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Using biogeochemical models to inform astrobiology strategy

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Biogeochemical models use geochemical, geophysical, and organismic data to explore how ecosystems behave. On Earth, where biology is ubiquitous, they tell us how biotic and abiotic chemical reactions progress and influence the wider environment, and over the last few decades biogeochemists have fitted organism-specific and environment-specific properties such as rate constants and forcing functions to myriad systems. Including biokinetics – e.g., substrate/nutrient uptake and inhibition due to toxins – is critical to the success of these models and their estimates of biological productivity.

In astrobiology and geomicrobiology, we often assess habitability by calculating the free energy of known metabolisms. While this is an important first step, it alone does not guarantee that the energy is kinetically available, sufficient to drive metabolism, or capable of meeting survival demands[1]. Here we use the open-source NutMEG model[2] to demonstrate how using biokinetic rate laws from biogeochemical models allows us to predict habitability and biosignature production rates at astrobiologically relevant sites from geochemistry alone. Furthermore, it enables assessment of the relative importance of biosignatures against the abiotic background and, in potentially uninhabitable settings, identifies the key limiting substrates, nutrients, or inhibitors. Importantly, the models are grounded in our understanding of life in Earth's habitats[3], but allow flexibility for us to explore which adaptations are required to overcome the challenges Earth-like life would face in extreme extraterrestrial environments. Targeted exemplar applications of our approach include: 1) photosynthesis in stratified lake ecosystems as analogs for ancient Earth and Mars; 2) microbial prominence in Earth's deep subsurface; and 3) potential for substrate limitation on Enceladus and its effect on biosignature production rates. The approach is versatile and can be applied in a variety of contexts, from well-understood Earth systems, to present and past habitats throughout our solar system, and ultimately to exoplanets.

References:

1. Higgins et al., (2021), *JGR:Planets* **126** (11)
2. NutMEG (v2.0), available at: https://github.com/pmhiggins/NutMEG
3. Cockell et al., (2024), *Astrobiology* **24** (6)