Metabolic Network Analysis and Metatranscriptomics of a Cosmopolitan and Streamlined Freshwater Lineage

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# Abstract

# Introduction

Microbes are critical players in freshwater systems, where they support essential ecosystem functions such as nutrient cycling. Of the freshwater bacteria, Actinobacteria of the lineage acI are among the most abundant, constituting upwards of 50% of the total bacteria in a variety of aquatic systems (Zwart et al. [1998](#ref-Zwart1998), Glöckner et al. ([2000](#ref-Glockner2000)), Zwart et al. ([2002](#ref-Zwart2002))). Despite their abundance, no isolates of the acI lineage have been stably propagated in pure culture.

Nevertheless, the acI lineage has been extensively studied in a community context using both DNA sequencing and single-cell targeted experiments. Most fundamentally, the acI have been phylogenetically divided into three clades (A, B, and C) and thirteen tribes (Newton et al. [2011](#ref-Newton2011a)) on the basis of their 16S rRNA gene sequences. Several studies have used fluorescent in situ hybridization (FISH) and catalyzed reporter deposition (CARD) or microautoradiography (MAR) to identify substrate uptake capabilities of the acI. These studies reveal that the acI are capable of consuming amino acids generally (Salcher, Pernthaler, and Posch [2010](#ref-Salcher2010), Salcher, Posch, and Pernthaler ([2013](#ref-Salcher2013))); the individual amino acids arginine, glutamate, glutamine, and leucine (Buck et al. [2009](#ref-Buck2009), Pérez, Hörtnagl, and Sommaruga ([2010](#ref-Perez2010)), Salcher, Pernthaler, and Posch ([2010](#ref-Salcher2010)), Eckert et al. ([2012](#ref-Eckert2012)), Salcher, Posch, and Pernthaler ([2013](#ref-Salcher2013)))); the saccharides glucose (Buck et al. [2009](#ref-Buck2009), Salcher, Posch, and Pernthaler ([2013](#ref-Salcher2013))), and N-acetylglucosamine (NAG) [Beier and Bertilsson ([2011](#ref-Beier2011)), Eckert et al. ([2012](#ref-Eckert2012)), Eckert et al. ([2013](#ref-Eckert2013)); the deoxynucleoside thymidine (Pérez, Hörtnagl, and Sommaruga [2010](#ref-Perez2010), Salcher, Posch, and Pernthaler ([2013](#ref-Salcher2013))), and acetate (Buck et al. [2009](#ref-Buck2009)). However, due to limited phylogenetic resolution of some FISH probes, the studies cannot always link the uptake of these substrates to clades or tribes within the lineage.

Instead, metabolic reconstructions of single-cell genomes (SAGs) and metagenome-assembled genomes (MAGs) have been used to propose substrate uptake capabilities of clades aI-A and acI-B. Notably, to date, no genomes from clade acI-C have been included in these studies. These studies indicate both tribes are capable of consuming a wide array of N-containing compounds, including ammonium, branched-chain amino acids, polyamines, di-peptides, and cyanophycin (Ghylin et al. [2014](#ref-Ghylin2014), Garcia et al. ([2015](#ref-Garcia2015))), with clade acI-A also capable of consuming oligopeptides (Ghylin et al. [2014](#ref-Ghylin2014)). The lineage is also capable of consuming numerous saccharides, including the five-carbon sugars xylose, ribose, arabinose (Garcia et al. [2013](#ref-Garcia2013), Ghylin et al. ([2014](#ref-Ghylin2014)), Garcia et al. ([2015](#ref-Garcia2015))) as well as poly- and oligo-saccharides (Ghylin et al. [2014](#ref-Ghylin2014), Garcia et al. ([2015](#ref-Garcia2015))). Notably, transporters for glucose and NAG have not yet been identified (Garcia et al. [2013](#ref-Garcia2013), Ghylin et al. ([2014](#ref-Ghylin2014))), despite FISH studies showing uptake of those substrates. Clade acI-B is also predicted to consume sucrose and maltose (Garcia et al. [2015](#ref-Garcia2015)); it also contains a chitinase for the breakdown of NAG (Garcia et al. [2013](#ref-Garcia2013), Garcia et al. ([2015](#ref-Garcia2015))). Finally, the acI are predicted to contain the actinobacterial opsin protein actinorhodopsin (Garcia et al. [2013](#ref-Garcia2013), Garcia et al. ([2014](#ref-Garcia2014)), Ghylin et al. ([2014](#ref-Ghylin2014)) Garcia et al. ([2015](#ref-Garcia2015))), a light-harvesting transmembrane protein (Sharma et al. [2008](#ref-Sharma2008), Sharma et al. ([2009](#ref-Sharma2009))), as well as the complete pathway for the biosynthesis of its cofactor retinal (Ghylin et al. [2014](#ref-Ghylin2014)).

Finally, a recent study has predicted a number of auxotrophies in a metagenome-assembled genome, including for the amino acids isoleucine, leucine, valine, tyrosine, tryptophan, phenylalanine, asparagine; and the cofactors biotin (Vitamin B7), cobalamin (Vitamin B12), folate (Vitamin B9), niacin (Vitamin B3), pantothenate (Vitamin B5), and riboflavin (Vitamin B2) (Garcia et al. [2015](#ref-Garcia2015)).

