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Biogeochemical drivers of Rare Earth Element and Radionuclide mobility in northern mining-impacted soils

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Rare earth elements (REEs) are essential to low-carbon technologies and aerospace applications, yet their fate, transport and environmental impacts in mining residues and surrounding soils following mining and processing activities remain poorly understood. At the Strange Lake deposit (northern Québec, Canada), REEs (e.g., Dy, Tb) can co-occur with naturally occurring radionuclides (U, Th) [1]. In receiving soils, hydrological conditions may create dynamic redox gradients and transient biogeochemical hotspots that drive element redistribution [2-5]. Current regulatory frameworks rely on single-contaminant, single-plant-species approaches which may not fully account for the coupled effects of soil heterogeneity, redox fluctuations, and organic matter interactions that govern contaminant fate. The overarching objective of this research is to determine how plant-rhizosphere-soil interactions regulate REE and radionuclide mobility under dynamic environmental conditions. Here, we focus on how redox oscillations interact with microscale soil heterogeneity to control contaminant cycling.

Flow-through soil reactors reproduce key features of mining-impacted soils, including Fe-Mn oxide coatings, clay and organic-rich microenvironments. Two scenarios are investigated: rainfall-driven leaching of pre-contaminated soils and infiltration of REE-bearing waste-rock leachates into initially uncontaminated soils. Porewater chemistry is monitored across redox cycles while solid-phase digestions and microscale imaging approaches are used to quantify element partitioning and spatial heterogeneity. We propose that redox conditions act as first-order controls on contaminant dynamics, with REE and U mobility influenced by coupled redox-driven mineral transformations, clay reactivity, and organic complexation, while Th is generally predicted to remain largely particle-bound. Microscale heterogeneity generates biogeochemical hotspots that dominate element redistribution and cause porewater chemistry to deviate from bulk solid composition. By explicitly linking microscale processes to system-scale transport, this work advances a process-based framework for predicting redox-driven contaminant behavior in heterogeneous soils, laying the foundation for plant-focused studies with direct implications for environmental risk assessment and sustainable REE resource development.

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