Thinking outside the channel: modeling nitrogen cycling in networked river ecosystems

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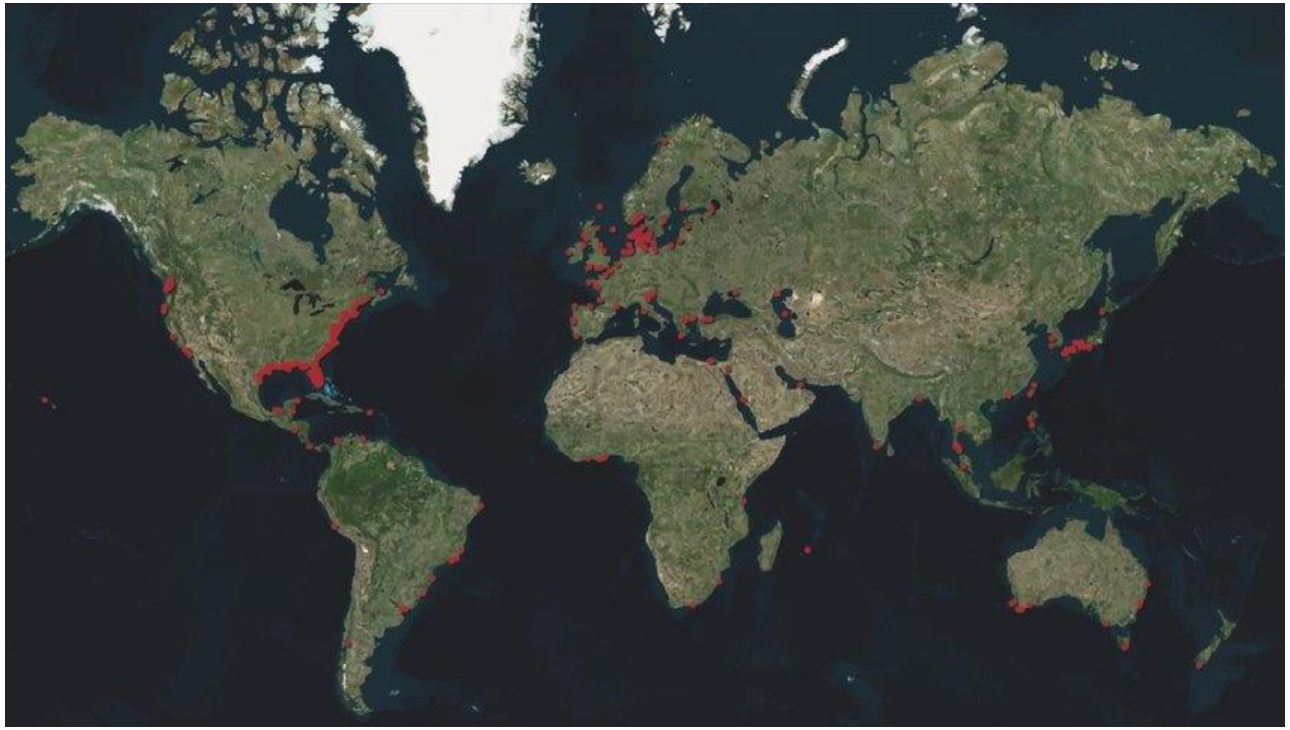
Introduction

- **Agricultural and urban development** alters nitrogen and other biogeochemical cycles in rivers worldwide.
- Understanding **nitrogen exchanges** along a river is crucial to **predict how much nitrogen is transported** and how much will end up in the sea.
- Too much nitrogen in the sea = **hypoxic zones** = very detrimental to marine ecosystems

So how do we measure this nitrogen?



Scientifically documented hypoxic zones in the world's coastal waters since 1980.

(1) Grimvall, Anders & Sundblad, Eva-Lotta & Sonesten, Lars. (2017). Mitigating marine Eutrophication in the presence of strong societal driving forces.