These metabolic reconstructions all assume that an organism’s genome content says something about its ecology, an assumption underlying the emerging paradigm of reverse ecology (**???**). While metabolic reconstructions represent a common entry point to reverse ecological analyses, other approaches take cues from systems biology, focusing not just on the “parts” (genes) encoded in the genome, but on the way those parts come together and interact (**???**). In particular, this approach to reverse ecology analyzes genomes in terms of their metabolic networks with a focus on their topological properties. One such property is an organism’s “seed set,” the set of compounds that an organism cannot synthesize and must exogenously acquire from its environment (Borenstein et al. [2008](#ref-Borenstein2008)). As such, these compounds may represent both auxotrophies, essential metabolites for which biosynthetic routes are missing, and nutrients, for which routes for degradation (not synthesis) are present in the genome.

In this work, we expand existing genome-based analyzes of the acI lineage trough such a reverse ecological approach. We re-analyze previously-described acI genomes, as well as six additional single-cell genomes (SAGs) and 15 metagenome-assembled genomes (MAGs), including for the first time genomes from the acI-C clade. For this analysis, we have developed a high-throughput reverse ecological analysis to predict seed compounds for each clade, using metabolic network reconstructions generated from KBase (http://kbase.us). Predicted seed compounds confirm the ability of the acI to metabolize N-rich organic compounds and an array of carbohydrates, while also revealing clade-specific differences in auxotrophies and degradation capabilities. We also present the first metatranscriptomic analysis of gene expression across the three acI clades. These data show that the acI express a diverse array of transporters at a high level, which may be key to the success of their passive and planktonic lifestyle. Finally, we observe actinorhodopsin to be among the most highly expressed genes in all three lineages, strongly suggesting a photoheterotrophic lifestyle for the acI.

# Materials and Methods

## Single-Cell Genome Generation, Selection, and Sequencing

Single-cell genomes were collected from the top of the water column (depth <1m) from each of two lakes, Mendota (Madison, WI, USA) and Damariscotta (Lincoln County, ME USA), in 2009. Samples were cryopreserved and sent to the Single Cell Genomics Center at the Bigelow Laboratory for Ocean Sciences for sorting, as previously described (Martinez-Garcia et al. [2012](#ref-Martinez-Garcia2012), Garcia et al. ([2013](#ref-Garcia2013))). Partial 16S rRNA genes amplified previously (Martinez-Garcia et al. [2012](#ref-Martinez-Garcia2012)) were phylogenetically classified using a controlled nomenclature for freshwater bacteria (Newton et al. [2011](#ref-Newton2011a)) by insertion into references trees created in the ARB software package (Ludwig et al. [2004](#ref-Ludwig2004)).

Actinobacterial SAGs used in this study were then sent to the JGI for sequencing and assembly, also as previously described (Ghylin et al. [2014](#ref-Ghylin2014)). Briefly, shotgun libraries were constructed for each of the SAGs from re-amplified MDA products and sequenced on an Illumina HiSeq2000. All general aspects of and detailed protocols for library construction and sequencing can be found on the JGI website (http://www.jgi.doe.gov/).

For assembly, raw sequence data was first passed through a filtering program developed at JGI to eliminate known sequencing and library preparation artifacts. Assembly was then performed using Velvet [Zerbino and Birney ([2008](#ref-Zerbino2008)) and ALLPATHS-LG (Butler et al. [2008](#ref-Butler2008)). Additional details of the assembly process have been previously described (Ghylin et al. [2014](#ref-Ghylin2014)) and are available through the JGI Genome Portal (http://genome.jgi.doe.gov) Genome sequences are available through IMG (https://img.jgi.doe.gov/cgi-bin/mer/main.cgi). Genome-specific information can be accessed in both databases by searching for the IMG Taxon OIDs given in Table 1.

## Metagenome Sampling, Sequencing, Assembly, and Binning

Sample collection, DNA sequencing, metabgenomic assembly, and genomic binning for the Trout Bog samples have been described previously (Bendall et al. [2016](#ref-Bendall2016)), and similar procedures were followed for Lake Mendota samples. A summary is provided here.

For Lake Mendota, depth-integrated water samples were collected from the top 12 meters at 96 time points during ice-free periods from 2008 to 2011. For Trout Bog, depth-integrated water samples were collected from the epilimnion (44 samples) and hypolimnion (45 samples) layers during ice-free periods from 2007 to 2009. All samples were filtered on 0.2 μm polyethersulfone filters (Supor, Pall Corp) prior to storage at -80°C, as described previously (Bendall et al. [2016](#ref-Bendall2016)). DNA was extracted from these filters using the FastDNA kit (MP Biomedicals) and sent to the JGI for sequencing, as described previously (Bendall et al. [2016](#ref-Bendall2016)).

Shotgun libraries were constructed for each of the samples and sequenced on an Illumina GA IIx (four Trout Bog samples) or an Illumina HiSeq2000 (all other samples), following a 2x150 indexed run recipe as previously described (Bendall et al. [2016](#ref-Bendall2016)). All general aspects of and detailed protocols for library construction and sequencing can be found on the JGI website (http://www.jgi.doe.gov/). Metagenomic sequence reads are publicly available on the JGI Genome Portal (http://genome.jgi.doe.gov/) under Proposal ID 394.

