, suggesting that this variability is driven by environmental factors.

Fitness was further affected by the ability to synthesize the polar extracellular adhesin known as the holdfast (**Fig. 5 & S2**). We systematically analyzed genes involved in synthesis, secretion, and attachment of the holdfast in each cultivation condition. Most holdfast genes yield partial to complete defects in holdfast development when disrupted (27); we categorized these genes as ‘unique functions’ genes. However, two sets of holdfast biosynthesis genes have redundant functions: two Wzy-family polymerase genes that function in holdfast development and three paralogs of the HfsE glycosyltransferase that have genetically redundant activities in holdfast synthesis (27). Transposon disruption of genes in the unique function group resulted in a modest but consistent fitness advantage in M2X and a fitness disadvantage in both filtered and unfiltered lake water, relative to PYE (**Fig. 5A & S2A**). When considered as a group, the fitness consequence for loss of holdfast was significantly different between growth conditions ($p < 0.0001$) (**Fig. 5A**). Disruption of holdfast genes with redundant functions, which do not result in loss of holdfast development (27), had no consequence on fitness.

Cultivation in freshwater uncovers phenotypes associated with genes of unknown function

We hypothesized that many genes of unknown function play important roles in natural environmental contexts but not in typical laboratory media. Of the group of genes outside the ± 3σ fitness (advantage or disadvantage) score cutoff, hypothetical genes or genes of unknown function accounted for 16% in filtered lake water, 15% in unfiltered lake water, and 7% in defined medium (**Table 3**). Across these three conditions, a total of five hypothetical genes were shared. *CCNA_03860* was the only hypothetical gene for which disruption provided a fitness benefit across all three conditions relative to PYE. Further investigation of CCNA_03860 identified a conserved domain belonging to the YkuD superfamily, which has been shown to have L,D-transpeptidase catalytic activity, providing an alternate pathway for peptidoglycan cross-linking (28, 29). Disruption of *CCNA_01724*, *CCNA_03864*, *CCNA_03909*, and *CCNA_00375* resulted in reduced fitness across all three conditions relative to PYE. The majority of hypothetical genes and genes of unknown function that met the ± 3σ cutoff criterion exhibited negative fitness values (92%), indicating that disruption is detrimental in these conditions compared to PYE. This result supports our hypothesis that genes of unknown function play important roles in supporting growth in natural environments.

DISCUSSION

Tn-seq fitness scores can provide a readout of environmental state

Bacterial genomes carry relatively little noncoding DNA. Genes that confer no fitness benefit tend to decay over time (30) implying that genes that are maintained are beneficial at least under some circumstances. Yet traditional microbial cultivation approaches often fail to yield discernable mutant phenotypes for many classes of genes. To understand the functional capacity of bacterial genomes, it is necessary to interrogate gene function in more environmentally relevant contexts, embracing spatial

and temporal heterogeneity. The genomic-scale fitness analysis of *Caulobacter* transposon mutants reported in this study provides new understanding of genes that affect growth in a *bona fide* freshwater environment. Relative to a complex peptone medium (PYE), disruption of genes involved in amino acid biosynthesis, nucleotide biosynthesis, lipopolysaccharide biosynthesis, and nucleotide sugar biosynthesis, and other classes of metabolic genes results in large fitness defects in natural freshwater from Lake Michigan. However, fitness effects were variable across lake water replicates, using water collected across several days; this variability likely reflects physicochemical and biological variability in the lake and suggests an important role for transient response genes in fluctuating environments.

Consequences on strain fitness of disrupting genes that function in motility and attachment in freshwater

The energetic cost of flagellar biosynthesis and motility is well established (31, 32). Our data indicate that transposon disruption of genes required for the synthesis of the single polar flagellum of *Caulobacter* enhanced fitness in lake water relative to PYE medium (**Fig. 5**). This is consistent with a *Salmonella* Tn-Seq study that revealed a fitness advantage in strains with disrupted flagellar genes (33). Notably, we found that fitness effects were not uniform across all flagellar genes: disruption of class II genes, which has the greatest impact on flagellar gene expression, also led to greater effects on fitness, compared to class III and IV genes. The fitness enhancement in lake water is not related to the energy consumed by motor rotation, as strains with insertions in the *motA* and *motB* stator genes, which assemble a full but non-rotary flagellum (26), showed no fitness difference (**Fig. 5).** We conclude that the relative fitness advantage of flagellar gene disruption is related to the cost of biosynthesis of flagellar proteins. It seems certain that over longer cultivation timescales, and in more spatially complex environments, the *Caulobacter* flagellum provides a fitness advantage, as flagellar genes are maintained in natural freshwater environments.

Our data reveal that disruption of genes required for holdfast biosynthesis is disadvantageous when strains are cultivated in lake water relative to PYE. This fitness cost was evident in both filtered (particle-free) and unfiltered lake water relative to PYE (**Fig. 5**), suggesting that the effect is not due to adhesion to particles in the medium. Instead, it is possible that the holdfast confers a growth advantage by enabling adherence to the flask surface, where polymeric nutrients concentrate to form conditioning films (34, 35).

Genetic evidence that a complex medium is a more environmentally relevant growth condition for Caulobacter *than a typical defined mineral medium*

Fitness defects of *Caulobacter* mutants were often more severe in a defined mineral xylose medium (M2X) than in lake water, relative to PYE. This is consistent with our observation that the overall fitness profiles of *Caulobacter* Tn strains cultivated in lake water more closely resemble PYE than M2X, suggesting that cultivation of *Caulobacter* in dilute complex medium is a better proxy for natural freshwater. *Caulobacter* belongs to a group of dimorphic prosthecate (i.e. stalked) alphaproteobacteria that are often specialized for oligotrophic, dilute environments (9, 14). Indeed, the inhibition of growth and stalk development due to excess nutrients was the first physiological property of *Caulobacter* spp. to be described (36). Complex and defined media of varying compositions have been outlined for cultivation of *Caulobacter* and related genera, but it is notable that dilute peptone (less than 0.2% w/v) generally supports growth of all dimorphic prosthecate bacteria (14). This observation supports the notion that the natural nutrient environment of this class of bacteria is best captured by cultivation in a dilute complex medium that contains amino acids and other trace complex biomolecular components. While it is likely that a more optimal defined medium exists that better captures the conditions of natural freshwater, our data provide evidence that an M2-based medium exerts highly specific metabolic constraints on the bacterial cell and may not be an ecologically or physiologically relevant growth condition.

An approach to study hypothetical genes and domains of unknown function in freshwater bacteria

The explosion of bacterial genome sequence information has far outpaced our ability to characterize gene function using traditional approaches, leading to the accumulation of thousands of 'unknown' protein families. Many of these families are conserved throughout the bacterial domain, which is evidence that they confer a selective benefit in particular conditions. This leads to the following question: under what circumstances do these conserved families provide a fitness advantage? At the outset of this study, we hypothesized that many of these unknown protein families would prove to be important in the natural ecological context of a bacterium. Among the genes whose disruption leads to the greatest fitness effects (± 3σ) in filtered lake water relative to PYE, approximately 15% are hypothetical or conserved genes of unknown function (**Tables 3, S7–S8**). The mutagenesis, cultivation, and sequencing approach we describe here indicates that these genes of unknown function play an important role in *Caulobacter* physiology in a natural freshwater environment. Going forward, one can take advantage of lake-specific growth phenotypes to begin to define the functions of these genes in an ecologically relevant context.

MATERIALS AND METHODS

Bacterial strains and primers. Strains used in this study and their descriptions are listed in **Table S1**. Primer name, sequence, and function are also listed in **Table S1**. All primers were synthesized by Integrated DNA Technologies (Coralville, IA, USA).

Composition of laboratory media. *Caulobacter* was grown in PYE complex medium (0.2% peptone (Fisher Scientific Lot No. 005604), 0.1% yeast extract (Fisher Scientific Lot No. 166295), 0.5 mM $MgSO_4$, 0.5 mM $CaCl_2$) or M2X minimal defined medium (6.1 mM Na_2HPO_4, 3.9 mM KH_2PO_4, 9.3

mM NH_4Cl, 0.5 mM $MgSO_4$, 10 μM $FeSO_4$ (EDTA chelate; Sigma Chemical Co.), 0.25 mM $CaCl_2$) supplemented with 0.15% xylose (10). *Escherichia coli* strains for transposon conjugation were grown in LB broth (1% peptone, 0.5% yeast extract, 0.5% NaCl). Solid growth medium was made by adding 1.5% agar to the above liquid media.

Lake water collection and filtration. Water from Lake Michigan was collected at Promontory Point, Chicago, Illinois, USA (Latitude: 41.794, Longitude: -87.579). Parameters such as water temperature, phosphate and nitrate/nitrite level (Aquacheck Water Quality Test Strips; Hach), and pH (pH indicator strips, Fisher Scientific) were tested on-site and are listed in **Table 2**. Water collection occurred in 2016, on Nov 30, Dec 6, Dec 9, and Dec 12. Lake water was filtered using Nalgene™ Rapid-Flow™ Sterile Disposable 0.1 µm Filter Units with PES Membrane (Thermo Scientific).