Modelling biogeochemical processes

Biogeochemical processes cannot be experimentally measured over the hundreds of km of river worldwide

=> **need for models** try to reproduce these exchanges

Current perception of nitrogen cycling

In previous and current models, nitrogen is considered to have :

- 2 sources: **upstream input** and loading from **terrestrial exchanges** (hyporheic exchanges, vertical and longitudinal)
- 1 output: removal occurs **only through denitrification**

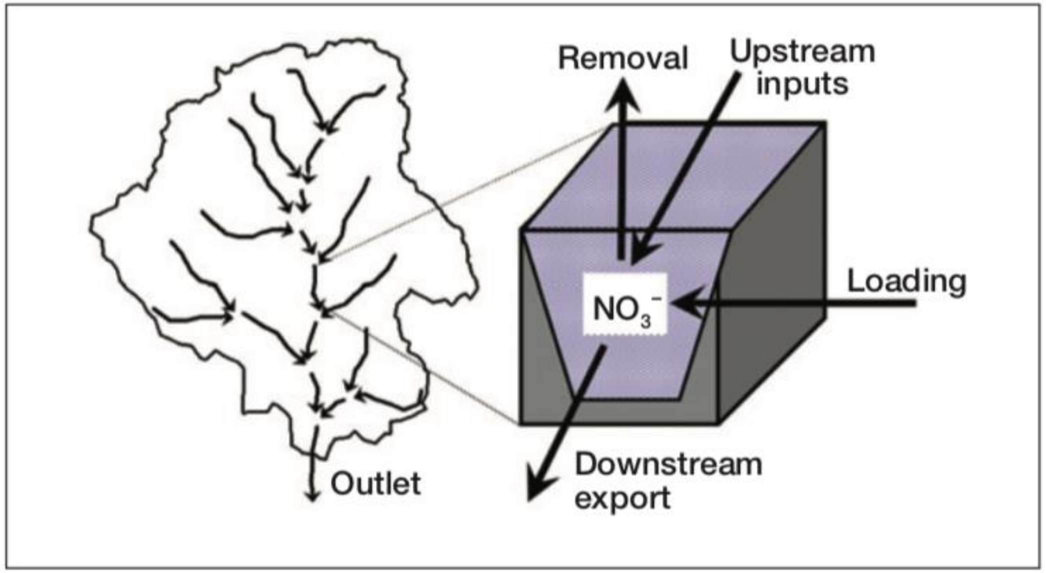


Figure 1. *River-network model structure. Following the methods presented by Mulholland et al. (2008), river networks were divided into segments, defined as the length of stream between tributary junctions. Water and NO_3^- flux into (upstream inputs and loading from the terrestrial landscape) and out of (downstream export and removal via denitrification) each segment were modeled. Fluxes are described in WebPanel 1.*

Problem

The existing models show many **limits** when trying to explain nitrogen cycling in streams and in **considering all the contributing factors**.

Question

Do the **assumptions** used for current nitrogen exchange models in rivers **provide coherent and reliable results**?

Hypothesis

Take the assumptions of all of these models as hypotheses to describe downstream transport and denitrification of NO3- in river networks, and to **test them.**

Common assumptions

(1) **catchment topography drives water and NO_3^- accumulation.**

(2) **channel width increases in proportion to discharge**

(3) **streambed denitrification is the primary mechanism of nitrogen removal**

(4) **NO_3^- concentration is the primary determinant of streambed denitrification rate.**

Currimundi, Sunshine Coast, Queensland.
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Methods

Goal: **verify or deny** hypotheses commonly used in river-network models by **evaluating how realistic the model results are**.

Model to be evaluated: model of river-network NO3 -dynamics **described by Mulholland *et al.*** (2008) (similar to most existing models)

Study area: **8 catchment basins in the US**, all have different characteristics (size, surrounding activities, human impact)

- Sampling:

- NO3- concentrations
- channel width
- water discharge

Table 1. Descriptions of study catchments

Site location	*Biome*	*Basin area (km^2)*	*% agriculture*	*% urban*
Little Tennessee River, North Carolina (NC)	Warm temperate deciduous forest	361	10	7
Mill Creek, Kansas (KS)	Grassland	1008	16	3
Tualatin River, Oregon (OR)	Humid coniferous forest	1828	27	21
Flat Creek, Wyoming (WY)	Semiarid coniferous forest	400	0.4	2
Ipswich River, Massachusetts (MA)	Cool temperate deciduous forest	381	6	31
Little Rabbit River, Michigan (MI)	Cool temperate deciduous forest	126	72	9
Río Piedras, Puerto Rico (PR)	Moist evergreen tropical forest	40	27	42
Rio Grande, New Mexico (NM)	Arid grassland	40 780	0.7	1

Notes: Land-cover data derived from the USGS 2001 National Land Cover Dataset (http://seamless.usgs.gov).

Steps of the modelling process

Step 1:

Model parameters for denitrification from in-situ measurements of whole stream-reach denitrification for 9 headwaters of each catchment (from 1st to 3rd order)

= What's needed for denitrification?