Raw sequence data was passed through a filtering program developed at JGI to eliminate known sequencing and library preparation artifacts. Prior to assembly, reads were merged with FLASH (Magoc and Salzberg [2011](#ref-Magoc2011)), as previously described (Bendall et al. [2016](#ref-Bendall2016)). Merged reads were pooled by lake and layer into three co-assemblies using SOAPdenovo (Luo et al. [2012](#ref-Luo2012a)), and contigs from the resulting assemblies were assembled into a final assembly using Minimus (Sommer et al. [2007](#ref-Sommer2007)), as previously described (Bendall et al. [2016](#ref-Bendall2016)). Additional details of the assembly process and metagenomic sequence reads are available through the JGI Genome Portal (http://genome.jgi.doe.gov) under Proposal ID 394.

Genomes were binned from each metagenomic co-assembly using MetaBat (Kang et al. [2015](#ref-Kang2015)), as described previously (Bendall et al. [2016](#ref-Bendall2016)). Briefly, contigs were classified into bins using tetranucleotide frequency and coverage patterns across the time-series and then manually curated, as previously described (Bendall et al. [2016](#ref-Bendall2016)). Genome sequences are available through IMG (https://img.jgi.doe.gov/cgi-bin/mer/main.cgi). Genomes were classified using taxonomic assignments from a set of 37 highly-conserved single-copy marker genes using Phylosift (Darling et al. [2014](#ref-Darling2014)), as previously described (Bendall et al. [2016](#ref-Bendall2016)).

## Metatranscriptome Sampling and Sequencing

Four samples were collected from the top of the water column (depth <1m) from Lake Mendota (Madison, WI, USA) over a twenty-four hour period on August 20 and 21, 2015. For each sample, between 200 and 400 mL lake water was filtered onto a 0.2 μm polyethersulfone filter (Supor, Pall Corp) and stored at -80°C until extraction.

Prior to extraction, three samples were spiked with an internal standard to enable quantification of total transcript abundance, following an established protocol (Satinsky et al. [2014](#ref-Satinsky2014a)). Briefly, a 970-nucleotide-long mRNA standard was synthesized using a a T7 RNA polymerase and the Riboprobe In Vitro Transcription System (Promega, Madison, WI), according to the manufacturer’s protocol. A fixed quantity of each standard (1.172 x 10^10 copies) was added independently to each lysis tube immediately prior to the addition of the sample filter.

Samples were subject to TRIzol-based RNA extraction (Thermo Fisher Scientific, Waltham, MA) followed by on-column DNAse digestion and RNA purification using an RNeasy Mini Kit (Qiagen, Venlo, Netherlands). RNA was then sent to the University of Wisconsin-Madison Biotechnology Center (https://www.biotech.wisc.edu) for sequencing. There, samples were prepared for sequencing using the TruSeq RNA Library Prep Kit v2 (Illumina, San Diego, CA), with the addition of a step for selective ribosomal RNA depletion using the Ribo-Zero rRNA Removal Kit (Bacteria) (Illumina). The resulting cDNA libraries were pooled in an equimolar ratio, and sequenced on an Illumina HiSeq2500.

Raw paired-end reads were then merged using FLASH (Magoc and Salzberg [2011](#ref-Magoc2011)) using default parameters. Finally, additional rRNA and ncRNA sequences were removed using SortMeRNA (Kopylova, Noe, and Touzet [2012](#ref-Kopylova2012)) using default parameters. SortMeRNA was run using eight built-in databases for bacterial, archaeal, and eukaryotic small and large ribosomal subunits and ncRNAs, derived from the SILVA 119 (Quast et al. [2013](#ref-Quast2013)) and RFAM (Nawrocki et al. [2015](#ref-Nawrocki2015)) databases.

Additional information, including all protocols and scripts for RNA analysis, can be found on Github (https://github.com/McMahonLab/OMD-TOILv2). Raw RNA sequences can be found on the National Center for Biotechnology Information (NCBI) website under BioProject PRJNA######.

## Identification of acI SAGs and MAGs

Novel acI SAGs were identified using partial 16S rRNA genes and a reference taxonomy for freshwater bacteria, as described above. To identify acI MAGs, a phylogenetic tree containing all acI SAGs and Actinobacterial MAGs was constructed as described below. Actinobacterial MAGs forming a monophyletic group with the acI SAGs were deemed acI MAGs.

## Genome Completeness and Phylogenetic Relationships

CheckM (Parks et al. [2015](#ref-Parks2015)) was used to estimate genome completeness based on 204 single-copy marker genes conserved across the phylum Actinobacteria. Phylogenetic analysis of Actinobacterial SAGs and MAGs was performed using a concatenated alignment of single-copy marker genes obtained via Phylosift (Darling et al. [2014](#ref-Darling2014)). Maximum likelihood trees were generated using RAxML (Stamatakis [2014](#ref-Stamatakis2014)) using the automatic protein model assignment option (PROTGAMMAAUTO) and 100 bootstraps.

