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The future lifespan of oxygen-based biosignatures on Earth

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The modern Earth's biosphere is powered by oxygenic photosynthesis, which exploits ubiquitous H_2O as an electron donor and thus maintains a large net primary production of $\sim$100 Gt C per year. This primary carbon productivity results in a stoichiometric release of molecular oxygen (O_2) to surface environments, with the result that Earth's modern ocean-atmosphere system is extremely well-oxygenated. Such abundant O_2 (and commensurately abundant O_3) may serve as an important potential biosignature in future direct-imaging characterization of exoplanet atmospheres. However, the fundamental timescale of remotely observable O_2/O_3 in Earth's atmosphere is uncertain, particularly for Earth's remote future. Understanding the width of this 'taphonomic window' for atmospheric oxygenation on Earth is foundational for predicting the likelihood of oxygen-based biosignatures on Earth-like planets beyond our solar system.

Here, we examine this problem using an Earth system model of biogeochemistry and climate that tracks the coupled carbon, oxygen, phosphorus, and sulfur cycles, and captures the global redox budget between the exogenic system (atmosphere, ocean, and crust) and the mantle. Our model, which builds upon previous similar Earth system models, incorporates a global biogeochemical CH_4 cycle, a scheme for parameterized O_2-O_3-CH_4 photochemistry, the radiative impact of CH_4 on global energy balance, and the dependence of marine phytoplankton growth rate to temperature and carbon availability. The model is designed to capture the major components of the biogeochemistry and climate of Earth-like planets, but is abstracted enough to allow for a stochastic approach involving large model ensembles that are run for billions of years.

We find that a continuous decrease in atmospheric CO_2 levels and a concomitant increase in global surface temperature driven by the steady brightening of the Sun lead to the suppression of biospheric O_2 production. The mean lifespan of Earth's well-oxygenated biosphere ($pO_2 \sim 10\%$ of the present atmospheric level; PAL) is $\sim$0.75 Gyr, with mean lifespans increasing to $\sim$0.95 Gyr for atmospheric pO_2 values of 0.1% PAL, respectively. We also find that a 'collapse' of Earth's oxygenated biosphere, with atmospheric pO_2 essentially dropping to levels reminiscent of the Hadean/Archean Earth, could conceivably be triggered within the next $\sim$1 Gyr, with an attendant increase in atmospheric CH_4. Implementation of a stochastic approach reveals that the net input flux of reducing power from the mantle to the exogenic system is a fundamental control on the lifespan of oxygen-based biosignatures on Earth, and that an oxygen collapse is unavoidable unless this redox flux is less than -0.5 Tmol O_2 equivalents y-1, which we consider unlikely. Our results imply that remote detection of O_2 (and possibly O_3) in Earth's atmosphere will become challenging within the next $\sim$1.0 Gyr, emphasizing the need for robust atmospheric biosignatures for anoxic atmospheres.