frontiers | Frontiers in Environmental Science

TYPE Editorial
PUBLISHED 07 November 2025
DOI 10.3389/fenvs.2025.1730350

OPEN ACCESS

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RECEIVED 22 October 2025
REVISED 27 October 2025
ACCEPTED 28 October 2025
PUBLISHED 07 November 2025
CORRECTED 11 November 2025

CITATION
Jiang Y, Levison J and Schilling K (2025) Editorial: Nitrate from field to stream: Characterization and mitigation. *Front. Environ. Sci.* 13:1730350. doi: 10.3389/fenvs.2025.1730350

Editorial: Nitrate from field to stream: Characterization and mitigation

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KEYWORDS

agriculture, nutrients, water quality, beneficial management practice, nitrate leaching

Editorial on the Research Topic
Nitrate from field to stream: characterization and mitigation

Introduction

Agricultural production plays a vital role in ensuring global food security. Nitrogen (N), an essential nutrient for crop growth, is often applied to agricultural systems as inorganic fertilizer, manure, or added to the soil via legume fixation to increase crop yields. However, excess N, in the form of nitrate, readily leaches from agricultural systems, harming water quality in groundwater, rivers, streams, lakes, and estuaries. Despite efforts to improve practices for agricultural N management, groundwater nitrate levels still often exceed drinking water guidelines for human health in many regions (Bijay-Singh and Craswell, 2021). High nitrate levels are a leading reason for violations at regulated U.S. drinking water utilities (Pennino et al., 2017). In the EU, a recent report showed that 14% of drinking water wells surpass the nitrate concentration limit (European Environment Agency, 2024a). Excessive nitrate leaching in the U.S. Corn Belt has been linked to the formation of large hypoxic zones in the Gulf of America and about one-third of coastal waters and rivers (Metaxoglou and Smith, 2025). Additionally, lakes in the EU are considered eutrophic partly due to high nitrate runoff from agricultural areas (European Environment Agency, 2024b). In Canada, nitrate contamination from agriculture affects many aquifers, including those in Abbotsford- Sumas, Assiniboine Delta, Annapolis Valley, and Prince Edward Island. When nitrate enters stream networks, some of it is converted to N_2O through denitrification, contributing roughly 10% of global N_2O emissions and thus to global warming (Beaulieu et al., 2011).

This Research Topic brings together articles advancing the science of identifying and reducing N losses from agricultural fields to streams. The Research Topic covers various aspects of N loss characterization and mitigation, including in-field N management, downstream mitigation, innovative monitoring strategies, and assessment at watershed scales. It provides a comprehensive overview of current research, highlighting new monitoring and mitigation strategies, as well as the sources, dynamics, and controls of N loss.

In-field studies

Four of the 16 studies examined the effects of beneficial management practices (BMPs) on N losses at the field scale. These included a diverse crop rotation in the Midwest US (Gentry et al.), multi-species pasture mixes for livestock production in New Zealand (Graham et al.), manure application timing and carbon-to-nitrogen (C/N) ratios in Germany (Delin et al.), and different fertility sources for potatoes in Prince Edward Island (PEI), Canada (Burton et al.). The diverse crop rotation was found to reduce nitrate leaching by up to 50% compared to conventional corn-soybean rotations. The inclusion of new rotational crops sometimes delayed planting under unfavorable weather, potentially compromising yields. While these rotations show promise for improving the resilience of row crop production, further research is needed to identify varieties and seeding rates that maximize yield and profitability under variable conditions (Gentry et al.). A multi-species pasture mix, hypothesized to reduce nitrate leaching from livestock operations, did not outperform the conventional two-species mix, underscoring the need for rigorous BMP evaluation before adoption (Graham et al.). Research on manure management showed that early fall application with a C/N ratio of 10 significantly increased nitrate leaching, whereas a higher ratio (up to 18) did not, highlighting the importance of both timing and composition in managing nitrate losses (Delin et al.).

Implementing BMPs to reduce nitrate leaching may inadvertently increase nitrous oxide (N_2O) emissions, a potent greenhouse gas. However, measuring both nitrate leaching and N_2O emissions together is uncommon in BMP studies, making it difficult to assess the trade-offs of N losses between the two pathways. One article reported on both tile drainage nitrate, dissolved N_2O, and soil surface N_2O emissions from a conventional potato-barley-red clover rotation in PEI (Burton et al.). The study found that nitrate losses via tile drainage from the potato phase were an order of magnitude greater than N_2O emissions from both tile drainage and the soil surface. Since tile drainage represents only a portion of total soil drainage (Jiang et al., 2011), total nitrate leaching is likely even higher. This large disparity suggests that the priority of mitigating N loss from the rotation should be placed on nitrate leaching. The results also emphasize the importance of measuring both nitrate and N_2O losses when evaluating BMPs to prioritize mitigation efforts effectively.