## Metabolic Network Reconstruction and Reverse Ecology

### Genome Annotation and Model Processing

Genome annotations and metabolic network reconstructions were performed using KBase (http://kbase.us/). Unannotated contigs for each genome were pushed to KBase and annotated using the “Annotate Microbial Contigs” method using default options, which uses components of the RAST toolkit (Brettin et al. [2015](#ref-Brettin2015), Overbeek et al. ([2014](#ref-Overbeek2014))) for genome annotation. Genome-scale metabolic network reconstructions were performed using the “Build Metabolic Model” app using default parameters, which relies on the Model SEED framework (Henry et al. [2010](#ref-Henry2010a)) to build a draft metabolic model.

Metabolic models were then downloaded via KBase, pruned, and converted to metabolic network graphs. In particular, biomass, exchange, transport, spontaneous, and DNA/RNA biosynthesis reactions were removed from the model, and reactions were mass- and charge-balanced. Next, currency metabolites (compounds used to carry electrons and functional groups) and highly-connected compounds (those which participate in many reactions, such as CO2 and O2) were removed following an established procedure (H. Ma and Zeng [2003](#ref-Ma2003)). Finally, the network model was converted to a metabolic network graph, in which nodes denote compounds and edges denote reactions. A directed edge from compound *a* to compound *b* means that *a* is a substrate in a reaction which produces *b*. Supplemental Figure 2 illustrates process by which a genome gets converted to a pruned metabolic network graph, for a genome containing only glycolysis.

Finally, all genome-level metabolic network graphs for a single acI clade were combined to generate a composite clade-level metabolic network graph for that clade. Beginning with two genomes, nodes and edges unique to the second genome are identified and appended to the network graph for the first genome, giving a composite metabolic network graph. The process is repeated for each genome belonging to the clade, until all of the network graphs have been incorporated into the composite. Figure 3A shows metabolic network graphs for three acI-C genomes, and Figure 3B shows the composite metabolic network graph for clade acI-C.

### Calculation and Evaluation of Seed Compounds

Seed compounds for each composite clade-level metabolic network graph were calculated using established methods (Borenstein et al. [2008](#ref-Borenstein2008)). Briefly, the metabolic network is decomposed into its strongly connected components (SCCs), sets of nodes where each node in the set is reachable from every other node. Seed compounds can then be found by identifying source components (components with no incoming edges) on the condensation of the original graph: each source component represents a seed set, and the nodes within that component represent seed compounds. Supplemental Figure 3 illustrates this process for a simple network containing only glycolysis, and Figure 3B shows seed compounds for clade acI-C. Finally, all predicted seed compounds were manually evaluated to identify those which may be biologically meaningful. Examples are given in the Results section.

### Re-annotation of Peptidases and Glycoside Hydrolases

Many seed compounds were associated with reactions catalyzed by peptidases or glycoside hydrolases, and genes associated with these reactions were re-annotated. Peptidase sequences were annotated using the MEROPS batch BLAST interface using default parameters (Rawlings, Barrett, and Finn [2015](#ref-Rawlings2015)). Glycoside hydrolases were first annotated using dbCAN (Yin et al. [2012](#ref-Yin2012)) to assign these genes to glycoside hydrolase families, as defined in the Carbohydrate-Active enZYmes Database CAZY (Lombard et al. [2014](#ref-Lombard2014)). Hidden Markov Models for these sub-families were then downloaded from dbCAN, and HMMER3 (Eddy [2011](#ref-Eddy2011)) was used to assign these genes to individual sub-families using default parameters. Re-annotated peptidases and glycoside hydrolases are given in Supplementary Tables S2 and S3, respectively.

## Integrating Reverse Ecology with Metatranscriptomics

### Protein Clustering, Metatranscriptomic Mapping, and Clade-Level Gene Expression

OrthoMCL (Li, Stoeckert, and Roos [2003](#ref-Li2003)) was used to identify clusters of orthologous genes (COGs) in the set of acI genomes. OrthoMCL was run using default options. Annotations were assigned to protein clusters by choosing the most common annotation among all genes assigned to that cluster. Then, metatranscriptomic reads were mapped to a single fasta file containing all acI genomes using BBMap (https://sourceforge.net/projects/bbmap/) with the ambig=all and minid=0.85 options. With this command, reads are allowed to map equally well to multiple sites. An 85% percent identity cutoff was chosen as it minimizes the percent of reads which map to multiple sites.

Next, a custom implementation of HTSeq-Count (Anders, Pyl, and Huber [2014](#ref-Anders2014)) was used to count the total number of reads which map to each (genome, gene) pairing. Any read which mapped to multiple sites within the collection of acI genomes was discarded. Using the COGs identified by OrthoMCL, the total number of reads which map to each (clade, COG) pairing was then counted. This gives a measure of gene expression for the clade-level composite genome. Because ambiguous reads were discarded after mapping, this measure of gene expression provides an underestimate of the true expression level.

For each clade, read counts were then normalized by sequencing depth and ORF length and expressed on a reads per kilobase million (RPKM) basis (Mortazavi et al. [2008](#ref-Mortazavi2008)), while accounting for different ORF lengths within a COG. RPKM counts were averaged across the four metatranscriptomes to give the average expression across a 24-hour period. Finally, within each clade, the percentile rank expression for each COG was calculated. Figure 3C shows the calculated RPKM values for clade acI-C, along with the presence/absence of each COG in three acI-C genomes.

