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Metabolic evolution and the self-organization of ecosystems

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Metabolism mediates the flow of matter and energy through the biosphere. We examined how metabolic evolution shapes ecosystems by reconstructing it in the globally abundant oceanic phytoplankter Prochlorococcus. To understand what drove observed evolutionary patterns, we interpreted them in the context of its population dynamics, growth rate, and light adaptation, and the size and macromolecular and elemental composition of cells. This multilevel view suggests that, over the course of evolution, there was a steady increase in Prochlorococcus' metabolic rate and excretion of organic carbon. We derived a mathematical framework that suggests these adaptations lower the minimal subsistence nutrient concentration of cells, which results in a drawdown of nutrients in oceanic surface waters. This, in turn, increases total ecosystem biomass and promotes the coevolution of all cells in the ecosystem. Additional reconstructions suggest that Prochlorococcus and the dominant cooccurring heterotrophic bacterium SAR11 form a coevolved mutualism that maximizes their collective metabolic rate by recycling organic carbon through complementary excretion and uptake pathways. Moreover, the metabolic codelpendencies of Prochlorococcus and SAR11 are highly similar to those of chloroplasts and mitochondria within plant cells. These observations lead us to propose a general theory relating metabolic evolution to the self-amplification and self-organization of the biosphere. We discuss the implications of this framework for the evolution of Earth's biogeochemical cycles and the rise of atmospheric oxygen.

**Results and Discussion**

Metabolism Provides Clues About Large-Scale Evolutionary Driving Forces. To examine the driving forces shaping the evolution of Prochlorococcus, we reconstructed (Fig. 2) the evolution of its metabolic core (\textsuperscript{SI} Appendix, Fig. S1). Because all biosynthetic pathways originate there, its evolution is highly constrained, and any innovations likely reflect major driving forces (5). Previous studies identified some unique presence/absence patterns for core metabolic genes in both Prochlorococcus and Synechococcus and relative to other cyanobacteria. For example, both have replaced the cyanobacterial RuBisCO and related proteins of the CO\textsubscript{2}-concentrating mechanism with proteobacterial variants (17–19), lost key genes in the cyanobacterial TCA cycle (20) and glycolysis (21), and acquired a menaquinone-based malate dehydrogenase (22). Photosynthesis proteins are, in turn, universally preserved in Synechococcus, but unevenly distributed across Prochlorococcus ecotypes (9, 23).

Expanding on these studies, we surveyed cyanobacteria for the presence/absence of core metabolic genes (\textsuperscript{SI} Appendix, Table S1 and Fig. S1) and mapped this distribution onto their phylogeny to reconstruct a phylometabolic tree (Fig. 2) that resolves the evolution of Synechococcus and Prochlorococcus (Fig. 1). All of the variations are part of a sequence of innovations that remodeled the metabolic core as Prochlorococcus diverged from the rest of cyanobacteria (Fig. 3). Key innovations occur in ancestral freshwater lineages (Fig. 3 and \textsuperscript{SI} Appendix, Table S1), indicating that underlying selection pressures preceded the emergence of the marine lineages.

**Significance**

Understanding what drives self-organization in complex systems and how it arises is a major challenge. We addressed this challenge using dominant oceanic photosynthetic and heterotrophic microbes as a model system. Reconstructing the metabolic evolution of this system suggests that its self-organization and self-amplification were coupled and driven by an increasing cellular energy flux. Specifically, the evolution of cells steadily increased their metabolic rate and excretion of organic carbon. We describe how this increases cellular nutrient uptake and thereby ecosystem biomass. The release of organic carbon, in turn, promotes positive feedbacks among species that reinforce this evolutionary drive at the ecosystem level. We propose the evolutionary self-organization of oceanic microbial ecosystems contributed to the oxygenation of Earth.

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Typical relative abundance distributions of *Prochlorococcus* ecotypes as a function of depth and accompanying light intensity and nutrient concentration profiles in stratified oceanic waters. Ecotype populations are geographically and temporally dynamic, but in warm, stable water columns return to this same depth-differentiated state (12). The deepest branching ecotypes are most abundant at the bottom of the euphotic zone, where nutrient concentrations are high and light energy low. The most recently diverging ecotypes are most abundant near the surface, where the reverse is true (10–14). HL, high-light-adapted; LL, low-light-adapted.

The remodeling of *Prochlorococcus*’ metabolic core includes the disruption of photospiration and the TCA cycle (Fig. 3 and SI Appendix, Fig. S1), raising the possibility that intermediates of truncated pathways are excreted from the cell. Photoplankton commonly excrete organic carbon as an outlet of excess reducing power under nutrient limitation or intense light (24). Analogously, when facing a large energy supply from organic carbon, some heterotrophs will effectively drain reducing power into the environment by excreting partially oxidized organic carbon rather than fully oxidizing it to CO$_2$ (25–28), whereas some photoheterotrophs use CO$_2$-fixation as a sink for excess reducing power (29). For photosynthetic cells in the oligotrophic surface oceans, where the solar energy supply may commonly outpace the nutrient supply (Fig. 1), the combination of increased CO$_2$-fixation and increased excretion of organic carbon could thus well be under strong selection. This is consistent with observations that *Prochlorococcus* has the most efficient carbon-concentrating mechanism (30) and highest known rate of CO$_2$-fixation per photosynthetic pigment (31) of any photoplankton, even though its small size and slow growth (6, 32) suggest a relatively small carbon flux requirement. Lastly, selection to rid the system of excess reducing power is consistent with the acquisition of the Plastoquinol Terminal Oxidase (PTOX) in the LLI and HL clades of *Prochlorococcus* (Fig. 3 and SI Appendix, Table S1), which adds an additional outlet for excess reducing power in their photosynthetic electron transfer chain (SI Appendix, Fig. S1) (33–36).

