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Editorial: Exploring the overlooked nitrogen transformation pathways for nitrogen loss or retention from the soil scenario: a contemporary and holistic approach towards sustainability

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Editorial on the Research Topic
Exploring the overlooked nitrogen transformation pathways for nitrogen loss or retention from the soil scenario: a contemporary and holistic approach towards sustainability

The nitrogen (N) cycle is not a simple chain of reactions but a dynamic and interconnected web of microbial processes, where countless invisible players collectively determine the fate of N in ecosystems (Figure 1). It is best understood as a modular and evolving network of transformations, continuously shaped by the metabolic diversity and adaptability of microbial communities (1). The trajectory of these transformations, whether N is lost through denitrification or anaerobic ammonium oxidation (ANAMMOX), or retained within the system through dissimilatory nitrate reduction to ammonium (DNRA), is governed largely by the composition, interactions, and functional capacity of the inhabiting microbial guilds (2, 3). What makes N unique among soil elements is not only its abundance but also its major role in plant growth, development, and productivity, directly linking belowground microbial processes with aboveground ecosystem functions (4). Yet, N transformations in soil are anything but uniform. Contrasting aerobic and anaerobic conditions create vastly different biochemical landscapes, where microbes act as unseen engineers, orchestrating redox reactions that regulate nutrient retention, greenhouse gas fluxes, and soil fertility (5, 6). Among the less well-understood microbial pathways is denitrifying anaerobic methane oxidation (DAMO), a process in which Methylomirabilis bacteria or Methanoperedens archaea use methane as an electron donor to reduce nitrate or nitrite. Despite its profound implications for both the N and carbon cycles, DAMO, along with DNRA and ANAMMOX, remains underrepresented in

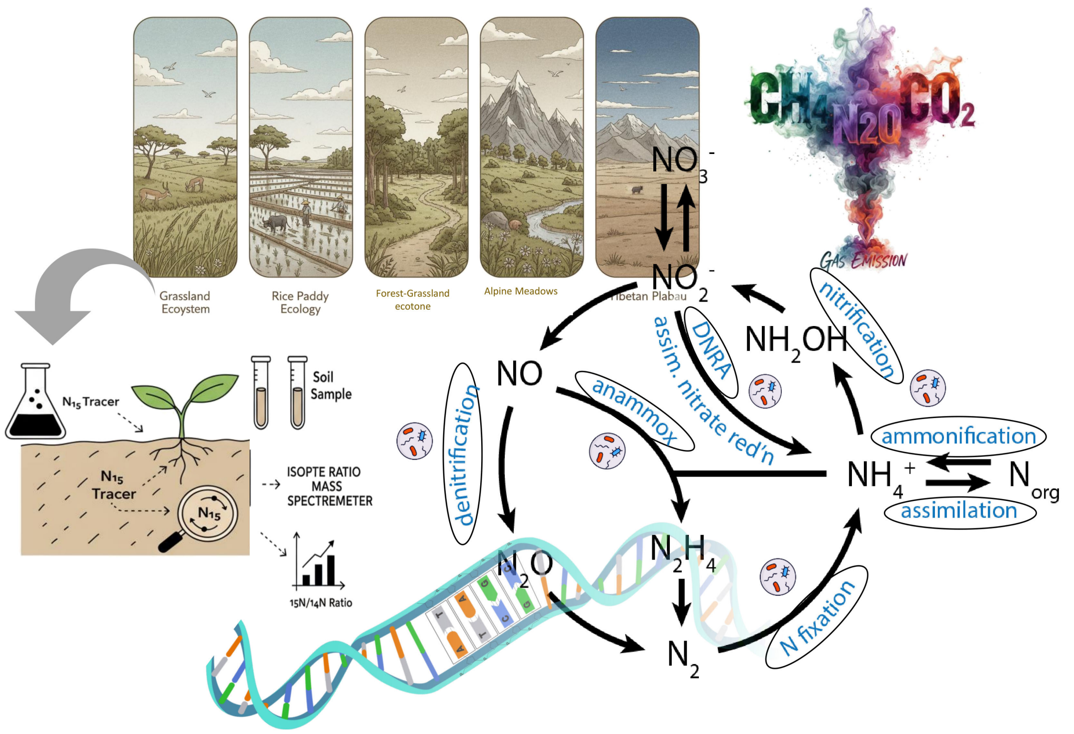

FIGURE 1
Diagram illustrating nitrogen cycling across different ecosystems: grassland, rice paddy, forest-grassland ecotone, alpine meadows, and Tibetan plateau. Processes include nitrification, denitrification, ammonification, and nitrogen fixation. It involves tracing nitrogen-15 isotopes in soil samples to measure isotope ratios. Gas emissions are represented as CH_4, N_2O, and CO_2. The cycle connects soil, plant uptake, and emissions, emphasizing nitrogen transformations and emissions.

models of the global N budget. Their absence from mainstream N research reflects the methodological challenges of detecting and quantifying these processes *in situ*, yet it also signals a frontier brimming with unanswered questions.