### Re-annotation of Transporter Genes

Many highly-expressed genes were annotated as transport proteins, and these proteins were re-annotated to assign function to COGs identified by OrthoMCL. Protein sequences were BLASTed against the TCDB reference database (Saier et al. [2014](#ref-Saier2014)) using blastp and given the annotation of the best-BLAST hit. If a COG contained genes with multiple annotations, the majority annotation was selected for that COG. Examples are given in the Results section.

## Availability of Data and Materials

All genomic and metatranscriptomic sequences are available through IMG and NCBI, respectively. Reverse ecology calculations were performed using the Python package reverseEcology, written expressly for this purpose and available on the Python Package Index. A reproducible version of this manuscript is available at https://github.com/joshamilton/reverseEcologyMS.

# Results

## Genome Statistics and Phylogenetic Affiliation

We have assembled a reference genome collection containing 17 SAGs and 19 MAGs from members of the acI lineage. The SAGs, 11 of which have been previously described (Garcia et al. [2013](#ref-Garcia2013), Ghylin et al. ([2014](#ref-Ghylin2014))), come from four temperate lakes in the United States and Europe, while the MAGs come from two temperate lakes in the United States (15 MAGs, nine of which have been previously-described (Bendall et al. [2016](#ref-Bendall2016))), Spanish and American reservoirs (three MAGs (Ghai et al. [2014](#ref-Ghai2014), Tsementzi et al. ([2014](#ref-Tsementzi2014)))), and a mixed culture from a European temperate lake (Garcia et al. [2015](#ref-Garcia2015)). The full list of genomes is given in Table 1.

A phylogenetic tree of these genomes is shown in Figure 1. The acI lineage has previously been shown to contain three distinct clades (Newton et al. [2011](#ref-Newton2011a)), and our concatenated gene tree recapitulates this topology. Of note, three MAGs were classified as belonging to the acI-C clade, and represent the first genomes from this group. Additionally, five MAGs fell into one of the seven tribes defined by our SAGs.

Genome completeness estimates for the new genomes range from 51 to 87% (Table 1), with estimated genome sizes between 1 and 2 MB. The GC content of these genomes was also low (40 to 50%), and both estimated genome size and GC content are consistent with other acI genomes (REFs, Ghai, McMahon, and Rodriguez-Valera [2012](#ref-Ghai2012)). Estimated genome size and GC content of clade acI-C were not statistically different from clades acI-A and acI-B.

## Estimated Completeness of Tribe- and Clade-Level Composite Genomes

Metabolic network reconstructions created from these genomes will necessarily be missing reactions, as the underlying genomes are incomplete. Previous studies have shown that the percentage of correctly identified seed compounds (true positives) is approximately equal to the completeness of the reaction network (Borenstein et al. [2008](#ref-Borenstein2008)), and the number of false positives is approximately equal to the incompleteness of the network (Borenstein et al. [2008](#ref-Borenstein2008)).

Using conserved single-copy marker genes (Parks et al. [2015](#ref-Parks2015)), We estimated the completeness of tribe- and clade-level composite genomes to determine the finest level of taxonomic resolution at which we could confidently compute seed compounds (Figure 2). At the tribe level, with the exception of tribe acI-B1, tribe-level composite genomes are estimated to be incomplete (Figure 2A). At the clade level, clades acI-A and B are estimated to be complete, while acI-C remains incomplete (Figure 2B). As a result, seed compounds were calculated for composite clade-level genomes, with the understanding that some true seed compounds for the acI-C clade will not be predicted.

## Protein Clustering and Metatranscriptomics

OrthoMCL identified a total of 5013 protein clusters across the three clades (Table S8). Of these, 1078 represent core genes, defined as present in at least one genome belonging to that clade.

* read recruiting - % of MG/MT reads which map to acI reference genome collections (still need to map the MGs)
* what does this say about…
* are acI active or dormant?
* quality of our reference genomes wrt conditions that day?

## A Workflow for High-Throughput Reverse Ecological Analysis of Metabolic Networks

A central contribution of this work is a computational pipeline to compute an organism’s seed compounds from a graph-based representation of its metabolic network. To recap, unannotated contigs are converted to metabolic network reconstructions using KBase. The reconstructions are then converted to metabolic network graphs (Supplemental Figure S2) and combined to give composite metabolic network graphs for each clade (Figure 3). Seed compounds are then computed for each clade, using its composite metabolic network graph (Figure 3, Supplemental Figure S3).

Metabolic network reconstructions for the acI genomes contained between 110 and 339 genes, encoding between 241 and 587 reactions which interconvert between 374 and 699 metabolites. On average, these genes account for 25% of the genes in the genome, a value consistent with metabolic network reconstructions for other organisms. Clade-level composite metabolic network graphs were considerably larger, with between 602 and 811 metabolites.

These composite metabolic network graphs contained a large number of disconnected components (groups of nodes that are not connected to the bulk of the network, Supplemental Figure S4). For simplicity, these components were dropped from the graph, and seed compounds were computed for the single largest component. In all cases, the single largest component contained at least 80% of the nodes in the original graph.