Downstream nitrate mitigation

Two studies evaluated constructed wetlands for nitrate removal in contrasting climates: Atlantic Canada (Crossley et al.) and Iowa, US (Anderson et al.). Another investigated the capacity of a low-grade weir to remove nitrate from a tile-drained ditch in Minnesota, US (Strock and Ranaivoson). Despite their different settings, the constructed wetlands removed 39% and 74% of incoming nitrate flux, respectively, whereas the weir increased nitrate removal by 58%. These articles highlight that temporarily retaining high-nitrate water in wetlands or behind weirs in flowing streams can be an effective strategy for reducing nitrate in agricultural watersheds.

Although the results are promising, Anderson et al. (2025) further noted that nitrate removal by the wetland on the experimental tributary accounted for only a small fraction of the total watershed nitrate load. Scaling up to remove 74% of the nitrate load across the entire Mud Creek watershed would require more than 1,800 wetlands of similar size, highlighting the impracticality of relying solely on wetlands for watershed-scale mitigation. This stresses the importance of placing BMP assessments under a broad watershed context.

Improved quantification of nitrate

Although nitrate is frequently monitored at many sites, concentrations can be highly variable in response to rainfall runoff. They can be difficult to estimate at local and regional scales, given the limited availability of calibration data. Some articles focused on improving N monitoring using a variety of approaches. Chappell (2025) used high-resolution monitoring of nitrate and hydrological dynamics to develop a model to quantify the rain-driven nitrate dynamics in a small headwater basin in the United Kingdom. In a sandy sub-catchment of an agriculturally intense region in Canada, Zeuner et al. (2025) evaluated data Research Topic methods at varying spatial scales and frequency (e.g., monthly sampling, 2-h auto-sampling, and *in situ* multiparameter instruments) to better understand groundwater N transport. High-frequency sampling using autosamplers was useful to capture storm-related transport of nitrate, but some issues were identified with data collection (e.g., impacts of sediment transport; power failure). When data are sparse, Elsayed et al. (2025) showed that machine learning (ML) regression models can be developed to quantify nitrate and other surface water concentrations using a variety of easily measured input variables, including hydrological, meteorological, and field conditions. In a different approach to sparse nitrate data, Liang et al. (2025) first demonstrated that the lack of adequate monitoring data can lead to substantial biases in nitrate load estimation and then showed how the use of a process-based watershed model can be used to improve load estimation when there are systematic data gaps in the monitoring record.

The transformation and loss of nitrate and other nutrients within the stream network can be very difficult to quantify. Jordan et al. (2025) report on the efficacy of using nutrient injection experiments as a monitoring tool to assess nutrient retention efficiency in stream reaches of South Carolina. They found that the presence of engineered pools in restored stream channels can help to trap and reduce nutrients. The effectiveness of temporarily trapping and treating nitrate within channels is consistent with results shared by Strock and Ranaivoson (2025) for their low-grade weir site in Minnesota.

Evaluating nitrate at the watershed scale

The impacts of nitrate loss and transport at smaller field or reach scales are often manifested at the outlets of larger watersheds (Danalatos et al., 2022). Developing watershed-scale mitigation strategies and quantifying their impacts often necessitates the use of models. Two independent studies assessed the impacts of land use on nitrate loads in two agricultural watersheds in PEI using the SWAT model (Oliver et al.; Jiang et al.). Both found that replacing forage red clover in the conventional potato-cereal-forage rotation in PEI with soybean effectively reduced nitrate loads. Also using SWAT, Qi et al. (2025) conducted comparative modeling (using the original and new tile drainage and N modules) to assess model performance for simulation of N-loss in a typical Midwestern tile-drained watershed, noting that when observations are scarce, the processes in the new N module can magnify uncertainty in N-gas-flux estimates. In a distinctly different modeling approach, the Source List Model and the InVEST Model were used to assess total nitrogen emissions, including nitrate losses into rivers, as well as their sources, in the Huang-Huai-Hai Plain (5,423 km^2) of China (Yu et al.). Despite considerable uncertainties in the models, they yielded similar proportions of emissions from various sources and provided meaningful insights for developing management strategies in the region.

Concluding thoughts on special issue

The series of articles published in this Research Topic of Frontiers in Environmental Science highlights the challenges of evaluating and mitigating nitrate loss from fields to streams, while also serving to underline the interconnectedness of the research. Reducing nitrate loss at the field scale may be the first line of defense against excessive off-site transport, but this research Research Topic also shows that there are downstream remedial measures that can be taken to reduce nitrate once it has left the field. Once strategies are in place, improving quantification of nitrate loads and evaluating watershed-scale effectiveness using analytical and numerical models will be needed to document long-term performance. Overall, while the special Research Topic can include only a small sampling of the type of research being conducted by the scientific community on nitrate loss, mitigation, and transport, the Research Topic captures the many facets of this work that will be useful to a wide range of stakeholders.

We would like to express our sincere gratitude to all the authors for their contributions to this Research Topic and to the reviewers for their detailed evaluations and insightful comments that strengthened the manuscripts.

Author contributions

YJ: Writing – original draft, Writing – review and editing. JL: Writing – original draft, Writing – review and editing. KS: Writing – original draft, Writing – review and editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

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The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Correction note

This article has been corrected with minor changes. These changes do not impact the scientific content of the article.

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