Measurement of Caulobacter *growth in waters of Lake Michigan and Lake Superior*. Colonies of *Caulobacter* were inoculated into 2 mL of PYE in glass culture tubes (13 × 100 mm) and grown overnight at 30°C with shaking at 200 rpm, for a total of five biological replicates. At saturation, 1 mL of culture was centrifuged at 8,000 ×*g* and washed twice in 1 mL of filtered lake water. The washed pellet was resuspended in filtered lake water to a final OD_{660} of 0.1, and 0.5 µL (approximately 0.5–1 × 10^5 cells) was inoculated into 5 mL of filtered lake water in a glass culture tube (20 mm × 150 mm) in technical duplicate. Cultures were grown at 30°C with shaking at 200 rpm. At various time intervals over the course of 48 h, 20 µL of culture was removed to perform 10-fold serial dilutions for colony enumeration. A total of 5 µL of each dilution was spotted onto PYE agar plates, which were incubated at 30°C for 2 days. Growth was monitored by enumeration of colony forming units (CFUs).

Construction of a barcoded Tn-Himar (BarSeq) Caulobacter *mutant library*. The recipient strain (*Caulobacter*) was grown overnight in 2 mL of PYE at 30°C with shaking at 200 rpm. This starter

culture was used to inoculate 20 mL of PYE and grown at 30°C overnight with shaking at 200 rpm until saturated. The donor *E. coli* strain (APA752, gift from Adam Deutschbauer, University of California-Berkeley, USA), carrying the pKMW3 (kanamycin resistant) Himar transposon vector library (8), was inoculated into 20 mL of LB containing kanamycin (30 µg mL^{-1}) and diaminopimelate (300 µM) and grown overnight at 37°C with shaking at 200 rpm. To mate the barcoded transposon pool into *Caulobacter*, both the recipient strain and the donor strain were centrifuged at 8,000 ×*g* for 2 min and resuspended in a total volume of 500 µL of PYE medium. The cultures were mixed at a 10:1 ratio of recipient to donor and mixed by gentle pipetting. The mixed culture was centrifuged again at 8,000 ×*g*, and the supernatant decanted. The cells were resuspended in 30 µL of PYE, spotted onto a PYE agar plate containing diaminopimelate (300 µM), and incubated overnight at 30°C. After growth, the mating spot was scraped from the plate and resuspended in 6.5 mL of PYE. This suspension was spread evenly (500 µL per plate) over 14 large (150 × 15 mm) PYE agar plates containing 25 µg mL^{-1} kanamycin and incubated for approximately 3 days at 30°C. Cells were harvested from all the plates and inoculated into 400 mL of PYE containing 5 µg mL^{-1} kanamycin. This cell mixture was grown at 30°C with shaking at 200 rpm for three doublings. Cells were centrifuged at 8,000 ×*g*, resuspended in 70 mL of PYE containing 15% glycerol, and stored as 1 mL aliquots at -80°C.

Mapping of the sites of Tn-Himar insertion in the Caulobacter *BarSeq library*. Genomic DNA was extracted using guanidium thiocyanate as previously described (37). DNA quality and quantity was measured using a NanoDrop^{OneC} (Thermo Scientific). The quality of extracted genomic DNA from the *Caulobacter* library was also checked by using a Bioanalyzer (Agilent) prior to the sequencing run. The DNA was sheared (~300 bp fragments), cleaned with a standard bead protocol, end-repaired and A-tailed, and a custom double-stranded Y adapter was ligated. The custom adapter was prepared by annealing Mod2_TS_Univ (ACG CTC TTC CGA TC*T) and Mod2_TruSeq (phos-GAT CGG AAG AGC ACA CGT CTG AAC TCC AGT CA) as described (8). The sheared fragments containing

transposon fragments were enriched by PCR using the primers Nspacer_BarSeq_pHIMAR (5′ ATG ATA CGG CGA CCA CCG AGA TCT ACA CTC TTT CCC TAC ACG ACG CTC TTC CGA TCT NNN NNN CGC CCT GCA AGG GAT GTC CAC GAG 3′) and P7_MOD_TS_index1 (5′ CAA GCA GAA GAC GGC ATA CGA GAT CGT GAT GTG ACT GGA GTT CAG ACG TGT GCT CTT 3′) using GoTaq® Green Master Mix according to the manufacturer's protocol in a 100-µL volume with the following cycling conditions: 94°C for 2 min, 25 cycles at 94°C for 30 s, 65°C for 20 s, and 72°C for 30 s, followed by a final extension at 72°C for 10 min. After a second bead cleanup, the *Caulobacter* BarSeq library was sequenced using a standard Illumina sequencing primer on an Illumina HiSeq2500 at the University of Chicago Genomics Facility with a 150-bp single-end read. The locations of Himar transposon insertions were aligned and mapped using BLAT (38), and unique barcode sequences were associated with their corresponding genome insertion location using a custom Perl script (MapTnSeq.pl). Sets of barcodes that consistently map to one location in the genome were identified using a custom Perl script (DesignRandomPool.pl). These scripts have been described by Wetmore and colleagues (8) and are available at https://bitbucket.org/berkeleylab/feba.

Cultivation of the BarSeq transposon library in Lake Michigan water, and harvest of genomic DNA after cultivation. A total of 2 mL of the *Caulobacter* BarSeq library was inoculated into 18 mL of complex medium (PYE). The culture was split into two tubes (20 × 150 mm) with a volume of 10 mL each and left to outgrow in a cell culture roller drum (Fisher Scientific) at 30°C for 4 h at speed 4. The tubes were moved to an incubator set at 30°C with shaking at 200 rpm, and the cultures were grown for an additional 2 h. Cultures were combined and centrifuged for 20 min at 3,000 ×*g* at 4°C. The cell pellet was resuspended and washed in 10 mL of filtered lake water, and centrifuged again at 3,000 ×*g* for 20 min at 4°C. The resulting pellet was resuspended in 5 mL of filtered lake water, and the OD_{660} measured. Flasks containing filtered or unfiltered lake water (2.5 L total volume, 4 replicates per condition per experiment) were inoculated with the washed library with the aim of an initial starting

concentration of approximately 2.5 × 10^7 total cells per flask. Flasks were incubated at 30°C with shaking at 150 rpm. At 0 and 64 h, an aliquot of culture was removed to perform serial dilutions and spotted on PYE agar plates. Growth was monitored by enumeration of CFUs on plates after 2 days of incubation at 30°C. After ~64 h of growth, cells were collected by filtration using an Express Plus® Membrane 0.22 µM filter (Millipore). Filters were stored at -80°C until needed. To mimic saturating conditions with the same number of doublings in defined M2X and complex PYE laboratory medium as in lake water, we inoculated the cultures at a concentration that after five doublings (the estimated number of doublings in lake water), the cultures reached saturation. Cells were pelleted at 10,000 ×g for 1 min and stored at -20°C. Genomic DNA from all samples was extracted using guanidium thiocyanate as previously described (37), with the exception that the lake water samples were lysed directly from the filters they were collected on. DNA quality and quantity was measured using a NanoDrop^{OneC} (Thermo Scientific).

PCR amplification of Tn-Himar barcodes and sequencing. PCR amplification for each sample was performed as previously described (8) using a standard reaction protocol for Q5 DNA polymerase (New England BioLabs) with the primers BarSeq_P1 (reverse primer, 5′ AAT GAT ACG GCG ACC ACC GAG ATC TAC ACT CTT TCC CTA CAC GAC GCT CTT CCG ATC TNN NNN GTC GAC CTG CAG CGT ACG 3′) and 1 of 16 forward primers (BarSeq_P2_IT001 to BarSeq_P2_IT016, listed in **Table S1**) containing unique 6-bp TruSeq indexes that were sequenced using a separate index primer. Cycling conditions were as follows: 98°C for 4 min followed by 25 cycles of 30s at 98°C, 30s at 55°C, and 30s at 72°C, followed by a final extension at 72°C for 5 min. PCR products per medium condition were mixed together for PCR purification using GeneJET PCR Purification Kit (Thermo Scientific). Purified samples were run on a 2.5% agarose gel to confirm correct product size (~200 bp). A total of 10 µL per purified PCR product was pooled, assessed for quality, and quantified using a Bioanalyzer. The amplified barcodes from the reference (PYE) and treatment (M2X, unfiltered lake

water, and filtered lake water) were sequenced on an Illumina HiSeq4000 at the University of Chicago Genomics Facility, multiplexing all 16 samples in one lane. Tn-Himar 150-bp single-end read raw sequence data for transposon insertion site mapping and the 50-bp single-end PCR amplicon barcode sequence data (for BarSeq analysis) have been deposited in the NCBI Sequence Read Archive under BioProject accession PRJNA429486; BioSample accession SAMN08348121; SRA accession SRP128742.

Analysis of Tn-Himar strain fitness. We followed the fitness calculation protocol of Wetmore and colleagues (8), using scripts available at https://bitbucket.org/berkeleylab/feba. Briefly, the total count of each barcode in each sample was calculated using a Perl script (MultiCodes.pl) and, from this table of barcodes, strain fitness was calculated using an R script (FEBA.R). The fitness of each strain was calculated as a normalized $\log_2$ ratio of barcode counts in the treatment sample to counts in the PYE reference sample. The fitness of genes was calculated as the weighted average of strain fitness values, the weight being inversely proportional to a variance metric. Successful gene fitness calculations required at least 3 reads per strain and 30 reads per gene. Insertions in the first 10% or last 10% of a gene were not considered in gene fitness calculations.