That the evolution of *Prochlorococcus* permanently increased the excretion of organic carbon in its late-branching strains is also consistent with limited laboratory observations. At moderate light levels in nutrient replete medium, strains from HL clades that dominate surface waters (Fig. 1) excrete up to 30% of fixed carbon, and recently diverging strains excrete the most (37). Cells excrete significant amounts of glycolate (37), one of the dead ends in the metabolic network (SI Appendix, Fig. S1). P-starved cells excrete slightly less carbon (37), but this could be due to the coincident cessation of growth. Nevertheless, a higher fraction of the carbon excreted by P-starved cells consists of glycolate and other small carboxylic acids (37). Many photoplankton excrete glycolate under intense light or nutrient limitation (24, 38), but retain the capacity to recycle it by using the three-subunit iron–sulfur protein glycolate oxidase (GlcDEF, rxn 13 in SI Appendix, Fig. S1), shown to be the enzymatic workhorse for this function in cyanobacteria (23). However, this gene is absent in all but the deepest-branching LLIV clade of *Prochlorococcus* (SI Appendix, Table S1), suggesting a permanent opening of this pathway early in its evolution (Fig. 3). Finally, the bulk of organic carbon excreted by *Synechococcus* consists of polysaccharides (39), which are commonly excreted by nutrient-limited microbes (26, 40), suggesting that these compounds could similarly act as a redox safety valve in *Prochlorococcus*, which dominates in one of the most nutrient-poor environments on Earth (7–9) (Fig. 1).

We further examined the possibility that the evolution of *Prochlorococcus* increased its excretion of organic carbon as an outlet of excess reducing power (Fig. 3) through additional genomic analyses. Functionally related and coexpressed genes are commonly located near each other, so we searched the genomic neighborhoods of core metabolic genes for transporters across clades (SI Appendix, Fig. S2). We identified chromosome rearrangements repositioning a series of transporters, including three export and one import transporters, near key metabolic genes, consistent with selection acting to fortify the control of transport pathways (SI Appendix, Fig. S2). Chromosome rearrangements are seen in freshwater picocyanobacteria (SI Appendix, Fig. S2), again suggesting that these pathways came under selection before the emergence of the marine lineages and the loss of photospiration in the LLI/III clade of *Prochlorococcus* (Fig. 3 and SI Appendix, Fig. S1). This analysis suggests that, in addition to glycolate, pyruvate and citrate (or isocitrate) are exported, whereas malate is imported (SI Appendix, Figs. S1 and S2).

Furthermore, because environmentally driven variations in the expression of genes can give insight into their function [i.e., “reverse ecology” (41)], and the metabolism of *Prochlorococcus* is highly choreographed to the diel light:dark cycle (42, 43), we examined the gene expression of a HL-adapted strain grown in the LLII/III clade of *Prochlorococcus* (Fig. 3 and SI Appendix, Table S1). This analysis suggests that, in addition to glycolate, pyruvate and citrate (or isocitrate) are exported, whereas malate is imported (SI Appendix, Figs. S1 and S2).

![Fig. 2. Illustration of approach to metabolic reconstructions. Phylogenetic trees reflect the evolution of metabolic network phenotypes because they integrate constraints from phylogenetics and metabolism (15, 16). All sequenced genomes within a given clade are searched for the presence/absence of enzymes catalyzing the reactions of different pathways. Mapping pathway variability patterns onto phylogenies of the clade suggests the order of metabolic innovations. In this example, three alternative pathways (pink, yellow, and blue) connect essential and universal pathways (black). Genes for the yellow pathway are nearly universally distributed (Inset), suggesting that it is the ancestral pathway, with the pink and blue pathways deriving from it. Maintaining continuity of flux results in trees of functional phenotypes. Biochemical differences between alternative pathways (e.g., ATP/trace metal requirements or oxygen sensitivities of their enzymes) suggest evolutionary driving forces](https://www.pnas.org/doi/10.1073/pnas.1619573114)
invoking cross-feeding interactions to explain excretion of organic carbon by Prochlorococcus is problematic, however, because in unstructured populations typical of oceanic microboros, the apparent cost of fixing and excreting carbon leads to a “public goods” dilemma: Nonproducer cells that avoid the cost of production would outcompete producer cells and suppress cross-feeding (48). Direct benefits for the excretion of organic carbon by individual Prochlorococcus cells are therefore needed to explain cross-feeding interactions. Benefits of excreting organic carbon hypothesized for aerobic heterotrophs (26, 49–51) provide relevant clues, but do not fully translate to Prochlorococcus evolution (see SI Appendix, SI Text for further discussion).