Decomposition of composite metabolic network graphs into their SCCs resulted in a bow-tie structure, in which a single giant component contains a substantial fraction of the compounds (Supplemental Figure S4). Across the three clades, the giant component contained 61% of the metabolites, a substantially larger fraction than reported for other organisms (H. W. Ma and Zeng [2003](#ref-Ma2003a)).

The total number of predicted seed sets (source components in the SCC decomposition) ranged from 63 to 95, and the number of seed compounds ranged from 70 to 102. This discrepency arises because some seed sets contain multiple compounds (an example is discussed below). However, such seed sets were rare (4% of all seed sets), and contained at most six compounds. The majority of seed compounds (96%) belonged to seed sets containing only a single compound. A total of 125 unique seed compounds were identified across the three clades, and a complete list can be found in Supplementary Table S9.

## Evaluation of Potential Seed Compounds

Seed compounds were predicted using the results of an automated annotation pipeline, and as such are likely to contain inaccuracies [REF]. As a result, we screened the set of predicted seed compounds to identify those which represented biologically plausible auxotrophies and degradation capabilities. This subset of seed compounds were then manually curated. Supplemental Tables S2 and S3 contain the final set of proposed auxotrophies and degradation capabilities, respectively, for clades acI-A, B, and C. Here, we present a series of brief vignettes explaining why compounds were retained or discarded discarded as biologically plausible. For biologically plausible compounds, we also provide examples of manual curation efforts.

**Carbamoyl phosphate**. Carbamoyl phosphate was predicted as a seed compound for all three clades. Carbamoyl phosphate synthase is the first step in arginine and pyrimidine biosynthesis, and catalyzes the reaction:

2 ATP + L-glutamine + hydrogen carbonate + H2O → L-glutamate + carbamoyl phosphate + 2 ADP + phosphate + 2 H+

This reaction contains a number of currency metabolites (ATP, ADP glutamine, glutamate), as well as the highly-connected metabolites carbonate, water, phosphate and protons. All of these metabolites were removed from the network during pruning. Thus, the reaction responsible for carbamoyl phosphate synthesis was effectively removed from the network, rendering this compound a seed compound. Manual inspection of individual genomes revealed the gene for carbamoylphosphate synthase, confirming carbamoyl phosphate is not an auxotrophy.

**R-enoyl-ACP**. A number of R-enoyl-ACP compounds were predicted to be seed compounds in clades acI-A and B. These compounds were associated with a single COG annotated as an “Enoyl-[acyl-carrier-protein] reductase,” the enzyme which catalyzes the final step in fatty acid elongation. Many other predicted seed compounds were predicted to partcipate in fatty acid and phospholipid biosynthesis, including a number of saturated fatty acids (associated with a COG annotated as a “long-chain-fatty-acid–CoA ligase”) and 1-acyl-sn-glycerol 3-phosphate compounds (associated with a COG annotated as an “1-acyl-sn-glycerol-3-phosphate acyltransferase”). Given the broad substrate specificity of these enzymes, KBase automatically assigns these enzymes to the catalysis of a number of reactions. It is highly likely that manual curation will reveal complete fatty acid and phospholipid biosynthesis pathways, so and other such compounds were excluded from further consideration.

**L-Aspartate-4-semialdehyde, L-homoserine, and O-Phospho-L-homoserine.** Clade acI-C was predicted to have a seed set containing these three compounds. These three compounds can be interconverted via the following reactions:

Homoserine dehydrogenase: L-Aspartate-4-semialdehyde <--> L-homoserine  
  
Homoserine kinase: L-homoserine <--> O-Phospho-L-homoserine

making the three compounds the vertices of a strongly connected component. The first reaction, homoserine dehydrogenase, is the final step in homoserine biosynthesis, so these compounds suggest an auxotrophy for homoserine. Homoserine biosynthesis proceeds via the following reactions:

aspartate kinase: aspartate --> L-aspartyl-4-phosphate  
aspartate semialdehyde dehydrogenase: L-aspartyl-4-phosphate --> L-Aspartate-4-semialdehyde  
homoserine dehydrogenase: L-Aspartate-4-semialdehyde --> homoserine

The presence of L-Aspartate-4-semialdehyde as a seed compound suggests the reaction “aspartate semialdehyde dehydrogenase” is missing, and were unable to manually identify a candidate gene for this reaction. Furthermore, the acI-C composite genome contains the other two reactions in the pathway. Thus, on the evidence available, we conclude acI-C is auxotrophic for homoserine.

**L-arogenate.** This compound was predicted as a seed compound for clade acI-C, suggesting an auxotrophy for tyrosine. Tyrosine can be synthesized via the following route:

chorismate mutase: chorismate --> prephenate  
prephenate aminotransferase: prephanate --> L-arogenate  
arogenate dehydrogenase: L-arogenate --> L-tyrosine

L-arogenate was predicted to be a seed compound based on the presence of “arogenate dehydrogenase”, the final step in the pathway. The reaction “chorismate mutase” is also present, but we were unable to find a candidate gene for the reaction “prephenate aminotransferase,” suggesting an auxotrophy for tyrosine. However, L-tyrosine can be synthesized from chorismate via an alternative pathway:

chorismate mutase: chorismate --> prephenate  
prephenate dehydrogenase: prephenate --> 4-hydroxyphenylpyruvate  
tyrosine aminotransferase: 4-hydroxyphenylpyruvate --> L-tyrosine

All three genes in this pathway are present in the genome, indicating acI-C is not auxotrophic for tyrosine.