Genes for which Tn-Himar disruption resulted in significant growth defects or growth enhancement in the assayed conditions relative to PYE complex medium were determined by calculation of a mean fitness value and also a mean t-value per gene.

To assess the distribution of fitness scores, we calculated the standard deviation of each condition using the frequency distribution of the mean fitness value of each gene (filtered lake water = 0.41, unfiltered lake water = 0.40, defined medium = 1.1). When the outlier region of the defined medium dataset (< -2.5) was removed, the calculated standard deviation was 0.36; therefore, a standard deviation of 0.4 was chosen and applied to all conditions. Genes with a mean fitness value ± 3σ from

the mean (less than -1.2 and greater than +1.2) were selected for further examination. The complete data set of fitness values for each condition is listed in **Table S2**.

We examined t-values, the weighted fitness value of a gene divided by a variance metric (as previously described (8)), to provide a metric to assess the significance of fitness values (see **Table S9** for a full list of t-values for each gene). Mean t-values ± the standard deviation for each experimental condition are as follows: M2X (-0.03 ± 1.11), Lake Michigan water filtered (0.01 ± 1.04), Lake Michigan water unfiltered (0.01 ± 1.05). The complete data set of fitness values for each condition is listed in **Table S2**. Mean fitness value and mean t-values plus or minus standard deviation (for the complete *Caulobacter* genome) are presented in **Table S5**.

Analysis of Caulobacter *Tn5-seq fitness.*A *Caulobacter* Tn5 insertion library containing 3×10^5 independent insertions was constructed as previously described (39). The lake water fitness experiment for the Tn5 library (from Lake Michigan water collected in April 2016) was performed similarly to the Tn-mariner (BarSeq) library experiments with the following exceptions: A total of 200 µL of the *Caulobacter* Tn5 library was inoculated into 20 mL of PYE for the initial outgrowth for a total of 5 h. Library outgrowth was inoculated into 2 L for the complex medium (PYE) and unfiltered lake water samples, and 2 replicates of 2 L each for the filtered lake water samples. Lake water cultures were filtered after a total of approximately 60 h of growth, while the complex medium condition was filtered after 12 h to approximate the same number of doublings. However, our complex medium condition doubled over 6 times, versus 4 doublings for the lake samples, resulting in 2 orders of magnitude of growth in the complex medium condition and 1 order of magnitude of growth for each lake water condition.

A standard library preparation was performed at the University of Chicago Genomics Facility to ligate standard Illumina adapters to our sheared and sized selected samples. A nested PCR approach was used on these samples to specifically amplify transposon-containing DNA fragments for

sequencing. A low cycle PCR amplification for each sample was first performed using a standard reaction protocol for KOD Xtreme™ Hot Start Polymerase with 5% DMSO and 0.3 µM primer using the primers F1 (5′ ACC TAC AAC AAA GCT CTC ATC AAC C 3′) and P7 (5′ CAA GCA GAA GAC GGC ATA CGA 3′) (39). Cycling conditions were as follows: 95°C for 90 s, 5 cycles of 95°C for 15 s 68°C for 30 sec, and 72°C for 30 s; 95°C 15 s, 13 cycles of 55°C 30 s 72°C 30 s, followed by a final extension at 72°C for 5 min. Samples were treated with ExoSAP-IT™ PCR product cleanup reagent (Thermo Fisher Scientific) according to manufacturer's protocol. A second PCR step was performed with the transposon specific primer containing the adapter sequence using KOD Xtreme™ Hot Start Polymerase with 5% DMSO and 0.3 µM primer in a 62.5-µL reaction volume using the primers Tn5-left (5′ AAT GAT ACG GCG ACC ACC GAG ATC TAC ACA TCC TCT AGA GTC GAC CTG CAG GCA TGC AAG C 3′) and P7 (5′ CAA GCA GAA GAC GGC ATA CGA 3′) (39). Cycling conditions were as follows: 95°C for 3 min, 12 cycles of 95°C for 30 s 55°C for 30 sec, and 72°C for 30 s, followed by a final extension at 72°C for 5 min. Products were run on an 1% agarose gel to confirm products of appropriate size (~200 bp). After standard bead cleanup, the samples were sequenced on an Illumina HiSeq2500 at the University of Chicago Genomics Facility using a custom sequencing primer TnSeq-out (5′ CCT GCA GGC ATG CAA GCT TCA GGG TTG AGA TGT GTA 3′) (39).

Fitness analysis was performed as previously described (16) using the TRANSIT software (available at https://github.com/mad-lab/transit). We used the comparative analysis functions of TRANSIT to compare our complex medium and lake water conditions. For this, TRANSIT utilizes a permutation test, which compares and quantifies differences in sequencing read counts in a gene between two different conditions to determine if they are statistically significant (16). The comprehensive data set from this analysis is available in **Table S3**. Genes with an adjusted p value <0.01 are listed in **Table S4**. **Table S6** shows the shared gene list between the Tn5 and Tn-mariner approaches used in this study. The raw Tn5-seq data are deposited in the NCBI sequence read archive

under BioProject accession PRJNA429486; BioSample accession SAMN08348191; SRA accession SRP128742.

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REFERENCES

1. **Cao M, Goodrich-Blair H.** 2017. Ready or Not: Microbial Adaptive Responses in Dynamic Symbiosis Environments. J Bacteriol **199:**pii: e00883-00816.
2. **van Gestel J, Vlamakis H, Kolter R.** 2015. Division of Labor in Biofilms: the Ecology of Cell Differentiation. Microbiol Spectr **3:**MB-0002-2014.
3. **Vos M, Wolf AB, Jennings SJ, Kowalchuk GA.** 2013. Micro-scale determinants of bacterial diversity in soil. FEMS Microbiol Rev **37:**936-954.
4. **Azam F, Malfatti F.** 2007. Microbial structuring of marine ecosystems. Nat Rev Microbiol **5:**782-791.
5. **Stocker R.** 2012. Marine microbes see a sea of gradients. Science **338:**628-633.
6. **van Opijnen T, Camilli A.** 2013. Transposon insertion sequencing: a new tool for systems-level analysis of microorganisms. Nat Rev Microbiol **11:**435-442.
7. **Kwon YM, Ricke SC, Mandal RK.** 2016. Transposon sequencing: methods and expanding applications. Appl Microbiol Biotechnol **100:**31-43.
8. **Wetmore KM, Price MN, Waters RJ, Lamson JS, He J, Hoover CA, Blow MJ, Bristow J, Butland G, Arkin AP, Deutschbauer A.** 2015. Rapid quantification of mutant fitness in diverse bacteria by sequencing randomly bar-coded transposons. MBio **6:**e00306-00315.
9. **Poindexter JS.** 1964. Biological Properties and Classification of the Caulobacter Group. Bacteriol Rev **28:**231-295.
10. **Ely B.** 1991. Genetics of Caulobacter crescentus. Methods Enzymol **204:**372-384.
11. **Christen B, Abeliuk E, Collier JM, Kalogeraki VS, Passarelli B, Coller JA, Fero MJ, McAdams HH, Shapiro L.** 2011. The essential genome of a bacterium. Mol Syst Biol **7:**528.
12. **Lee PO, McLellan SL, Graham LE, Young EB.** 2015. Invasive dreissenid mussels and benthic algae in Lake Michigan: characterizing effects on sediment bacterial communities. FEMS Microbiol Ecol **91:**1-12.
13. **McMillan L, Stout R.** 1977. Occurrence of *Sphaerotilus*, *Caulobacter*, and *Gallionella* in Raw and Treated Water. J Am Water Works Assoc **69:**171-173.
14. **Poindexter JS.** 2006. Dimorphic Prosthecate Bacteria: The Genera Caulobacter, Asticcacaulis, Hyphomicrobium, Pedomicrobium, Hyphomonas and Thiodendron, p 72-90. *In* Dworkin M, Falkow S, Rosenberg E, Schleifer K-H, Stackebrandt E (ed), The Prokaryotes: Volume 5: Proteobacteria: Alpha and Beta Subclasses doi:10.1007/0-387-30745-1_4. Springer New York, New York, NY.
15. **Chao MC, Abel S, Davis BM, Waldor MK.** 2016. The design and analysis of transposon insertion sequencing experiments. Nat Rev Microbiol **14:**119-128.
16. **DeJesus MA, Ambadipudi C, Baker R, Sassetti C, Ioerger TR.** 2015. TRANSIT--A Software Tool for Himar1 TnSeq Analysis. PLoS Comput Biol **11:**e1004401.
17. **Stephens C, Christen B, Watanabe K, Fuchs T, Jenal U.** 2007. Regulation of D-xylose metabolism in Caulobacter crescentus by a LacI-type repressor. J Bacteriol **189:**8828-8834.
18. **Stephens C, Christen B, Fuchs T, Sundaram V, Watanabe K, Jenal U.** 2007. Genetic analysis of a novel pathway for D-xylose metabolism in Caulobacter crescentus. J Bacteriol **189:**2181-2185.
19. **Wolf YI, Makarova KS, Yutin N, Koonin EV.** 2012. Updated clusters of orthologous genes for Archaea: a complex ancestor of the Archaea and the byways of horizontal gene transfer. Biol Direct **7:**46.
20. **Hottes AK, Meewan M, Yang D, Arana N, Romero P, McAdams HH, Stephens C.** 2004. Transcriptional profiling of Caulobacter crescentus during growth on complex and minimal media. J Bacteriol **186:**1448-1461.