Integrating Evidence Across Levels of Organization Suggests a Unifying View of Evolution in Prochlorococcus. To gain a better understanding of the evolution of Prochlorococcus, we mapped observations of its metabolism (Fig. 3 and SI Appendix, Fig. S1) onto its population structure (Fig. 1), growth and light physiology, and the macroalomorphic and elemental composition of cells. This suggests two evolutionary trends. First, in stable water columns, more recently diverged (HL) ecotypes experience a higher photosynthetic electron flux density [\(\mu\text{mol electrons (g dry weight)}^{-1}\text{time}^{-1}\)], which can be parameterized as:

\[
\nu_e = I_{\text{PSII}}\Phi_{\text{PSII}},
\]

where \(I\) is light intensity (\(\mu\text{mol photons m}^{-2}\text{time}^{-1}\)), \(\sigma_{\text{PSII}}\) is the mass-normalized whole-cell photosystem II absorption cross-section \([\text{m}^2\text{of PSII (g dry weight)}^{-1}]\), and \(\Phi_{\text{PSII}}\) is the quantum efficiency of PSII (electrons photon\(^{-1}\)). An increase in the cellular electron flux density along the Prochlorococcus phylogeny is suggested most obviously by the layering of the relative abundance of its ecotypes that emerges when the water column stratifies after a mixing event in the open ocean (Fig. 1), with the HL cells always dominating the surface waters (10–14). However, \(\sigma_{\text{PSII}}\) also increases along the phylogeny, suggesting that more recently diverging strains also experience an increased electron flux at a given light level. This increase in \(\sigma_{\text{PSII}}\) is manifested in changes in the pigments (6, 9, 54, 55) and stoichiometry (56, 57) of the photosystems (Fig. 3 and SI Appendix, Fig. S1). These changes largely relinquish absorption of green and yellow light, but maintain or increase absorption of blue light—typifying the open ocean— in Prochlorococcus relative to Synechococcus (32, 58). At the same time Prochlorococcus is significantly smaller than Synechococcus (6), and cell mass decreases along its phylogeny (59), thus suggesting an increase in the mass-normalized absorption cross-section \(\sigma_{\text{PSII}}\). Fewer comparative studies exist for the quantum efficiency of PSII (\(\Phi_{\text{PSII}}\)) but it appears to be roughly similar along the Prochlorococcus phylogeny (57). The increasing excretion of organic carbon by Prochlorococcus thus appears to reflect a more general trend that increases the total cellular throughput of electrons (Fig. 3). Various genes related to the protection and repair of light damage have been added in HL clades of Prochlorococcus (52, 53), suggesting that later divergences were primarily related to fortifying cellular machinery to allow cells to generate an increased electron flux at the highest photon fluxes near the surface (Fig. 3).

In addition to an increasing electron flux density (\(\nu_e\)), integrating evidence across levels suggests the evolution of Prochlorococcus also decreased its limiting nutrient flux density, \(\nu_n\), [mole of \(n\) (g dry weight)\(^{-1}\text{time}^{-1}\)]. For steady-state growth under constant conditions, \(\nu_n\) can be parameterized as:

\[
\nu_n = \mu Q_n,
\]

where \(\mu\) is the specific growth rate (time\(^{-1}\)) and \(Q_n\) is the mass-normalized cellular quota of limiting nutrients [mole of \(n\) (g dry weight)\(^{-1}\)]. A decreasing nutrient flux density along the evolution of Prochlorococcus is suggested by a decrease in its maximal intrinsic growth rate \(\mu_{\text{max}}\) (time\(^{-1}\)) relative to Synechococcus.
(32) and an increased efficiency in its use of limiting nutrients. The latter is inferred from many features of Prochlorococcus, including less investment of N and P in the genome by reducing its size and guanine–cytosine content (60), decreased use of amino acids with N-rich side chains (61), a switch from \( P \)-to sullolipid membranes (62, 63), and less Fc use in metabolism and photosynthetic machinery (33, 34) (SI Appendix, Fig. S1). These changes suggest a decreasing \( Q_s \) for N, Fe, and P, the three main limiting nutrients in the oligotrophic oceans (64). An increasing \( \nu_e \) coinciding with a decreasing \( \nu_o \) over the course of Prochlorococcus evolution can be expressed as a single variable: the electron-to-nutrient flux ratio, \( \nu_e/\nu_o \) (Fig. 3).

**Electron Flux and Nutrient Acquisition.** What are the selective pressures maximizing \( \nu_e/\nu_o \), in Prochlorococcus? Photosynthetic electron flux transfers solar energy into metabolism via cofactors such ATP and NAD(P)H (65). An increased electron flux \( [\mu \text{mol electrons (g dry weight) }^{-1} \text{ time}^{-1}] \) thus suggests an increased metabolic rate \( [\text{kJ of absorbed solar energy} (\text{g dry weight})]^{-1} \text{ time}^{-1}] \). This principle is exemplified by the increasing metabolic activity and ATP/ADP ratios of plant chloroplasts and cyanobacteria when they shift from darkness into light (66, 67). Furthermore, the highest \( \nu_e/\nu_o \) phenotypes are the most recently diverging clades (Fig. 3), dominating near the surface where the solar energy supply is greatest and nutrient levels are lowest (Fig. 1), suggesting an advantage to higher metabolic rates at lower nutrient concentrations.

How metabolic rate affects nutrient uptake can be understood from Michaelis–Menten kinetics, which under strong nutrient limitation \( [\bar{n}] \ll K_{M,n} \) simplifies to (68) (SI Appendix, SI Text):

\[
\nu_o = [n] a_0^e = V_{max} [n] / K_{M,n},
\]