**Ala-Leu and gly-pro-L**. These di-peptides were predicted to be seed compounds for all three clades. The compounds are associated with the following reactions:

H2O + Ala-Leu --> L-Leucine + L-Alanine  
H2O + Gly-Pro --> Glycine + L-Proline

These reactions were associated with four COGs, annotated as aminopeptidases. These seed compounds suggest the ability for the acI to degrade peptides, but the broad specificity of aminopeptidases means these particular di-peptides are unlikely to be the only substrates. Similarly, a number of seed compounds were associated with COGs annotated as gluco- and galactosidases, which also have broad substrate specificity. As a result, these genes were further investigated as described below.

## Auxotrophies and Degradation Capabilities of the acI Lineage

Figure 4a summarizes predicted auxotrophies for the acI lineage. In all three clades, beta-alanine was identified as a seed compound, suggesting an auxotrophy for Vitamin B5. (Vitamin B5, also known as pantothenic acid, is a precursor to coenzyme A formed from beta-alanine and pantoate). In bacteria, beta-alanine is typically synthesized via the decarboxylation of aspartate [REF], and we were unable to identify a candidate gene for this enzyme in any acI genome (Supplemental Table S3). Pyridoxine phosphate and pyridoxamine phosphate (forms of Vitamin B6) were also predicted to be seed compounds, and numerous enzymes in the biosynthesis of these compounds were undetected in the genomes (Supplemental Table S3). Vitamin B6 serve as cofactors for numerous metabolic enzymes [REF], which were detected in all three acI clades.

Clades within the acI lineage also exhibited distinct auxotrophies. Clade acI-A was predicted to be auxotrophic for the cofactor tetrahydrofolate (THF), and numerous enzymes for its biosynthesis were missing (Supplemental Table S3). In turn, acI-C was predicted to be auxotrophic for UMP and the amino acids lysine and homoserine, and in all cases multiple enzymes for the biosynthesis of these compounds went not found in the acI-C genomes. However, because the acI-C composite genome was estimated to be around 80% complete, we cannot rule out the possibility that the missing genes might be found in additional genomes.

Furthermore, both clades acI-A and B were predicted to degrade D-altronate and trans-hydroxy proline, and acI-B was additionally predicted to degrade glycine betaine. **These compounds relate to the ecology of acI…**

Finally, all three clades were predicted to degrade the di-peptides ala-leu and gly-pro-L and the sugar maltose. Clades acI-A and acI-C were also predicted to degrade the polysaccharides stachyose, manninotriose, and cellobiose. In all cases, these compounds were associated with reactions catalyzed by peptidases or glycoside hydrolases, and genes associated with these reactions were re-annotated as described above. In most cases, these annotations were in agreement with annotations given by KBase (Supplemental Tables S4 and S5), despite the narrow substrate range reflected by the reactions assigned by KBase. The results of this re-annotation are shown in Figure 4b.

All three clades were predicted to contain both cytosolic- and membrane-bound aminopeptidases capable of releasing a variety of residues from both di- and polypeptides. **Compare to MAR-FISH and genomic studies.** The genes for these two enzymes were also highly expressed, being above the 78th percentile for gene expression in all three clades. Additionally, all three clades were predicted to encode an alpha-glucosidase, which was expressed above the 65th percentile in all three clades. Clades acI-A and C also encode an additional alpha-glucosidase and an alpha-amylase.

Furthermore, these two clades encode an alpha-galactosidase and an enzyme which could be a beta-glucosidase, beta-galactosidase, or a beta-D-fucosidase. **Compare to MAR-FISH and genomic studies.** With the exception of the alpha-galactosidase, these enzymes were more highly expressed in clade acI-A than in acI-C, being expressed above the 73rd percentile instead of the 15th. The alpha-galactosidase was expressed approximately equally in the two clades, around the 67th percentile for gene expression.

In the aggregate, these results suggest the acI lineage is capable of degrading a diverse array of peptides and polysaccharides, such as polyamine, spermidine, and **some polysaccharides that are abundant in lakes**, which are all known to be abundant in freshwater ecosystems [REFs].

## Compounds Transported by the acI Lineage

All acI clades encode for and express a diverse array of transporters (Figure 5 and Supplementary Table S6). Consistent with the presence of intra- and extra-cellular peptidases, all clades express numerous genes for the transport of peptides and amino acids, including at least one oligopeptide transporter, two branched-chain amino acid transporters, and a transporter for the polyamines spermidine and putrescine. Additionally, clades acI-A and B contain an additional di-peptide transporter, clades acI-A and C contain a transporter for basic amino acids (including lysine, for which acI-C is auxotrophic), and clade acI-A contains a transporter for glycine betaine. All clades also contain a transporter for ammonium. Of these, the ammonium, branched-chain amino acid, polyamine, and oligopeptide transporters are among the most highly expressed in these genomes, often above the 90th percentile of all expressed genes.

All clades also strongly express transporters consistent with the presence of glycoside hydrolases, including a glucoside transporter and transporters for the sugars maltose (a dimer of glucose), xylose, and ribose (both aldopentoses). All three clades also express a transporter for N-acetyl-glucosamine (a derivative of glucose), though this transporter is not expressed as highly as the other saccharide transporters.