21. **Ardissone S, Viollier PH.** 2015. Interplay between flagellation and cell cycle control in Caulobacter. Curr Opin Microbiol **28:**83-92.
22. **Benson AK, Wu J, Newton A.** 1994. The role of FlbD in regulation of flagellar gene transcription in Caulobacter crescentus. Res Microbiol **145:**420-430.
23. **Xu H, Dingwall A, Shapiro L.** 1989. Negative transcriptional regulation in the Caulobacter flagellar hierarchy. Proc Natl Acad Sci U S A **86:**6656-6660.
24. **Faulds-Pain A, Birchall C, Aldridge C, Smith WD, Grimaldi G, Nakamura S, Miyata T, Gray J, Li G, Tang JX, Namba K, Minamino T, Aldridge PD.** 2011. Flagellin redundancy in Caulobacter crescentus and its implications for flagellar filament assembly. J Bacteriol **193:**2695-2707.
25. **Ely B, Croft RH, Gerardot CJ.** 1984. Genetic mapping of genes required for motility in Caulobacter crescentus. Genetics **108:**523-532.
26. **Johnson RC, Ely B.** 1979. Analysis of nonmotile mutants of the dimorphic bacterium Caulobacter crescentus. J Bacteriol **137:**627-634.
27. **Toh E, Kurtz HD, Jr., Brun YV.** 2008. Characterization of the Caulobacter crescentus holdfast polysaccharide biosynthesis pathway reveals significant redundancy in the initiating glycosyltransferase and polymerase steps. J Bacteriol **190:**7219-7231.
28. **Kumar P, Kaushik A, Lloyd EP, Li SG, Mattoo R, Ammerman NC, Bell DT, Perryman AL, Zandi TA, Ekins S, Ginell SL, Townsend CA, Freundlich JS, Lamichhane G.** 2017. Non-classical transpeptidases yield insight into new antibacterials. Nat Chem Biol **13:**54-61.
29. **Bielnicki J, Devedjiev Y, Derewenda U, Dauter Z, Joachimiak A, Derewenda ZS.** 2006. B. subtilis ykuD protein at 2.0 A resolution: insights into the structure and function of a novel, ubiquitous family of bacterial enzymes. Proteins **62:**144-151.
30. **Mira A, Ochman H, Moran NA.** 2001. Deletional bias and the evolution of bacterial genomes. Trends Genet **17:**589-596.
31. **Martinez-Garcia E, Nikel PI, Chavarria M, de Lorenzo V.** 2014. The metabolic cost of flagellar motion in Pseudomonas putida KT2440. Environ Microbiol **16:**291-303.
32. **Smith DR, Chapman MR.** 2010. Economical evolution: microbes reduce the synthetic cost of extracellular proteins. MBio **1:**10.1128/mBio.00131-00110.
33. **Langridge GC, Phan MD, Turner DJ, Perkins TT, Parts L, Haase J, Charles I, Maskell DJ, Peters SE, Dougan G, Wain J, Parkhill J, Turner AK.** 2009. Simultaneous assay of every Salmonella Typhi gene using one million transposon mutants. Genome Res **19:**2308-2316.
34. **Loeb GI, Neihof RA.** 1975. Marine Conditioning Films, p 319-335, Applied Chemistry at Protein Interfaces, vol 145. American Chemical Society.
35. **Schneider RP, Leis A.** 2003. Conditioning Films in Aquatic Environments, Encyclopedia of Environmental Microbiology doi:10.1002/0471263397.env036. John Wiley & Sons, Inc.
36. **Loeffler F.** 1890. Weitere Untersuchungen uber die Beizung und Farbung der Geisseln bei den Bakterien. Centralbl Bakteriol Parasitenkd **7:**625-639.
37. **Pitcher DG, Saunders NA, Owen RJ.** 1989. Rapid extraction of bacterial genomic DNA with guanidium thiocyanate. Lett Appl Microbiol **8:**151-156.
38. **Kent WJ.** 2002. BLAT--the BLAST-like alignment tool. Genome Res **12:**656-664.
39. **Curtis PD, Brun YV.** 2014. Identification of essential alphaproteobacterial genes reveals operational variability in conserved developmental and cell cycle systems. Mol Microbiol **93:**713-735.

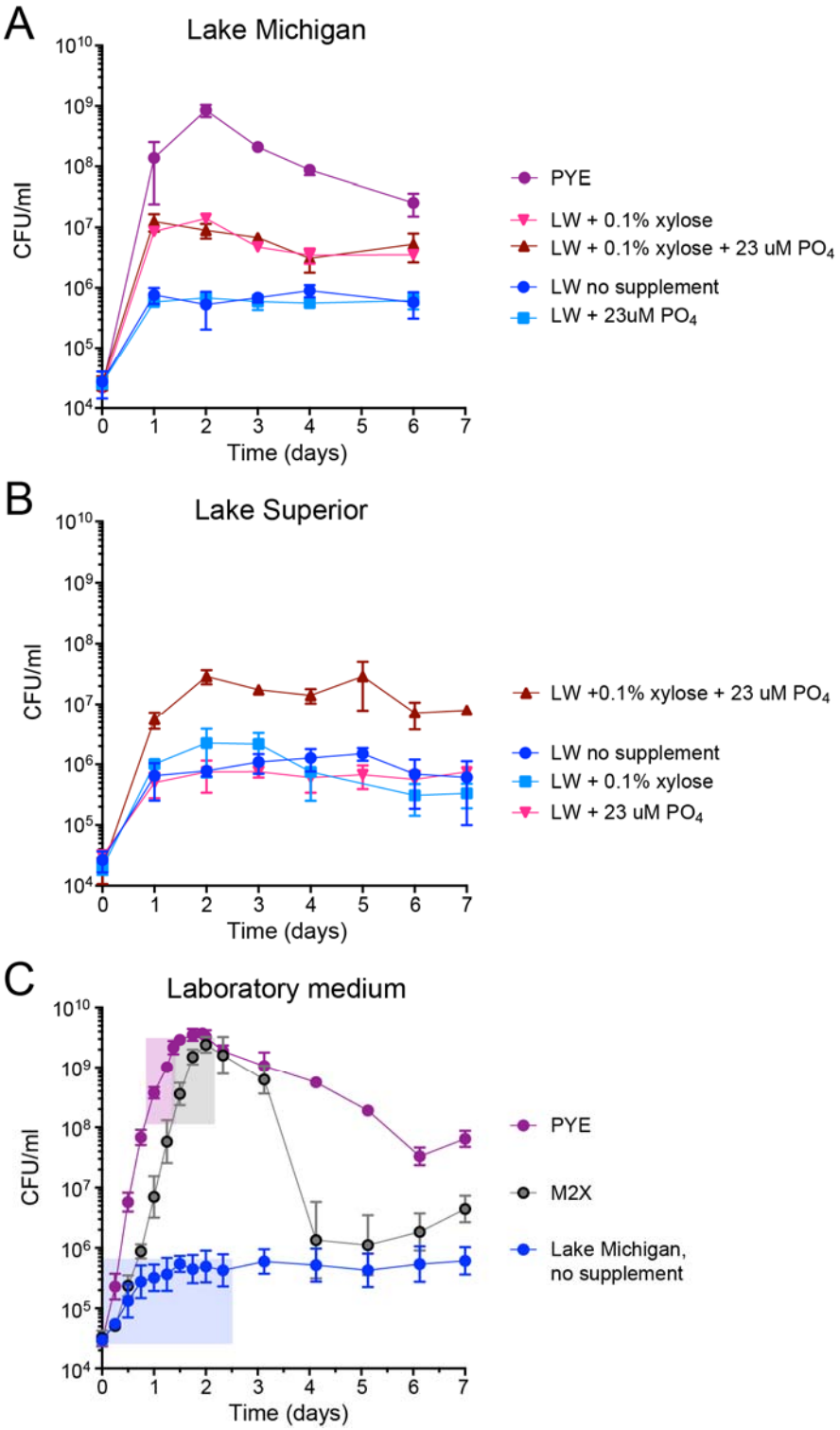

Figure 1. Growth of *Caulobacter* in laboratory medium, and supplemented or unsupplemented water from two Great Lakes. Overnight cultures washed with lake water (LW) were inoculated into 5 mL of filtered water from Lake Michigan (A) or Lake Superior (B). Growth assays in water supplemented with carbon (0.1% w/v xylose) and/or phosphorus (23 µM K_2HPO_4) as indicated; growth was monitored every 24 hours by enumeration of colony forming units (CFUs) by dilution plating. Lake water growth is compared to growth in a laboratory peptone yeast extract (PYE) medium. Data represent mean ± standard deviation of 5 replicates per condition. (C) Fine scale growth

of *Caulobacter* in PYE, M2-xylose defined medium (M2X), and filtered Lake Michigan water. Cells were grown as in A and B and monitored by enumerating CFUs. Data represent mean ± standard deviation of 5 replicates per condition. Boxes represent the approximate region of the growth curve (cell density and incubation time) in which the barcoded Tn-Himar mutant library (BarSeq) pools were cultivated.