Step 2:

Estimate **spatial patterns of NO3- loading rates (less NO3- observed if denitrification occuring)** in streams with a model-independent parameter optimizer

= Where does denitrification occur according to these measurements? (independent from model)

Step 3:

Estimate NO3- loading rates necessary for the model to exactly reproduce observed patterns of NO3- concentrations across each network

= How much nitrate would be needed to have these spatial patterns?

Step 4:

With this, **calculate spatial variation in NO3- loading rates** across each catchment (Figure 2), assuming that the hypothesized representation of nitrogen cycling was correct

= Where does denitrification occur according to the model?

Step 5:

Check if values are coherent

Realistic range = 0–6.96 kg km^{-2} d^{-1}

Margin of error:
The model was only **rejected when >10% of loading estimates for a catchment fell outside of a realistic range**

Results and Discussion

- The model yielded **coherent results for 2 of the 8 catchments**
- The results for the 6 other river networks deviated more or less from the model
- 1 river network without any result
- Litterature, catchment characteristics, modification of parameters to find deviation factors

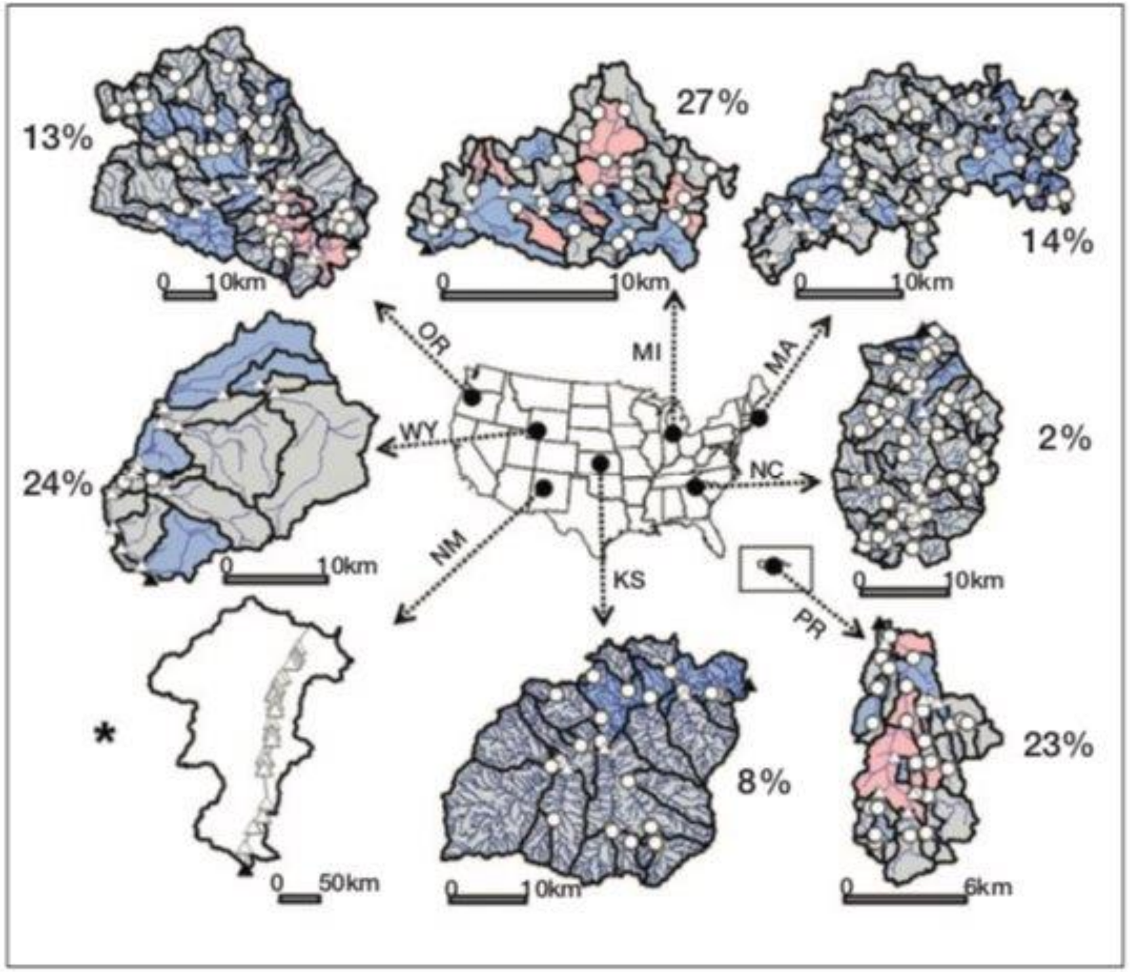


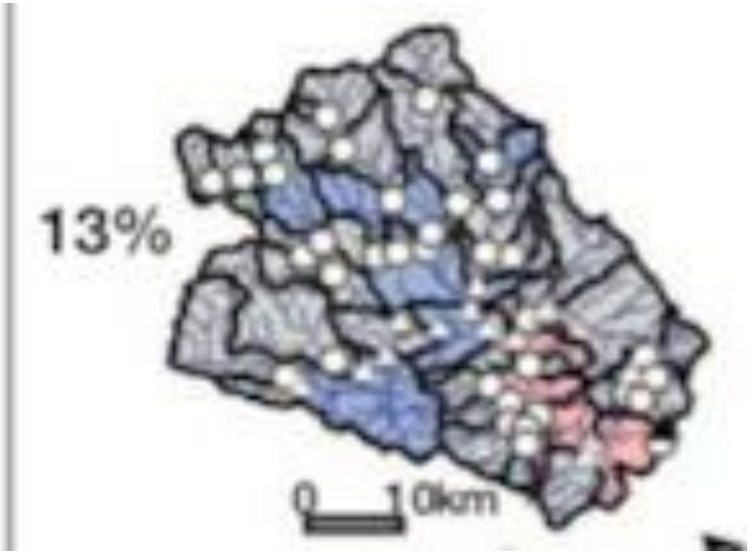
