An Optimal Control Theory-based Microbial Regulation Model to Offer a Generalizable Theory for Priming Effects

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Abstract

Priming leads to the significant changes in the decomposition rate of organic matter (OM) in natural ecosystems induced by minimal treatments. A fundamental understanding of priming effects is critical to accurately predict biogeochemical dynamics and carbon/nitrogen OM cycles in natural ecosystems. However, we poorly understand how the priming effect is mechanistically induced and what factors govern the process among microbial activities and environmental constraints. Here, we propose a generalizable theory to collectively explain diverse patterns of priming effects via the cybernetic approach that accounts for regulation as key features of microbial growth. The cybernetic model treats microorganisms as dynamic systems that optimally regulate metabolic functions with respect to environmental conditions to safeguard their survival. Motivated by priming phenomenon observed in the hyporheic corridor of a riverine ecosystem, we formulated our model to investigate how the addition of exogenous labile OM primes the microbial respiration of polymeric OM. Our model accounts for interspecies interactions between various assortments of microbial groups with distinct metabolic traits to enable prediction of both increase (positive priming) and decrease (negative priming) of OM turnover using the same model structure. Our modeling framework reveals that: (1) the priming effects are manifestations of microbial regulatory response to diverse environmental conditions, and (2) priming magnitude and direction are highly dependent on the polymeric OM richness and the extent of treatment with labile OM. Beyond elucidating qualitative understanding of the phenomenon, our model also suggests that interspecies interactions between microbial groups with distinct metabolic traits (i.e., population turnover, sensitivity to labile OM, and efficiency in degrading polymeric OM) potentially drive the priming effects. By integrating contextual knowledge and a generalizable theory, our holistic modeling framework is effective for investigation and prediction of biogeochemical dynamics of natural ecosystems across diverse biological and environmental settings.

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