Electron Donor Supply and Metabolic Efficiency as Limits on Net Primary Production in the Absence of Oxygenic Photosynthesis

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Most productivity on the surface of the Earth today is performed by oxygenic photosynthesis; however, this metabolism is biochemically complex, evolved only once, and arrived relatively late in Earth history. Oxygenic photosynthesis is unique in that it utilizes an essentially infinite source of electrons—water—for the reduction of CO_2 into organic carbon. Other autotrophic metabolisms, including anoxygenic photosynthesis, methanogenesis, and various lithotrophic metabolisms, require electrons from more limited electron donor compounds like ferrous iron, molecular hydrogen, or reduced sulfur. The availability of these electron donors is often determined by geological processes, and their abundance may limit primary production via those pathways. Moreover, the efficiency with which these electron donors are utilized—in terms of moles of organic carbon fixed per mole of electron donor compound—will be a strong constraint on net biological primary productivity. For example, the ability of phototrophs to conserve energy from light rather than requiring the respiration of electron donor compounds results in photosynthesis being substantially more efficient (biomass yield per electron donor) than lithotrophic counterparts.

Here, we leverage constraints on the biochemical efficiency of various metabolisms derived from environmental observation and culture-based experiments, along with geological estimates of electron donor fluxes through time, to infer the potential net primary production of the biosphere as environmental conditions change and evolutionary innovations accumulate. Moreover, we extend this logic to consideration of other planetary environments, including icy moons like Europa where photosynthesis is impossible but a lithotrophic biosphere may exist.