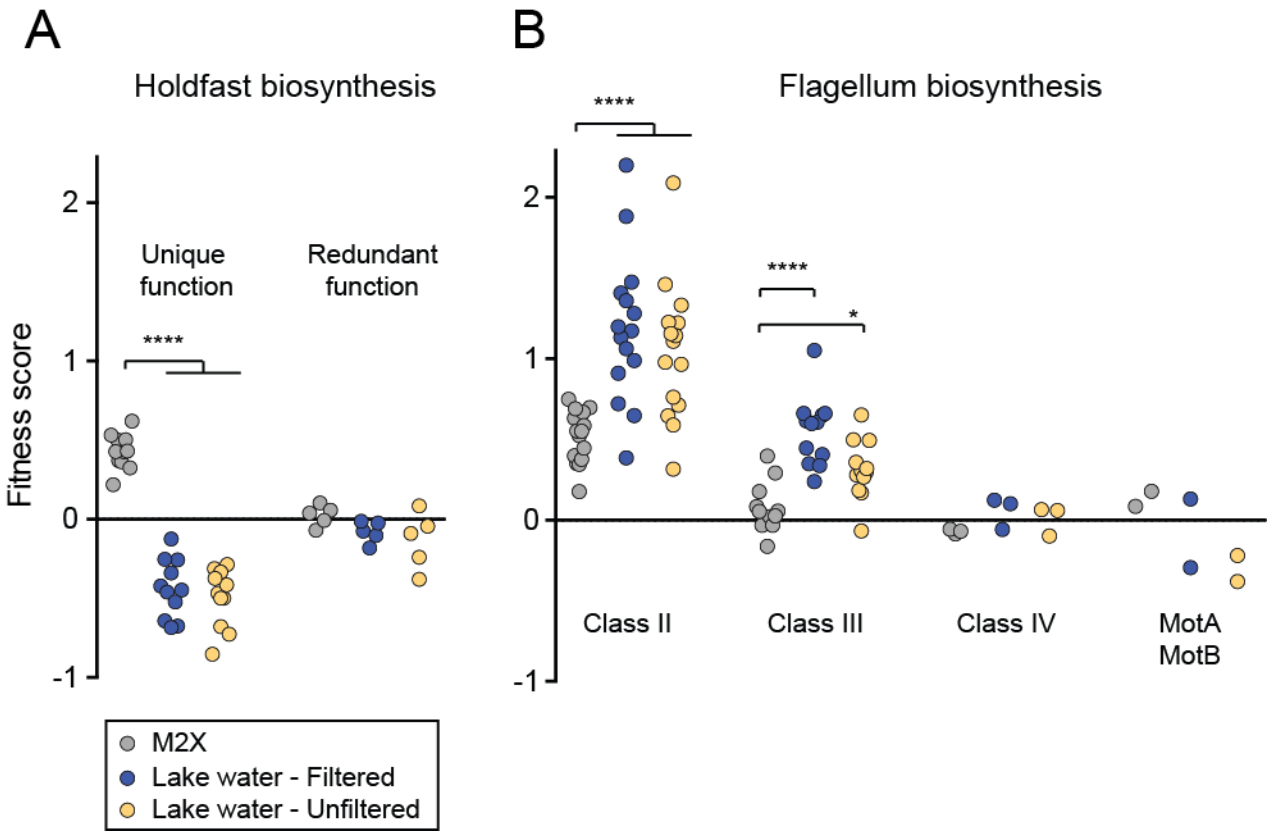

Figure 2. *Caulobacter* gene fitness score summary after cultivation in defined medium, filtered, or unfiltered Lake Michigan water. (A) Rank ordered mean fitness scores of each scorable *Caulobacter* gene across each of the four replicate experiments for each growth condition is plotted; black = mean fitness score; gray = independent replicate fitness scores. Red lines represent ± 3σ from the mean score of the entire dataset (which is approximately zero). (B) Distributions of mean gene fitness scores for each condition: defined M2X medium (gray), filtered Lake Michigan water (blue), and unfiltered Lake Michigan water (yellow). (C) Average gene fitness values between 0 and +2.5 plotted for each condition; defined M2X medium (gray), filtered Lake Michigan water (blue), and unfiltered Lake Michigan water (yellow). (D) Average gene fitness scores plotted for each of the three cultivation conditions: defined M2X medium (gray), filtered Lake Michigan water (blue), and unfiltered Lake Michigan water (yellow).

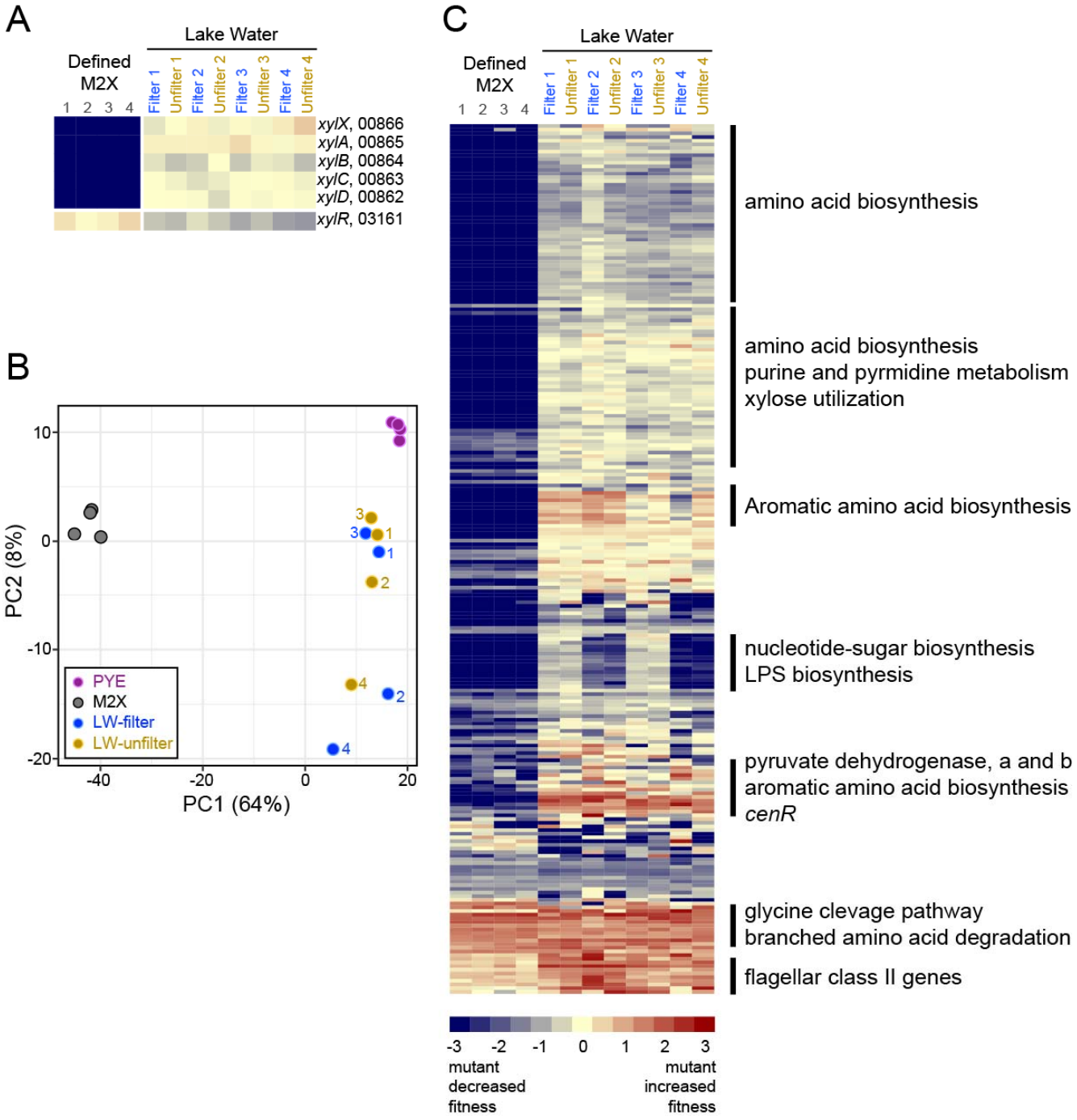

Figure 3. Functional summary of mutant strains with diminished or enhanced fitness in minimal defined medium and Lake Michigan water. (A) Heatmap of gene fitness scores for six xylose utilization genes (*xylX*, *xylA*, *xylB*, *xylC*, *xylD*, *xylR*) from each replicate experiment of cultivation of the Tn-Himar mutant library in M2X defined medium, filtered lake water, and unfiltered lake water. Scale bar is shown in C. (B) Principle component (PC) analysis (PCA) of genomic-scale fitness values for the barcoded *Caulobacter* Tn-Himar mutant library cultivated in complex peptone yeast extract (PYE) medium (reference set), defined M2X medium, filtered Lake Michigan water, and unfiltered Lake Michigan water. The plot shows PCA values for the four replicate datasets for each cultivation condition. Percent of variance contributed by the first two PCs is noted on the axes. (C) Heatmap of

gene fitness scores for genes with mean fitness scores higher than 1.2 or lower than -1.2 (± 3σ fitness score cutoff) in at least one cultivation condition. Genes are clustered, and fitness scores for each replicate experiment are presented as in B. Functions of genes within particular regions of this 238 gene cluster are noted; this entire cluster is split into three fully annotated clusters in Figures S3–S5.

