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A Mechanistic Explanation of the Hysteretic Temperature and Moisture Dependence of Soil Carbon Decomposition Dynamics

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Understanding and modeling how temperature and moisture regulate soil carbon decomposition is of paramount importance for the prediction of biogeochemistry-climate feedbacks. Existing theories have often represented the temperature and moisture effects using multiplicative factors, implicitly assuming that biogeochemical reaction, temperature, and moisture controls are linear in the logarithm space, although, in reality, the three are always entangled. Here we present a first-principle based formulation of how temperature and moisture influence biogeochemical reactions through their modulation of substrate transport, uptake, organic-mineral interaction, and microbial dynamics. We evaluated our model predictions with incubation and field data synthesized across a wide range of soils. We demonstrate that temperature and moisture interact non-multiplicatively in modulating biogeochemical reactions and consequently soil carbon decomposition dynamics. We show that many of the temperature and moisture response curves used in current models are consistent with specific environmental conditions over the observation period, but not for the much wider range of current and expected environmental variability. Under transient and variable environmental conditions, the temperature and moisture responses are hysteretic and much more variable and are difficult to represent accurately as deterministic and multiplicative functions. By resolving the more abundant spatiotemporal dynamics, our theory therefore has a great potential to significantly improve prediction of soil carbon dynamics and their interactions with climate.