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Reshaping of preferential flow paths and mechanisms of nitrogen biogeochemical evolution in the vadose zone under tillage disturbance

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Preferential flow, which is widespread in the vadose zone of agricultural dryland areas, significantly influences the transport, transformation, and environmental fate of nitrogen. This study employed field tracer tests, investigation sampling, metagenomics, and isotope labeling techniques to systematically identify the differences in nitrogen transformation functions between preferential flow pathways and the matrix zone in the vadose zone. It revealed that long-term agricultural tillage activities alter soil physical structure, thereby affecting the development characteristics of preferential flow and subsequently influencing nitrogen biogeochemical processes in the vadose zone. The study found that preferential flow zones in the vadose zone not only serve as rapid pathways for nitrogen transport but also, due to the redox gradients formed within them, act as microbial hotspots enriched with nitrification functional genes. Long-term tillage leads to the degradation of preferential flow path structures and homogenization of hydraulic conductivity. This alteration in physical structure triggers the succession and functional restructuring of nitrogen-related microbial communities in the vadose zone: nitrogen transport and transformation shift from early-stage nitrification hotspots in preferential flow channels to reduction-dominated processes, such as denitrification and dissimilatory nitrate reduction to ammonium (DNRA), primarily occurring in the matrix zone under long-term tillage conditions. Based on multivariate data, including nitrogen microbial taxa, functional genes, and reaction rates, this report elucidates the coupled response mechanism of "soil physical structure–hydrological processes–microbial community–biogeochemical function." The findings provide important insights for assessing and managing soil and groundwater nitrogen pollution risks in agricultural dryland areas.