This Research Topic was conceived to address precisely this gap by bringing together original research, perspectives, and reviews. It aimed to unravel how microbial communities and the pathways they mediate vary across soils, sediments, wetlands, estuaries, and agricultural landscapes. The contributions highlighted the ecological and functional shifts of microbial populations under aerobic versus anaerobic regimes and revealed the importance of linking taxonomy and phylogeny to function. With the advancement of next-generation sequencing, metagenomics, metatranscriptomics, proteomics, and integrative bioinformatics, researchers are now able to decode these underexplored processes at unprecedented resolution, illuminating genetic markers, metabolic regulation, and ecological outcomes. The exploration of microbial metabolic footprints, as well as the influence of organic and inorganic amendments, opens further opportunities to bridge fundamental microbial ecology with applied soil and crop management. Looking ahead, the potential applications are wide-ranging: from developing microbial inoculants and tailored consortia to employing genome editing tools for improving N use efficiency and soil health. Equally promising is the possibility of mitigating greenhouse gas emissions by harnessing beneficial plant-microbe-soil interactions, an urgent need under accelerating climate change.

In essence, this editorial initiative envisions the N cycle not as a closed textbook chapter, but as an evolving story in which unseen microbial protagonists continually reveal novel roles, interactions, and pathways. By weaving together overlooked processes, cutting-edge methodologies, and translational opportunities, we aim to inspire a reimagined perspective of the N cycle, one that is grounded in discovery and equally attuned to sustainable solutions. Recent contributions to this Research Topic reaffirm that N dynamics and microbial responses are far more nuanced than simple input-output relationships, being strongly mediated by ecosystem type, management practices, and microbial sensitivities. In forest-grassland ecotones, N additions markedly altered bacterial diversity through pH-driven shifts, while fungal communities remained comparatively stable (Li et al.). In degraded alpine meadows, diazotrophs were found to be more responsive to slope position and microtopography than to N inputs alone (Li et al.). Grazing experiments on the Qinghai-Tibetan Plateau demonstrated that mixed yak-sheep regimes stabilized diazotrophic communities by balancing nutrient return and vegetation dynamics (Sun et al.). Across contrasting grassland soils, N source rather than dose emerged as the dominant driver of microbial restructuring, with ammonium inputs reshaping functional profiles differently in steppe versus shrub systems (Ren et al.). In agricultural landscapes, management practices offered equally compelling insights. Conservation tillage not only enhanced wheat yields and soil health but also reduced greenhouse gas emissions, highlighting its dual potential for productivity and climate mitigation (Sadiq et al.). Chemical strategies contributed another level of understanding, copper pyrazole was shown to suppress nitrification and denitrification by targeting keystone microbial traits (Wang et al.), while field ^{15}N tracer experiments revealed that nitrification inhibitors promoted the stabilization of fertilizer-derived N into organic pools, sustaining fertility beyond a single growing season (Quan et al.).

Together, these studies show that N cycling is governed not merely by inputs, but by the holistic interplay of soil properties, microbial ecology, and land management. This knowledge provides critical insights for designing strategies that can simultaneously enhance agricultural productivity, safeguard ecosystem resilience, and address the challenges of global environmental change. The research presented here highlights how deeply intertwined microbial communities are with the functioning of the N cycle and its consequences for ecosystem health, productivity, and climate regulation. Yet, the story is far from complete. Future research must move towards integrating overlooked processes such as DNRA, DAMO, and ANAMMOX into global biogeochemical models, while also exploring the ecological trade-offs they create under changing environmental conditions. There is also a pressing need to link molecular-scale discoveries to field-level applications through long-term experiments that evaluate the performance of microbial inoculants, biocovers, or soil amendments under realistic management scenarios. Coupling advanced multi-omics with isotopic tracing and modeling will be key to capturing the true complexity of N transformations in space and time. Ultimately, the challenge and opportunity lie in translating microbial insights into practices that improve nutrient use efficiency, reduce greenhouse gas emissions, and sustain ecosystem resilience in an era of rapid global change.

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