Figure 2. Maps of the eight modeled catchments, which include stream hydrography (blue lines), discharge sampling points (triangles; solid triangles indicate catchment outlet), NO_3^- sampling points (circles), and catchment contributing area (CCA) for each NO_3^- sampling point (black lines). Color of CCA represents average simulated loading estimates that are realistic (gray; between 0 and 6.96 kg km^{-2} d^{-1}), unrealistic (high = red; > 6.96 kg km^{-2} d^{-1} and low = blue; < 0 kg km^{-2} d^{-1}), or indeterminable given model assumptions (white; see text). The percent of CCAs with unrealistic modeled NO_3^- loading estimates is indicated for each catchment. *See text for discussion of NM river-flow issues.

Continuity of rivers: influence of anthropogenic infrastructures

➡ **In 5 networks, the incoherent results were due to lack of consideration of the catchment hydrology**

- Anthropogenic infrastructures (headgates, tile drains…) → discontinuity in rivers
- In Tualatin River, re-parametrization of the model incorporating these infrastructures eliminates unrealistic estimates → a dominating pattern of nitrogen delivery to streams
- The case of dams

(2) T. Maavara *et al.*, "River dam impacts on biogeochemical cycling," *Nature Reviews Earth & Environment*, vol. 1, no. 2, pp. 103–116, Feb. 2020



Tualatin River, Oregon; triangles = wastewater facilities

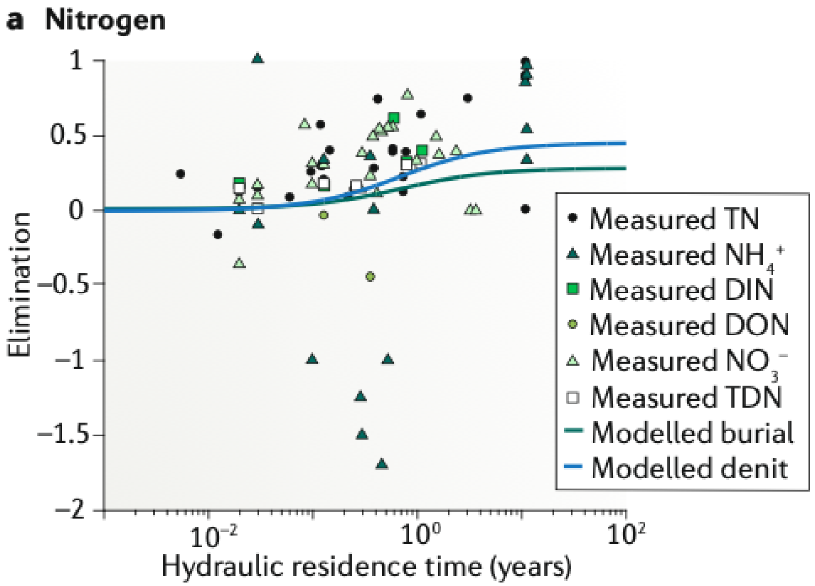


Fig.2: Elimination of nitrogen from reservoirs *(2)*

Ipswich river and Flat Creek networks : importance of hydrological connections

➡ **Oversimplification of river-network hydrogeomorphology: underpredictions of nitrogen removal**