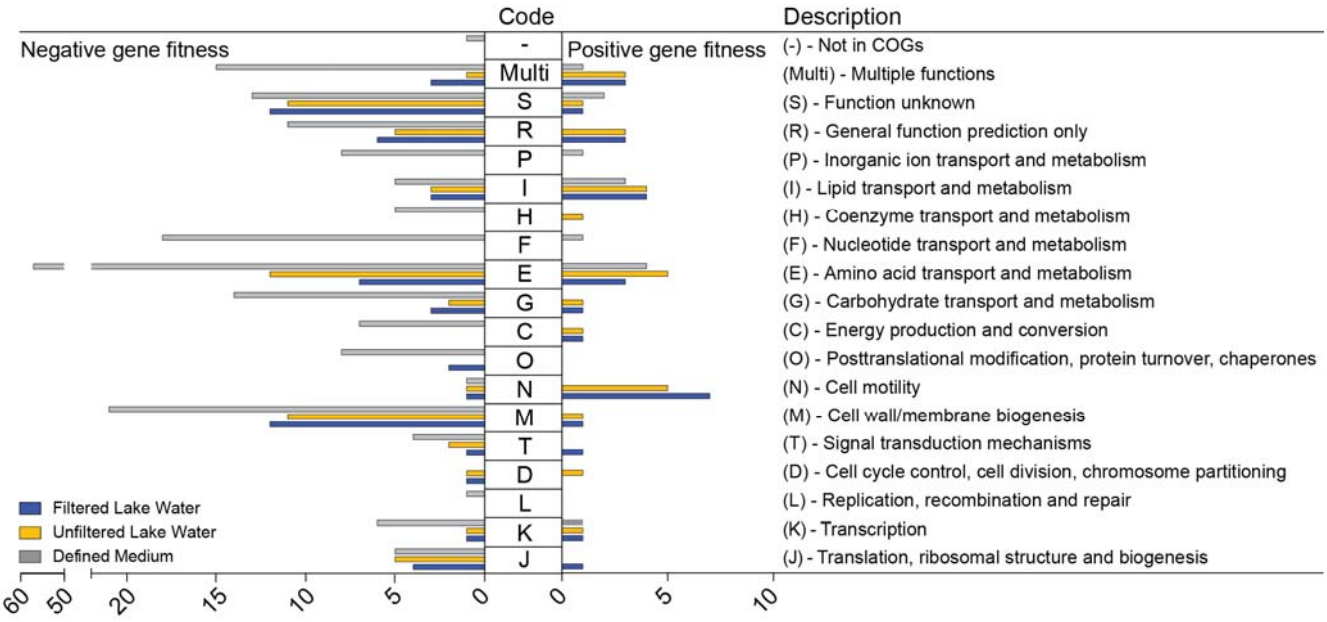

Figure 4. COG-based functional annotation. The analysis includes genes with fitness scores of absolute value greater than 1.2 (± 3σ fitness score cutoff). Each gene was assigned a cluster of orthologous group (COG) functional category (https://www.ncbi.nlm.nih.gov/COG/). The number of genes in each COG category is plotted; genes with negative fitness values (left) and genes with positive fitness values (right).

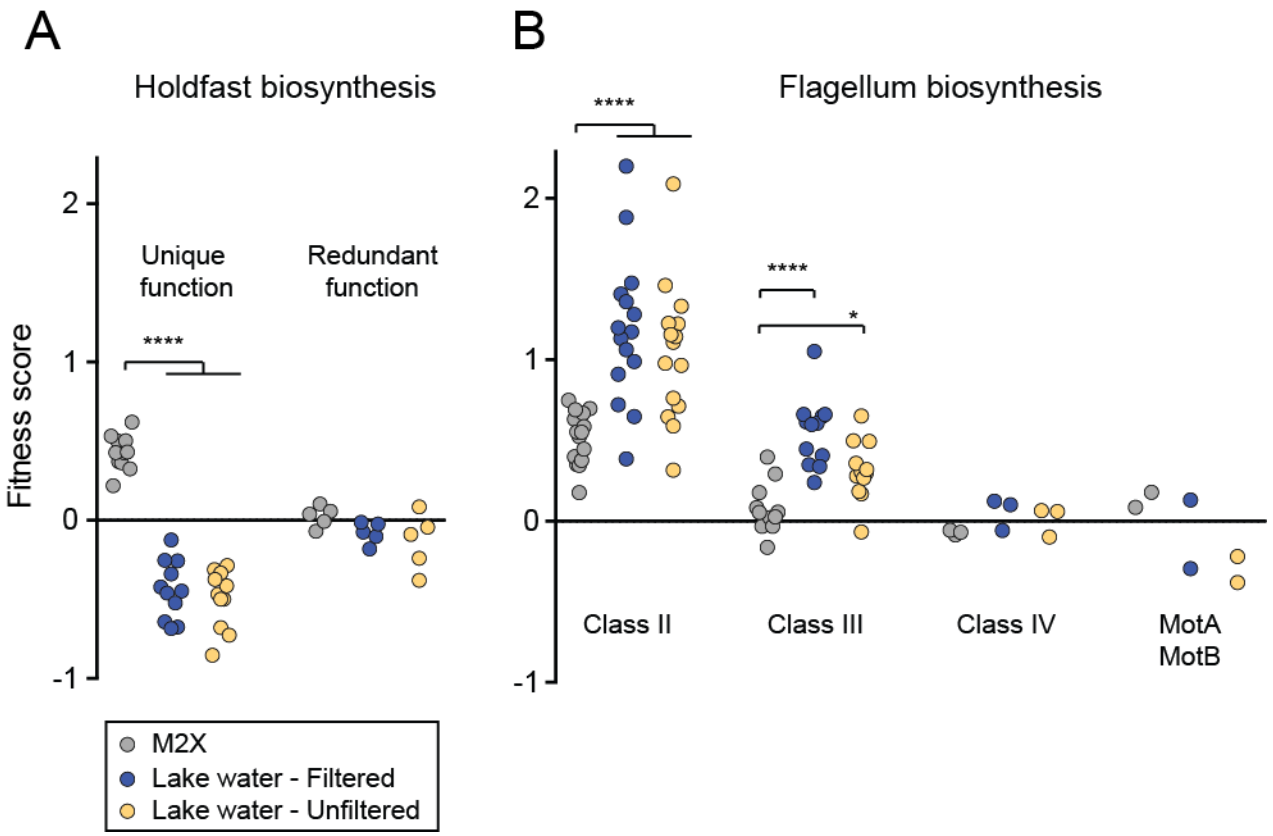

Figure 5. Genes with functions in flagellum and holdfast biosynthesis influence fitness in Lake Michigan water. Mean fitness scores of genes involved in (A) holdfast biosynthesis (14 genes) and (B) flagellum biosynthesis (36 genes) are plotted for each cultivation condition (four independent growth replicates): defined M2X medium (gray); filtered lake water (blue); and unfiltered lake water (yellow). Holdfast genes with unique function (i.e. single gene deletions have a holdfast defect) and redundant function (i.e. single mutants have no holdfast defect) are shown separately. Class II, Class III, and Class IV genes in the flagellar hierarchy and motA/motB stator complex genes are also shown separately. Clusters of holdfast and flagellum fitness score data, with individually annotated genes, are shown in Figure S2. One-way ANOVA was applied to assess differences in fitness scores between cultivation groups within the same gene class; Tukey's post test (**** $p < 0.0001$; * $p < 0.05$).

TABLES

Table 1: Transposon library statistics

Library	Unique insertion sites	Total TA sites	Percent sites hit	Average transposons per ORF	Mean reads
Tn5	115,788	N/A	2.9	30	90–150 (per Tn)
Tn-Himar (BarSeq)	46,395	49,437	93.8	24	7612 (per gene)

Table 2: Analysis of Lake Michigan water used for barcoded Tn-Himar fitness experiments

Water collection*	Nov. 30	Dec. 6	Dec. 9	Dec. 12
Date of experiment	Dec. 2	Dec. 6	Dec. 9	Dec. 12
Water temperature (°C)	7.5	7	3	2
Air temperature (°C)	7.8	4.4	-3.3	-7.2
pH	5.8	5.8	5.8	5.8
Phosphate	5 ppm	5 ppm	5 ppm	5 ppm
Nitrate/Nitrite**	undetectable	undetectable	undetectable	undetectable

*Water collection occurred in 2016 at Promontory Point, Hyde Park, Chicago, Illinois, USA.
**Limit of detection: Nitrite 0.15 mg/L, Nitrate 1 mg/L

Table 3: Average fitness scores for hypothetical genes and genes of unknown function with fitness scores ± 3σ from the mean (bold and shaded) in at least one condition.