where \( [n] \) is the nutrient concentration (moles of \( n \) \( \text{L}^{-1} \)) and \( a_0^e \) is the specific nutrient affinity \( [L \text{ (g dry weight)}^{-1} \text{ time}^{-1}] \). Specific affinity indicates how strongly cells absorb limiting nutrients (analogous to the pumping speed of a vacuum pump) and is equivalent to the saturated maximal nutrient uptake rate \( V_{max} \) [moles of \( n \) (g dry weight)] \( \text{time}^{-1} \text{ L}^{-1} \) over the Michaelis constant \( K_{M,n} \) (moles of \( n \) \( \text{L}^{-1} \)) (68) (SI Appendix, Fig. S3). \( V_{max} \) reflects the maximum handling rate for absorbed nutrients and is proportional to the metabolic rate (68, 69). The electron energy cost \( \Delta_{e}G \) (kJ \( \text{mol}^{-1} \)) of nutrient transport scales with natural log of the ratio of internal to external nutrient concentrations (65) (SI Appendix, SI Text) and can become very large in the extremely nutrient-poor oligotrophic oceans (69). For example, the free energy cost of phosphate uptake in the oligotrophic oceans is far greater than the free energy gain of ATP hydrolysis unless the ATP/(ADP \( \times \) P) ratio is increased drastically from commonly assumed metabolite concentrations of 1 mM for ATP, ADP, and P\( _i \) (SI Appendix, SI Text). An analogous, but slightly different, situation occurs for ammonia (\( NH_4^+ \)) uptake, which has the potential for a major futile cycle in the oligotrophic ocean, because its conjugate base \( NH_3 \) passively diffuses out of the cell (70) (SI Appendix, SI Text). It is therefore thought that cells poise their internal \( [NH_4^+] \) at the minimal viable value (71), which in turn similarly requires a significant increase in the ATP/(ADP \( \times \) P\( _i \)) ratio to drive forward glutamine synthesis (glutamate + \( NH_3 \) + ATP \( \rightarrow \) glutamine + ADP + P\( _i \)), the central highway for nitrogen into metabolism (65). (See SI Appendix, SI Text for detailed calculations and discussion.) Finally, while kinetic bottleneck reactions can be driven forward by increasing the ATP/(ADP \( \times \) P\( _i \)) ratio, this simultaneously increases the free energy cost of ATP synthesis, therefore requiring a greater proton motive force, and thus ultimately a greater photosynthetic electron flux (69).

The principles just outlined suggest that innovations increasing \( \nu_e \) may lower the minimal subsistence concentration of limiting nutrients \( [n]^* \) (the lowest value of \( [n] \) at which net positive growth is possible). When growth and loss processes are relatively rapid and tightly coupled, microbial strains with the lowest \( [n]^* \) dominate (72), suggesting that selection should favor such innovations. To understand how lower \( [n]^* \) shapes cells, we can substitute an expression for \( V_{max} \) that assumes reversible kinetics (SI Appendix, SI Text) into Eq. 3:

\[
[n] = \frac{K_{M,n}}{V_{max} \nu_o} = \frac{K_{M,n}}{[\bar{E}] [k^+ 1 - e^{-\Delta_{\sigma_e} / R T}]},
\]

where \( [\bar{E}] \) is the enzyme concentration [moles of enzyme (g dry weight)] \( -1 \text{ time}^{-1} \), \( k^+ \) is the rate constant [moles of \( n \) (moles of enzyme)] \( -1 \text{ time}^{-1} \), \( R \) is the gas constant \((J \text{ K}^{-1} \text{ mol}^{-1})\), and \( T \) is temperature (K). Eq. 4 suggests that there are two strategies for lowering \( [n] \) (SI Appendix, Fig. S3). First, cells can modify the kinetics (decreasing \( K_{M,n} \) and/or increasing \( k^+ \), \([\bar{E}]\) ) and thermodynamics (decreasing \( \Delta_{\sigma_e} \) ) of their metabolism, the latter by increasing \( \nu_e \) as we have just argued. Second, cells can lower their \( [n]^* \) by lowering their required flux of limiting nutrients \( \nu_o \) (Eq. 4), which can be achieved by lowering their minimal \( Q_s \) (i.e., streamlining (73)) or their \( \mu \) (Eq. 2), both of which are apparent in the evolution of Prochlorococcus as discussed above. Optimizing kinetics/thermodynamics and decreasing \( \nu_o \) can work synergistically, and both are helped by a decrease in cell mass, as is observed along the Prochlorococcus phylogeny (6, 59). That is, selection to lower \( \nu_o \) allows a decrease in total cell mass by minimizing the mass dedicated to nonessential components (73). If the amount of metabolic enzyme and photosynthetic machinery is kept fixed, this decrease in total cell mass would increase both \( [\bar{E}] \) (68) and \( \sigma_{\text{PSII}} \) (and thus \( \nu_e \), which makes \( \Delta_{\sigma_e} \) more negative). For nitrogen, increasing \( \nu_e \) in turn provides an additional avenue for lowering \( Q_s \) (and thus \( \nu_o \)), because pathways with a more negative \( \Delta_{\sigma_e} \) require less protein biomass for a given flux (74). Thus, maximizing \( \nu_e/\nu_o \) lowers the \( [n]^* \) of cells by making the \( \Delta_{\sigma_e} \) more negative (driving kinetic bottleneck reactions forward), thereby increasing the nutrient affinity (68, 69). As a result, the evolution of Prochlorococcus has driven nutrients to vanishingly low levels (<0.1 nM) in the oligotrophic oceans (64).

