Ecosystem $\delta^{15}N$ signature consistently integrates dissolved and gaseous N losses with microbial potential for nitrification and denitrification

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Global nitrogen deposition in forests can alleviate nitrogen limitations, impacting biodiversity, carbon storage, water quality, and greenhouse gas emissions. Predicting these effects relies on quantifying nitrogen fluxes, particularly nitrogen gas loss and soil retention. In central Europe, long-term catchment measurements and ^{15}N:^{14}N isotope data reveal key factors affecting dissolved and gaseous nitrogen fluxes in temperate forests, with stream nitrogen losses relating to forest floor nutrient ratios, increasing as ecosystems become more phosphorus-limited, and soil nitrogen storage increasing with iron and aluminium content. Gaseous nitrogen losses, estimated at 2.5 ± 2.2 kg N ha^{-1} yr^{-1}, comprise 20% ± 14% of total nitrogen deposition, and these losses rise with forest floor N:P ratio and dissolved nitrogen losses. We further integrated ecosystem $\delta^{15}N$ with soil microbiome gene data, finding that nitrogen losses correlated with soil $\delta^{15}N$, primarily driven by genes related to nitrite formation in nitrification and denitrification processes, which were more informative than those associated with nitrous oxide production. This suggests that nitrite formation is a critical step in nitrogen losses, and the genetic potential for ammonia oxidation and nitrate reduction serves as an indicator of ecosystem nitrogen losses.