Locus number		Defined	Filtered LW	Unfiltered LW
CCNA_01219	No conserved domains	**1.68**	-0.70	0.78
CCNA_03860	COG3786, L,D-peptidoglycan transpeptidase, YkuD superfamily	**1.33**	**1.53**	**1.41**
CCNA_03909	No conserved domains	**-1.20**	**-1.76**	**-1.84**
CCNA_00375	No conserved domains	**-1.21**	**-2.57**	**-2.83**
CCNA_03864	DUF3576, pfam12100	**-1.71**	**-1.32**	**-1.57**
CCNA_01724	COG4649, TPR_21 pfam09976	**-2.58**	**-1.25**	**-1.28**
CCNA_02875	No conserved domains	**-1.54**	**-2.19**	-0.39
CCNA_00927	No conserved domains	**-2.56**	**-2.11**	-0.67
CCNA_00913	No conserved domains	-0.28	**-2.48**	**-1.21**
CCNA_00895	No conserved domains	-0.19	**-2.14**	**-1.44**
CCNA_03273	COG4944, DUF1109, pfam06532 NrsF, anti-sigF	**-1.63**	-0.39	-0.27
CCNA_00519	No conserved domains	**-1.66**	-0.37	-0.61
CCNA_03692	COG1975, Xanthine and CO dehydrogenase maturation factor, XdhC/CoxF family	**-4.06**	-0.98	-0.65
CCNA_01178	DUF934, pfam06073, COG3749	**-4.36**	-0.60	-0.64
CCNA_02669	Uncharacterized membrane protein, DUF3422, pfam11902, COG4949	**-4.41**	0.38	0.20
CCNA_01176	DUF2849, pfam11011	**-4.98**	-0.81	-0.84
CCNA_01676	TamB, COG2911, pfam04357	**-6.40**	-0.52	-0.74
CCNA_01286	No conserved domains	0.25	-0.25	**-1.27**
CCNA_02053	No conserved domains	-0.56	-0.74	**-1.34**
CCNA_02160	No conserved domains	0.26	-1.02	**-1.38**
CCNA_03015	No conserved domains	-0.15	0.57	**-1.46**
CCNA_03945	No conserved domains	-0.43	0.24	**-1.90**
CCNA_02796	No conserved domains	-0.45	**-1.20**	-0.52
CCNA_03984	No conserved domains	0.01	**-1.22**	-0.25
CCNA_03883	No conserved domains	0.05	**-1.25**	0.99
CCNA_03420	No conserved domains	0.40	**-1.46**	0.42

LW, Lake Michigan water.

Supplemental Material

Tn5 and Tn-Himar: comparing gene essentiality and the effects of gene disruption on fitness across studies

A previous analysis of a highly saturated *Caulobacter* Tn5 transposon library revealed a set of genes that are required for growth in complex PYE medium (1); approximately 14% of genes in the genome were deemed essential. The total genome insertion coverage was lower in the Himar library described here than in the Tn5 dataset of Christen et al (2011), as Tn-Himar inserts specifically into TA dinucleotide sites (with 67% GC content, TA sites are relatively limited in the *Caulobacter* genome). Genes for which we failed to detect Tn-Himar insertions (**Table S12**) were largely consistent with essential genes reported by Christen et al (2011), with exceptions likely due to differential coverage of Tn5 versus Tn-Himar mutagenesis and differences in metrics used to define essentiality. A comparison of the essential genes defined by Christen et al (2011) and by our Tn5-seq and Tn-Himar fitness studies is presented in **Table S5**.

We have uncovered evidence for gene disruptions that both enhanced or reduced strain fitness in lake water and M2X relative to PYE. Such results are consistent for a number of genes across both the Tn5 and Tn-Himar datasets. Disruption of genes encoding three metabolic enzymes, a class C β-lactamase family protein (*CCNA_00255*), transaldolase (*CCNA_03729*), and methylcrotonyl-CoA carboxylase (*CCNA_02250*), enhanced *Caulobacter* fitness in Lake Michigan water relative to PYE using both Tn5 and Tn-Himar approaches (**Table S6**). The functional role of the β-lactamase family protein is unclear; the transaldolase and methylcrotonyl-CoA carboxylase may affect the anabolic/catabolic balance by modulating the pentose phosphate pathway and branched chain amino acid catabolism, respectively. Indeed, transcription of methylcrotonyl-CoA carboxylase is significantly upregulated in PYE relative to M2X in the published dataset of Hottes et al (2004), providing evidence that this activity is more important in complex PYE medium than in defined medium.

The Tn5 and Tn-Himar approaches identified a shared set of 26 genes for which disruption resulted in decreased fitness in lake water relative to PYE. The largest effects were observed for multiple genes involved in leucine, proline, homoserine, asparate, and glutamate biosynthesis. Again, these data are consistent with transcriptomic data in which amino acid biosynthesis genes are upregulated in M2X relative to PYE (2). Of note, disruption of the anthranilate synthase (*CCNA_01972*) gene, required for tryptophan biosynthesis, resulted in a significant reduction in fitness of *Caulobacter* cultivated in the presence of other microorganisms in unfiltered lake water, whereas strains grown in filtered water did not have a growth defect. A full comparison of fitness data from the Tn-Himar BarSeq and Tn5 approaches is presented in **Tables S6–S8**.

References

1. **Christen B, Abeliuk E, Collier JM, Kalogeraki VS, Passarelli B, Coller JA, Fero MJ, McAdams HH, Shapiro L.** 2011. The essential genome of a bacterium. Mol Syst Biol **7:**528.
2. **Hottes AK, Meewan M, Yang D, Arana N, Romero P, McAdams HH, Stephens C.** 2004. Transcriptional profiling of Caulobacter crescentus during growth on complex and minimal media. J Bacteriol **186:**1448-1461.

SUPPLEMENTAL FIGURES AND LEGENDS

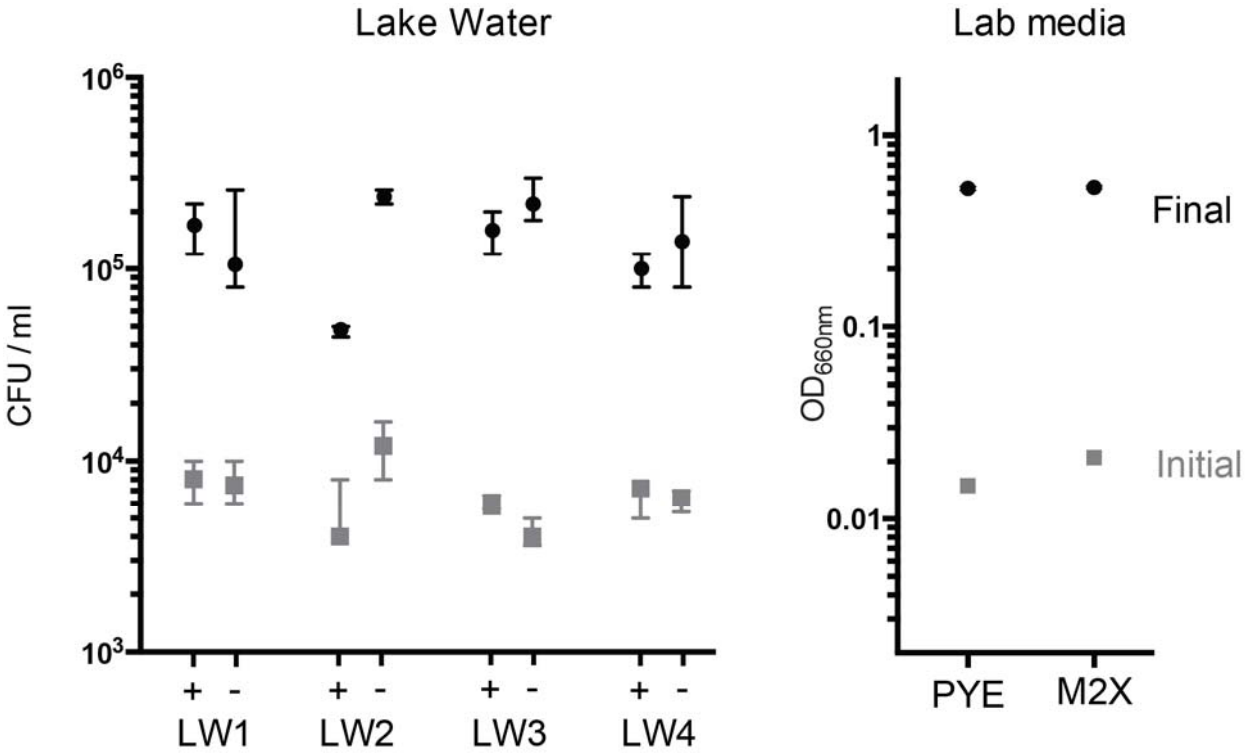

Figure S1: Numbers of barcoded Tn-Himar mutants increase 20–30-fold (on average) during cultivation in Lake Michigan water and laboratory media. Initial (gray) and final (black) cell densities for each Tn-Himar pool growth experiment. In lake water growth experiments, approximately 10^7 mutant cells were inoculated into each of the three flasks of 2.5 L of filtered (+) or unfiltered (-) water from Lake Michigan collected on 4 different days. Initial and final CFUs were enumerated for each flask. In complex (PYE) and defined (M2X) laboratory media, approximately 10^7 mutant cells were inoculated into 1.5 mL of medium. Initial and final OD_{660} of four replicates were measured. Mean ± range is presented.