**Benefits of Excreting Organic Carbon.** If selection to lower \( [n]^* \) drives the maximization of \( \nu_e/\nu_o \), why should it lead to an increased excretion of organic carbon? We argue this ultimately emerges from mass and energy conservation. That is, in the presence of kinetic bottlenecks, cells can drive up their ATP/ADP ratio by increasing their ATP/ADP supply rate, but to maintain steady state, they must also increase ATP consumption rates (49, 69). The same argument applies to the NAD(P)H/NAD(P) ratio. This is consistent with observations that some nutrient-limited aerobic chemoheterotrophs have increased glucose uptake rates, increased levels of respiration, increased excretion of polysaccharides (whose synthesis from glucose requires ATP consumption), and a high flux through various ATP-consuming futile cycles (25, 26, 49). For photosynthetic cells CO\(_2\)-fixation is a major sink for ATP and NAD(P)H, but cells are limited in the carbon flux density, \( \nu_C \), they can accommodate. This limit is proportional to growth rate (Eq. 2), and, because selection to lower \( [n]^* \) favors relatively slow-growing cells (Eq. 4), it is lower in the oligotrophic oceans. Thus, we argue that excreted organic carbon represents a kind of “carbon exhaust” that allows cells to maximize their nutrient affinity by increasing their metabolic rate above limits arising from carbon saturation.

This general mechanism is further illustrated by expanding Eq. 4. We assume that the electron flux must support carbon fixation sufficient to build biomass at a rate dictated by \( \nu_o \), that biomass has an elemental stoichiometry \( Q_{\text{C}}/Q_{\text{C}} \), that the efficiency of fixation is \#C/#e (carbon atoms electron\(^{-1}\)), and that a fraction \((0<\delta<1)\) of carbon is excreted/respired. \#C/#e depends on the oxidation states of the carbon source, biomass, and excreted carbon. For example, if the carbon source is CO\(_2\) and biomass and excreted carbon have the oxidation state CH\(_2\)O, then \#C/#e is 1/4 (i.e., CO\(_2\) + 4e\(^-\) + 4H\(^+\) \( \rightarrow \) CH\(_2\)O + ...
H₂O). Photoprotective mechanisms like the water–water cycle of POTOX (SI Appendix, Fig. S1) act to lower #C/#c. Together, these assumptions lead to the expression (see also SI Appendix, SI Text):

\[
[n] = \frac{K_{M,n}}{[E]^{[k]}} \frac{\nu_n}{1 - e^{-\Delta G/RT}} = \frac{K_{M,n} Q_n \nu_n (\#C/\#e)(1 - \beta)}{[E]^{[k] + Q_C}} \frac{1}{1 - e^{-\Delta G/RT}}.
\]

Thus, while increasing metabolic rate (i.e., lowering \(\Delta G\)) lowers \([n]\), it also acts to increase \([n]\) by increasing the carbon flux density, unless excess carbon is excreted \((\beta > 0)\) and increasing faster than \(\nu_e(\#C/#e)\) (Eq. 5). Selection to lower \([n]\) would thus favor a decrease in \(\nu_e\) and simultaneous increases in \(\nu_e\) (carbon excretion), exactly as we observed for the evolution of Prochlorococcus (Fig. 3).

### Metabolic Rate, Ecosystem Biomass, and Coevolutionary Dynamics.

What are the evolutionary and ecological consequences of Eq. 5? Focusing on the evolution of Prochlorococcus, it suggests that the layered population structure observed in stable water columns (Fig. 1) (10–14) reflects the sequential evolution of new ecotypes near the surface, each with increasing metabolic rates, drawing down limiting nutrients and restricting ancestral ecotypes to ever deeper waters (Fig. 4). This type of evolutionary dynamic in which a key innovation causes a population to expand along a shifted adaptive landscape produces adaptive radiations (75, 76) and has been argued to be the dominant contributor to global microbial diversity (77). This is consistent with observations that the broadly defined ecotypes of Prochlorococcus consist of hundreds of stable subpopulations that diverged millions of years ago (78). These are “niche constructing” adaptive radiations, since the shift in the adaptive landscape arises because new ecotypes chemically modify their own environment (Fig. 4) (79). Subpopulations form clusters defined by the acquisition of small cassettes of genes involved in electron transfer, redox stress, and/or synthesis of membrane polysaccharides (78). Increased production of the latter is a recognized outlet of excess reducing power (25, 26, 40). In addition to providing an electron sink, membrane polysaccharides also mediate biological interactions (e.g., with phage, grazers, or other bacteria), suggesting that an increase in electron flux could have produced ecological feedbacks that drove further differentiation within Prochlorococcus ecotypes (78) and in those with which it interacts (80). Lastly, this framework suggests that by promoting the fixation and excretion of increasing amounts of organic carbon as a by-product of increasing the nutrient affinity, the evolution of Prochlorococcus increased the long-term steady-state concentrations of dissolved organic carbon (DOC) in the oligotrophic oceans (Fig. 4), which are much higher (by a factor of up to ~2) than in the ocean (81). Because several compounds that Prochlorococcus may be excreting are known iron-binding ligands, including polysaccharides (82) and carboxylic acids like citrate (83), it may, in turn, also play a key role in buffering trace metal bioavailability in these environments.