The acI lineage also encodes for and expresses a number of transporters which do not have corresponding seed compounds, including transporters for nucleosides, pyrimidines, and the purine derivatives guanine and hypoxanthine. Clades acI-A and B contain a generic purine transporter, as well as a tricarboxylate transporter. With the exception of the purine transporter, these are also all highly expressed. Clade acI-A expresses a transporter for Vitamins B7 (the cofactor biotin), and clades acI-A and C express a transporter for Vitamin B12 (the cofactor cobalamin). Oddly, despite predicted auxotrophies for Vitamins B5 and B6, we were unable to find transporters for these two compounds.

Finally, all three clades express actinorhodopsin, a light-sensitive opsin protein which functions as an outward proton pump [REF]. In all clades, actinorhodopsin is among the top three most highly-expressed genes in that clade (Supplementary Table S10). Given that many of the transport proteins are of the ABC type, we speculate that actinorhodopsin may facilitate maintenance of the proton gradient necessary for ATP synthesis. Coupled with high expression levels of the diverse diverse transporters expressed by acI, this result strongly suggests that acI are photoheterotrophs.

# Discussion

Our predictions of substrate utilization capabilities of the acI lineage are largely congruent with previous studies. We predict that the consumption of N-rich compounds is a universal feature of the acI lineage, with all three clades predicted to consume ammonium, branched-chain amino acids (leucine, isoleucine, and valine), the polyamines spermidine and putrescine, and di- and oligopeptides. Notably, while all three clades contain peptidases which act on di-peptides, only clades acI-A and B contained a transporter for them. However, because our composite acI-C genome was predicted to be incomplete, we cannot state for certain that this transporter is truly absent. Finally, clades acI-A and C contain a transporter for other amino acids, which may act on the amino acids arginine, glutamate, glutamine which have been observed to be taken up in FISH studies.

Furthermore, we confirm the ability of all three clades to consume the five-carbon sugars xylose and ribose, as well as the six-carbon sugar maltose (previously thought to be restricted to clade acI-B). All three clades also contain both a glycoside hydrolase and a transporter capable of acting on alpha-glucosides, and we have also identified a transporter for N-acetylglucosamine. Notably, a transporter for glucose monomers remains undetected. Furthermore, we identify additional hydrolases capable of acting on beta-glucosides, and alpha- and beta-galactosides in clades acI-A and acI-C, enzymes which had previously been detected only in clade acI-A.

We also identified transporters for nucleosides (which may explain observed uptake of thymidine), pyrimidines, and the purine derivatives guanine and hypoxanthine. Clades acI-A and B contain a generic purine transporter, as well as a tricarboxylate transporter. Finally, all clades within the acI contain actinorhodopsin and the complete retinal biosynthesis pathway. The exception seems to be clade acI-C, which is missing the beta-carotene cleavage enzyme which produces retinal.

Our analysis also suggests that auxotrophies for some vitamins may be universal features of the lineage, as we predict all clades to be auxotrophic for Vitamins B5 and B6 (previously, Vitamin B6 had been identified as an auxotrophy for clade acI-B). In addition, we predict transporters for Vitamins B7 and B12 in clade acI-A, but do not predict auxotrophies for these vitamins. In addition, our analysis does not identify Vitamins B2, B3, B9, or B12 as auxotrophies for clade acI-B, a result which had been previously suggested.

Transport proteins for many all of these metabolites were among the most highly expressed in the genomes, suggesting that the success of acI’s passive lifestyle may be due to its ability to consume any substrate in its vicinity, without the need to activate expression of the necessary transport genes. The actinorhodopsin protein is highly expressed, and may facilitate synthesis of the ATP needed to drive acI’s many ABC-type transporters. In the aggregate, these results indicate the acI are photoheterotrophs, making a living on a diverse array of N-rich compounds, sugars, and oligo- and poly-saccharides.

Our analysis also provides new insights into auxotrophies within the acI-C lineage, identifying tetrahydrofolate (THF) as an auxotrophy for clade acI-A, and lysine, homoserine, and UMP as auxotrophies for acI-C. THF is a derivative of folic acid (Vitamin B9), which was previously identified as an auxotrophy for clade acI-B. Additionally, clade acI-B was previously identified as auxotrophic for a number of amino acids, though lysine and homoserine were not among them. In the aggregate, these results provide additional support to the hypothesis that distributed metabolic pathways and metabolic complmentarity may be common features of freshwater bacterial communities (Garcia et al. [2015](#ref-Garcia2015)).

While the reverse ecology pipeline presented here identified aspects of acI metabolism not observed previously, our approach does have some significant limitations. First, because our analysis relied on constructing clade-level composite genomes, we of necessity cannot say anything about the metabolism of individual tribes or interactions between them. And second, metabolic network analysis does account for biological pathway organization, and predicts organisms may synthesize compounds via non-canonical routes. An example is presented in the Supplemental Material. As a result, the pipeline may under-predict the number of auxotrophies for a genome, a limitation which may explain why we failed to predict many suspected auxotrophies for clade acI-B.

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# Conflict of Interest

The authors declare no conflict of interest.

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