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The role of anaerobic microbial ecosystems in shaping early Earth's climate evolution

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Earth's early climate was generally warm, perhaps even warmer than that of the modern, despite receiving less energy from the Sun. The primitive anaerobic ecosystem could have played a crucial role in maintaining a habitable climate by regulating the abundance of greenhouse gases (e.g., CO_2 and CH_4) in the atmosphere. However, significant gaps remain in our understanding of how primitive life and its environment co-evolved before the advent of oxygenic photosynthesis.

Here, we develop a theoretical model that integrates microbial ecosystems, atmospheric chemistry, climate, and the global carbon cycle. The model simulates Earth system evolution from 4.2 to 2.6 billion years ago, accounting for external forcings such as solar luminosity, volcanic outgassing, and continental growth. A stochastic approach explores key parameter variations to identify scenarios that sustain a warm climate (>273 K) without triggering optically thick organic haze ($CH_4/CO_2 < 0.1$), while remaining consistent with geologic records of carbonate carbon isotope, $d^{13}C$.

Our results suggest that there are plausible scenarios that are consistent with $d^{13}C$ records while maintaining warm climate, if organic carbon burial efficiency (defined as burial flux divided by net primary production) exceeds ~4%. We also find that chemotrophic ecosystems likely emerged by 3.65 billion years ago, while anoxygenic photosynthetic ecosystems may have originated before 3.42 billion years ago, with the highest probability around 3.7 billion years ago. These findings provide new insights into the interplay between the microbial ecosystem structure and climate on early Earth.