When extended to the ecosystem level, Eq. 5 provides a mechanistic view of how the evolution of all microbial cells in the open ocean is interconnected via the chemically coevolving environment (79, 84): Any innovation in any lineage that increases the energy flux and lowers nutrient concentrations (Fig. 4) pushes all other lineages to follow suit and adopt similar innovations. Unlike in the classic “Red Queen hypothesis,” in which evolution is a zero-sum game (85), here, the evolutionary dynamic increases resource capture, and thereby biomass, of the ecosystem. [Similarly, a paleontological survey of the distribution and body size of marine animals also led to the conclusion that the energy flux and biomass of ecosystems increases over evolutionary time (86).] The imprint of this collective dynamic can be seen in the broadly convergent features of all oceanic microbes. Slow growth, small cell size, streamlined genomes and proteomes, and use of nonphospholipid membranes—signature features of Prochlorococcus—are observed across both autotrophic and heterotrophic microbes in the oligotrophic oceans (61, 73, 87–89). Some of the photosynthetic machinery modifications that increased the electron flux of Prochlorococcus (Fig. 3) are also seen in diatoms and picoeukaryotes (33, 90, 91). Many oceanic heterotrophs in turn supplement their energy supply from organics by capturing sunlight with proteorhodopsin (92) and possess electron drains in their respiratory electron transfer chains (93). In general, heterotrophic growth in the oligotrophic oceans favors metabolic rate over efficiency—the fraction of carbon taken up from the environment that is converted into biomass is one of the lowest of any aquatic environment on Earth (94). These observations are all consistent with the notion that the maximization of \(\nu_e/\nu_{r*e}\) and thereby a lowering of steady-state nutrient concentrations (Eq. 5 and Fig. 4), has been a general evolutionary driving force in ocean ecosystems.

### Emergence of Mutualism in Oceanic Microbial Ecosystems.

Finally, if lowering \([n]\) increases the excretion of organic carbon into the environment, it could produce new opportunities for cooccurring heterotrophs, like the ubiquitous and abundant SAR11 (73, 95). SAR11 requires pyruvate and either glycolate, glycine, serine, or glyoxylate (96); the latter four all feed into the same pathway that starts from glycolate (96). Furthermore, coastal SAR11 strains can replace pyruvate with glucose metabolized via glycolysis, whereas open ocean strains lack glycolysis and have an obligate requirement for pyruvate (97). Similar adaptations are not observed in freshwater strains of SAR11 (98). Thus, oceanic SAR11 populations have evolved a dependency on exactly the compounds (pyruvate and glycolate) that our metabolic reconstructions suggest emerged as excretion pathways in Prochlorococcus (Fig. 3 and SI Appendix, Fig. S1).

We mapped the distribution of metabolic genes across clades (SI Appendix, Table S2) onto the phylogeny of marine SAR11 clades to further reconstruct the evolution of their metabolic core (96–98) (Fig. 5 and SI Appendix, Fig. S4). We aimed to resolve the innovations of open ocean lineages and look for evidence of selection on pathway controls by looking for transporters in the vicinity of metabolic genes. As in Prochlorococcus (Fig. 3 and SI Appendix, Table S1), the metabolic core of SAR11 (SI Appendix, Fig. S4) evolved through a sequence of innovations (Fig. 5 and SI Appendix, Table S2), including the step-wise completion of the glyoxylate shunt and the well-documented switch
from Emden–Meyerhoff–Parness (EMP) to Entner–Doudoroff (ED) glycolysis (97). Glycolysis is disrupted in the IA clade (97) (Fig. 5 and SI Appendix, Table S2), which is most abundant in surface waters where the Prochlorococcus HLL II clade dominates (Fig. 1) (99, 100). Glycolate uptake is also lost in this SAR11 clade (Fig. 5 and SI Appendix, Table S2), which suggests that pyruvate produced by the Prochlorococcus HLL II ecotype may have become its central source of carbon and energy (97).

Finally, similar to Prochlorococcus (SI Appendix, Fig. S2), chromosome rearrangements positioned a series of transporter proteins near key metabolic genes in SAR11 (SI Appendix, Fig. S5), consistent with selection on the control of transport pathways. We identified putative import transporters for pyruvate and glycolate, and putative export transporters for citrate and malate, the latter exclusive to the IA clade (Fig. 5 and SI Appendix, Fig. S5). The emergence of malate export in SAR11 would provide a potential source for the emergent malate uptake pathway of Prochlorococcus that is putatively activated at night (Fig. 3 and SI Appendix, Figs. S1 and S2).

Furthermore, the glyoxylate shunt is a TCA cycle bypass activated under redox stress in some microbes (101–103), while the evolutionary switch from EMP to the higher-rate ED variant of glycolysis has, in other microbes, been attributed to an increased energy supply (74). These observations are consistent with selection acting to maximize \( \nu_e/\nu_n \) in both systems and thereby producing pathways that transfer pyruvate and glycolate from Prochlorococcus to SAR11 and malate from SAR11 to Prochlorococcus. Oligotrophic waters have nanomolar concentrations of pyruvate and glycolate, with midday maxima for the latter, consistent with biological cross-feeding synchronized with the input of sunlight, although abiotic photochemistry may also contribute (104, 105).

Additional evidence for metabolic mutualism in these systems comes from observations regarding hydrogen peroxide (HOOH), a by-product of biological electron transport, photochemistry, and other abiotic processes (106). Prochlorococcus and some later-diverging clades of SAR11 have lost HOOH-detecting catalase (SI Appendix, Tables S1 and S2), and Prochlorococcus grows better in the presence of bacteria retaining catalase (107, 108). This led to the “Black Queen” hypothesis, which argues that subpopulations of ecosystems can save essential nutrients by giving up inevitably shared functions (such as detoxifying the freely diffusible HOOH), so long as they are preserved by others in the ecosystem (109). Our reconstructions suggest that the loss of catalase in Prochlorococcus and SAR11 coincides with increased excretion of organic carbon, which provides carbon and energy for catalase-containing bacteria (109).