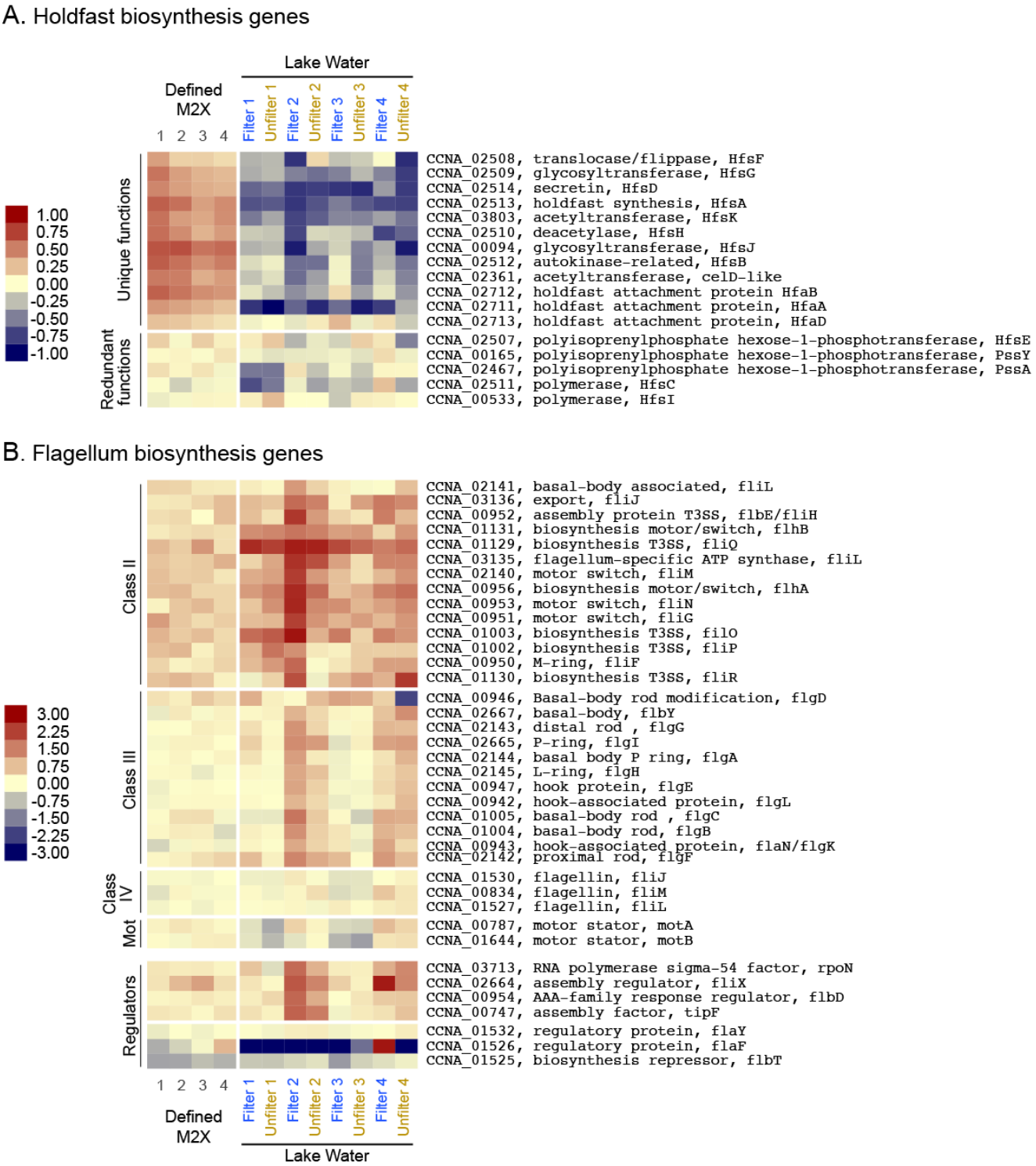

Figure S2. Heatmap of fitness scores for genes with established functions in (A) holdfast biosynthesis and (B) flagellum biosynthesis and motility calculated after cultivation in minimal defined M2X medium and in Lake Michigan water filtered or unfiltered. Holdfast genes with unique functions (i.e. single gene deletions have a holdfast development defect) and redundant functions (i.e. single mutants have no holdfast defect), as previously defined (27), are shown separately. Class two (II), class three

(III) and class four (IV) flagellar genes are marked on the cluster in panel B. Stator mot genes and flagellar regulators are also marked. Scale bars are shown for (A) and (B).

Figure S3. Heatmap of fitness scores for genes shown in Fig. 3C, with gene names visible.

Figure S4. Heatmap of fitness scores (continued) for genes shown in Fig 3C, with gene names visible.

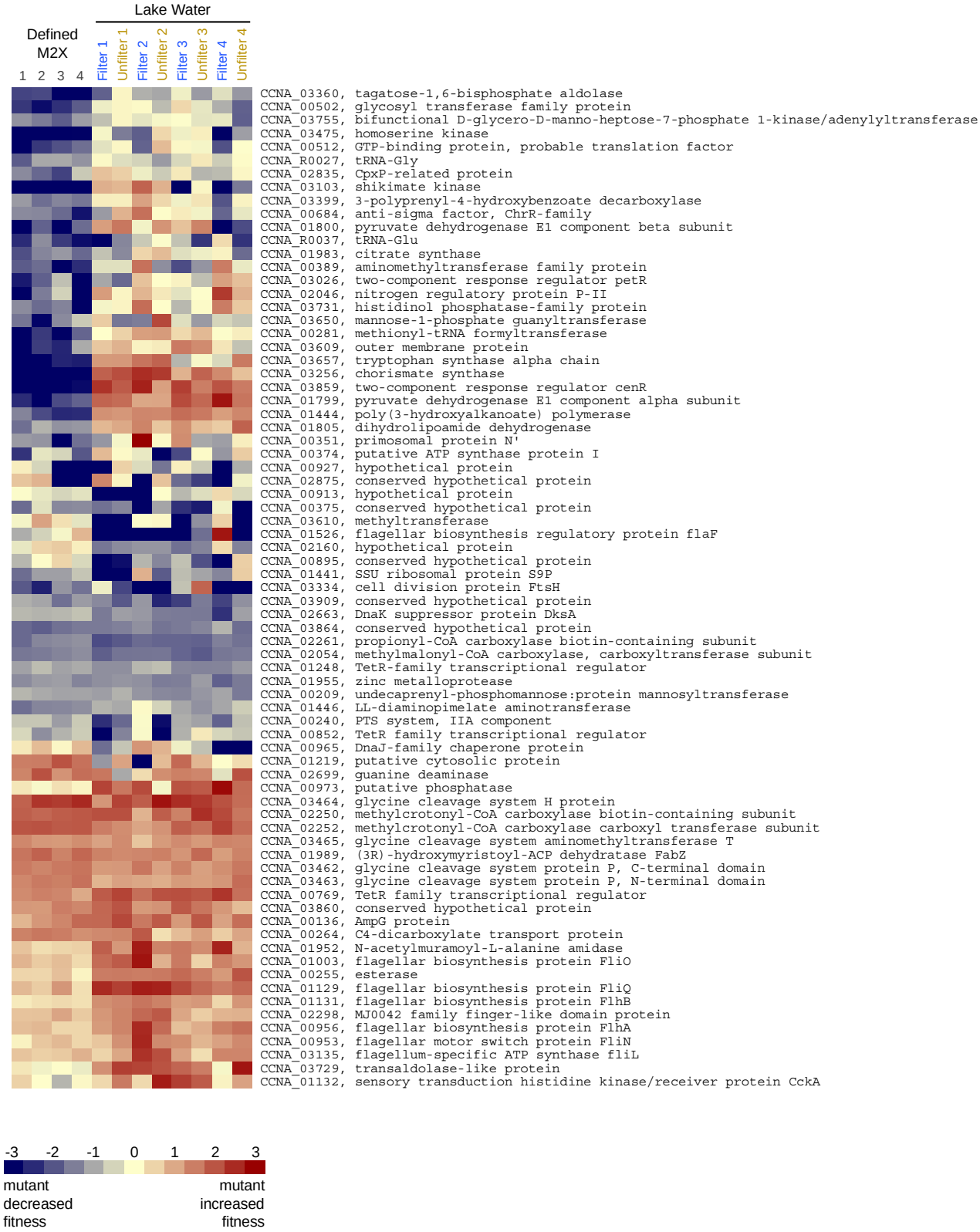

Figure S5. Heatmap (continued) of fitness scores for genes shown in Figure 3C, with gene names visible.

SUPPLEMENTAL TABLES

Table S1. Strains and primers used in this study

Table S2. Tn-Himar gene fitness values

Table S3. Tn5 library gene fitness values

Table S4. Tn5 library gene fitness, adjusted p-value <0.01

Table S5. Data sets for Christen et al 2011, our Tn5 library, and Tn-Himar library arranged by gene

Table S6. Shared genes between Tn5 and Tn-Himar fitness experiments

Table S7. Tn-Himar library genes that are ±3 standard deviations from the mean

Table S8. Tn-Himar library list of genes shared between minimal medium and lake conditions that are ±3 standard deviations from the mean

Table S9. Values of t-test from BarSeq analysis for all genes that met the threshold for fitness calculation outlined

Table S10. Genes for which Tn-Himar disruption results in a specific advantage (positive fitness or t value) or disadvantage (negative fitness or t value) in M2-xylose defined medium

Table S11. Genes for which Tn-Himar disruption results in a specific advantage (positive fitness or t value) or disadvantage (negative fitness or t value) in filtered or unfiltered Lake Michigan water, but not in M2-xylose defined medium (relative to complex PYE medium)

Table S12. Genes in *Caulobacter* that were not hit by Tn-Himar