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Balance and imbalance in biogeochemical cycles reflect the operation of closed, exchange, and open sets

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Biogeochemical reactions modulate the chemical composition of the oceans and atmosphere, providing feedbacks that sustain planetary habitability over geological time. In this work, we mathematically evaluate a suite of biogeochemical processes to identify combinations of reactions that stabilize atmospheric carbon dioxide by balancing fluxes of chemical species among the ocean, atmosphere, and geosphere. Unlike prior modeling efforts, this approach does not prescribe functional relationships between the rates of biogeochemical processes and environmental conditions. Our agnostic framework generates three types of stable reaction combinations: closed sets, where sources and sinks mutually cancel for all chemical reservoirs; exchange sets, where constant ocean-atmosphere conditions are maintained through the growth or destruction of crustal reservoirs; and open sets, where balance in alkalinity and carbon fluxes is accommodated by changes in other chemical components of seawater or the atmosphere. These three modes of operation have different characteristic timescales and may leave distinct evidence in the rock record. To provide a practical example of this theoretical framework, we applied the model to recast exiting hypotheses for Cenozoic climate change based on feedbacks or shared forcing mechanisms. Overall, this work provides a systematic and simplified conceptual framework for understanding the function and evolution of global biogeochemical cycles over geological timescales.