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Modeling Anaerobic Soil Organic Carbon Decomposition in Arctic Polygon Tundra: Insights into Soil Geochemical Influences on Carbon Mineralization

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Rapid warming of Arctic ecosystems exposes soil organic matter (SOM) to accelerated microbial decomposition, potentially leading to increased emissions of carbon dioxide (CO_2) and methane (CH_4) that have a positive feedback on global warming. The fate of permafrost carbon is determined in large part by soil moisture, and a significant portion of carbon may thaw in wet, anoxic conditions. Current estimates of the magnitude and form of carbon emissions from Earth system models include significant uncertainties, because the models do not explicitly represent anaerobic carbon decomposition. We coupled modeling principles developed in different disciplines, including a thermodynamically based microbial growth model for methanogenesis and iron reduction, a pool-based model to represent upstream carbon transformations, and a humic ion-binding model for dynamic pH simulation to build a more versatile carbon decomposition model framework that can be applied to soils under varying redox conditions. This new model framework was parameterized and validated using synthesized anaerobic incubation data from permafrost-affected soils along a gradient of fine-scale thermal and hydrological variabilities across Arctic polygonal tundra. The model accurately simulated anaerobic CO_2 production and its temperature sensitivity using data on labile carbon pools and fermentations rates as model constraints. Modeling and synthesis results demonstrate that CH_4 production is strongly influenced by water content, pH, methanogen biomass, and presence of competing electron acceptors, resulting in high variability in its temperature sensitivity. This work provides new insights into the interactions of SOM pools, temperature increase, soil geochemical feedbacks, and resulting CO_2 and CH_4 production. The proposed anaerobic carbon decomposition framework presented here builds a mechanistic link between soil geochemistry and carbon mineralization, making it applicable over a wide range of soils under different environmental settings. Data sets can be found at http://dx.doi.org/10.5440/1168992, http://dx.doi.org/10.5440/1393836, and http://dx.doi.org/10.5440/1288688