These observations suggest that metabolic mutualisms are self-amplifying feedback loops (110) that maximize the collective \( \nu_e/\nu_n \) and thus total productivity, of ecosystems. Specifically, recycling otherwise wasted electrons through complementary excretion/uptake pathways increases the average \( \nu_e \) of participating cells. Similarly, the loss of functions that are shared and require limiting nutrients (e.g., iron in catalase) in some members of the community decreases the average \( \nu_n \). Mutualisms thus raise the \( \nu_e/\nu_n \) of ecosystems—and lower the subsistence nutrient requirements of their cells (Eq. 5 and Fig. 4)—beyond what is possible for individual lineages in isolation. Because excreting organic carbon lowers the minimal subsistence nutrient requirements of individual cells, mutualisms of this kind are emergent properties of ecosystems and avoid public goods dilemmas (48). An upper bound may exist on the maximization of \( \nu_e/\nu_n \) due to the minimal requirements of being an autonomous cell. As the smallest photosynthetic cell (6), Prochlorococcus may be closest to this limit, reinforcing the notion that it has a central role in shaping the features of ecosystems in the surface oceans.

Are Plant Cells Microscopic Analogues of Oceanic Microbial Ecosystems? It occurred to us that the metabolic organization of oceanic microbial cells and green plant cells is similar (Fig. 6): Intermediate of lower glycolysis and photorespiration are central conduits of electron transfer from Prochlorococcus to SAR11 and from chloroplasts to mitochondria in plant cells, while TCA cycle intermediates facilitate electron transfer in the opposite direction in both systems (111–113). Similar patterns emerge at other levels of organization. Microbes other than Prochlorococcus/SAR11 in ocean communities, and organelles other than chloroplasts/mitochondria in plant cells, appear central to peroxide detoxification (108, 115). The heterotrophic bacteria SAR86 and SAR116 may be important for this function in the oligotrophic oceans, because they both possess catalase (114–116) and are abundant in warm stratified waters (117). Prochlorococcus and chloroplasts both have PTOX as an electron drain in their photosynthetic electron transfer chain, whereas SAR11 and mitochondria both have alternative oxidase (AOX) as an electron drain in their respiratory electron transfer chain (93, 113). Furthermore, like chloroplasts, Prochlorococcus uses chlorophyll \( b \) in addition to chlorophyll \( a \), which has not been observed in cyanobacteria other than Prochloron and Prochlorotrix (6). Finally, organelles of plant cells have also undergone reductive genome evolution, and, for mitochondria, it has been argued that this increased the cellular power density of eukaryotes (118)—similar to what we argued for oceanic microbial ecosystems. The extensive convergence of plant cells and oceanic microbial ecosystems highlights the constraints that metabolism imposes on the large-scale structure of evolution (5) and suggests that the metabolic codependencies of eukaryotic organelles can evolve without the physical intimacy of endosymbiosis.

Biospheric Self-Amplification and the Rise of Atmospheric Oxygen. We have proposed that maximizing the metabolic rate of cells lowers their minimal subsistence nutrient requirements and that this is achieved by maximizing the cellular electron-to-nutrient flux ratio (\( \nu_e/\nu_n \)), while increasing the excretion of organic carbon (Eq. 5). This leads to an evolutionary dynamic that increases total ecosystem biomass (Fig. 4) and paves the way for self-amplifying feedback loops that recycle organic carbon (Fig. 6) and reinforce the maximization of cellular metabolic rate at the ecosystem level. It has been argued that the hierarchical organization of pathways within metabolism reflects the outgrowth of self-amplifying feedbacks that increased the free energy consumption of the emerging biosphere (5, 119). Our framework extends those arguments into the world of phenotypically differentiated cells and microbial ecosystems, and is consistent with the theorem that the flow of energy through the biosphere promotes its self-organization into chemical cycles (2).
Our framework has implications for Earth history. If biotic self-amplification driven by the sun enhanced the burial of organics and carbonates (129, 121) simply by increasing their production, it would help explain the drawdown of atmospheric CO$_2$ and the rise of atmospheric O$_2$ across several stages of Earth history (122, 123). Perhaps not coincidentally, marine picocyanobacteria are estimated to have emerged near the transition from the Neoproterozoic (1,000–541 Ma) to the Phanerozoic (541 Ma to present) (124, 125), when sediments indicate the occurrence of global glaciations (126, 127), global carbon cycle perturbations (128–130), enhanced organic carbon burial (120, 121), and a second major rise in atmospheric O$_2$ toward modern levels (123, 131–133).

The proposed evolutionary dynamic (Fig. 4) may provide insights into the Neoproterozoic–Phanerozoic rise in atmospheric oxygen. It has been argued that after the Great Oxidation Event (GOE) the deep Proterozoic oceans remained largely anoxic and euvicnic (rich in H$_2$S) (134). Recent studies support anoxia, but suggest that the Proterozoic oceans were instead largely ferruginous (rich in Fe$^{2+}$), with euxinia restricted to productive continental margins (135–137). It was argued this general redox structure persisted because of N/Mo limitation (138, 139), with Mo scavenged by H$_2$S even with only limited global euxinia (137), and P limitation due to its scavenging by abundant Fe$^{2+}$ (140). We suggest an additional negative feedback involving iron, the most widely used metal cofactor for biological electron transfer (141). The free O$_2$ produced during the rise of oxygenic photosynthesis transformed iron from its soluble Fe$^{2+}$ form into its insoluble Fe$^{3+}$ form (142), effectively causing early oxygenic photosynthesizers to self-limit their expansion in the global oceans by locally extinguishing available iron. Extant oceanic microbes surmount this negative feedback on photosynthetic electron transfer through reduced cellular Fe demands (33, 90, 91) (SI Appendix, Fig. S1), and through Fe-ligation by DOC (143), including polysaccharides (82), citrate (83), and other carboxylic acids, all of which may be excreted by marine picocyanobacteria (37, 39) (SI Appendix, Fig. S1). Polysaccharides and small carboxylic acids also enhance the dissolution of minerals (144), and minerals in wind-blown dust are a major source of Fe (145) and P (146) to the surface oceans. Thus, we hypothesize that the evolution of marine picocyanobacteria (Fig. 4) increased both the bioavailability and the overall supply of iron under aerobic conditions and helped transform the oceans from an anoxic state rich in free iron (135, 136) to an oxygenated state (131, 133) with DOC-bound iron. This positive iron feedback, in contrast to the negative metabolic rate, was critical in pushing the marine biosphere past a major evolutionary bottleneck and paved the way for an expansion of oceanic oxygenic photosynthesis and a rise in atmospheric O$_2$ (123).

