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Nitrate thresholds control regime shifts in soil nitrogen cycling across a mangrove–agricultural gradient

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Anthropogenic nitrogen loading is restructuring biogeochemical cycles worldwide. Predicting when ecosystems transition from nitrogen retention to sustained nitrogen loss requires identifying the controls that regulate denitrification expression at ecosystem scale. Redox conditions, organic carbon availability, and denitrifier gene inventories are routinely invoked to diagnose nitrogen loss potential, yet these proxies do not determine whether loss pathways are functionally activated.

We investigated nitrogen-cycle organization along a spatially compressed mangrove–agricultural gradient (<500 m) in a Caribbean coastal system by integrating soil nitrogen pools, bulk organic $\delta^{15}N$, microbial community structure, and controlled anoxic nitrate-amended incubations. Mangrove and back-mangrove soils contain large nitrogen reservoirs (up to 1.4% N) and display isotopically depleted signatures ($\delta^{15}N \approx 2–3‰$). Adjacent agricultural soils contain smaller nitrogen pools (0.2–0.6% N) and exhibit pronounced isotopic enrichment ($\delta^{15}N \approx 6–8‰$), consistent with sustained fractionating nitrogen loss. Complete denitrifying communities occur across all zones. Under standardized anoxic conditions, nitrate reduction proceeds threefold more slowly in mangrove soils (0.56–1.15 nmol g^{-1} min^{-1}) than in agricultural soils (2.32 ± 0.15 nmol g^{-1} min^{-1}), indicating strong differences in inducible capacity.

To integrate long-term isotopic imprint and stoichiometric constraint, we developed ONI-CN, an isotopic–stoichiometric index combining $\delta^{15}N$ and soil C/N ratios. ONI-CN resolves two discrete nitrogen-cycle configurations: a closed, recycling-dominated state in mangrove soils and an open, loss-dominated state in agricultural soils. The transition between these states is abrupt, with no intermediate values along the gradient, defining a threshold response rather than a gradual continuum.

These findings identify nitrate availability as the governing control on denitrification expression across scales. Mangrove soils host a dormant functional nitrogen bank: a fully assembled denitrifying capacity maintained in a non-expressed state under chronic nitrate limitation. Once nitrate inputs exceed a critical threshold, nitrogen loss is rapidly activated and isotopic enrichment accumulates. This mechanism provides a predictive framework for regime shifts in coastal nitrogen cycling and clarifies how modest nutrient enrichment can reorganize biogeochemical functioning under accelerating anthropogenic forcing.