Sedimentary and genomic records suggest several additional positive feedbacks that could have pushed forth the Phanerozoic oxygenation of the ocean. Increased Fe bioavailability under aerobic conditions coinciding with the drawdown of nitrogen (Fig. 4) would have created opportunities for N$_2$-fixers, while ocean oxidation would have lifted their Mo-limitation by suppressing euxinia (137, 138), together increasing the supply of nitrogen to the oceans (124, 138, 139). This is consistent with the suggested overlap in the rise of marine picocyanobacteria and planktonic N$_2$-fixers (124, 125). Furthermore, sediments suggest an increase in oceanic P levels after the Neoproterozoic, and it was argued that this was because a drop in Fe$^{2+}$ concentrations lessened the scavenging of P (140). We add that if enhanced DOC-dissolution of minerals from dust enhanced the oceanic iron supply under aerobic conditions, as we argued above, it could have also increased the P supply (146), thus contributing to the reconstructed rise in P levels (140).

These scenarios are similar to those of how the rise of land plants impacted the Earth system. Nutrient-limited plants leach Fe, P, and other nutrients from rocks by excreting small carboxylic acids from their roots (which suggests an increased metabolic rate—Eq. 5) (147). It has therefore been argued that plant colonization of the continents during the Phanerozoic increased the weathering of rocks, and in turn, the precipitation of carboxylic acids, which, together with the increased burial of plant-derived organics, resulted in a drawdown of atmospheric CO$_2$ and a rise in atmospheric O$_2$ (148–150).

The convergent metabolic evolution of oceanic microbial ecosystems and land plants (Fig. 6), which, we have argued, may have impacted the Earth system in similar ways, suggests the temporal profile of the Earth’s oxygenation (122, 123) may be constrained by two biological stages. The first consisted of the expansion of self-damping cyanobacterial O$_2$-photosynthesis in shallow aquatic environments and is associated with the GOE (122, 123). The second consisted of the global expansion of eukaryotic or “eukaryote-like” O$_2$-photosynthesis—both onto the continents and into the deep open ocean (Fig. 6)—with a higher metabolic rate and correspondingly greater ability to mobilize Fe and P under oxidizing conditions, and is associated
with the Neoproterozoic Oxidation Event (122, 123, 132, 142). Genomic studies estimate that chloroplast endosymbiosis leading to the rise of all photosynthetic eukaryotes occurred between the late Neoproterozoic (2,500–1,600 Ma) and the early Neoproterozoic (~1,200 Ma). Palaeontological studies in turn find a significantly increased fossil diversity of eukaryotes (including photosynthetic eukaryotes) in the Neoproterozoic (155, 156), whose increasing body sizes and fecal pellets could have moreover strengthened the export and burial of organic carbon from the oceans (157, 158).

As a final note, one could argue that the emergence of modern human societies is a variant of the general framework we propose. As our populations expanded and extracted ever more electrons from fossil fuels, we have increased global CO$_2$, while drawing down natural resources and global O$_2$ (albeit a small amount relative to the contemporary inventory for the latter) (159, 160). In the process, we have become increasingly socially, technologically, and economically interconnected, analogous to what we have observed in the evolution of oceanic microbial ecosystems and plant cells. As in those systems, this has increased our collective ability to harvest more difficult-to-access natural resources. Managing the biogeochemical perturbation that our global emergence is imposing on the Earth system is one of humanity’s greatest challenges.

Materials and Methods
We analyzed 56 genomes of cyanobacteria representative of the diversity of this clade (161) obtained from the UniProt website, 56 genomes of Prochlorococcus and marine Synechococcus (162), and 16 SAR11 genomes obtained from the National Center for Biotechnology Information website. We searched these genomes for the presence and absence of a set of reference enzymes (SI Appendix, Tables S1 and S2) using the BLASTp and tblASTn algorithms (163). We reconstructed phylometabolic trees (Fig. 2) by mapping the distributions of metabolic genes onto the phylogenies of Prochlorococcus (Figs. 1 and 3) and SAR11 (Fig. 5).

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Transport in prokaryotes must be active. Bacterial ammonium transport.


Prochlorococcus marinus 309(5738):1242–1245.


Bacterium


Giovannoni SJ, et al. (2005) Genome streamlining in a cosmopolitan oceanic bac-


Boogerd FC, et al. (2011) Amb-mediated N\textsubscript{2}H\textsubscript{4} transport in prokaryotes must be active and as a consequence, regulation of transport by GlnK is mandatory to limit futile cycling of NH\textsubscript{3}/N\textsubscript{2}H\textsubscript{4}. FEBS Lett 585(1):23–28.


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