- Wetland complexes and hyporheic zones
- No changes when incorporating headwaters in the models
- Loading estimates negatively correlated with fraction of stream intersecting wetlands
- Hydrological connections are a major sink of nitrogen (delay transport, store in vegetation…)

Ipswich river wetland
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Cycling and stochiometry of nitrogen

➡ **Assimilation into biomass is the main removal flux for NO3-**

- **Cycling** : Unidirectional uptake of nitrogen rather than cycling with other elements
- **Stochiometry**: Variation of the strength relationship between the decline in denitrification efficiency with increasing NO3- concentrations

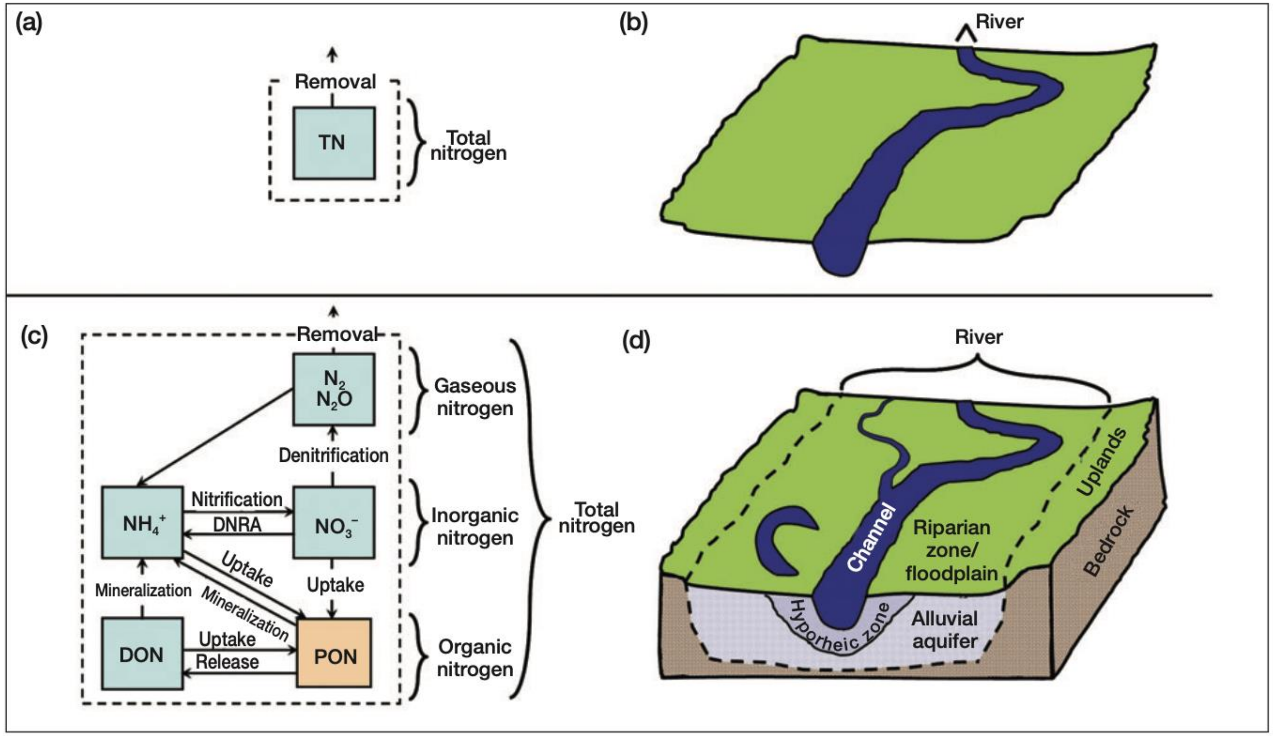


Figure 5. River-network models typically describe (a) one-way total nitrogen flux from (b) river channels. A more holistic conceptual model of nitrogen cycling in river ecosystems recognizes (c) multiple forms of nitrogen that undergo numerous transformations and (d) the role of non-channel river ecosystem components in nitrogen dynamics, including the hyporheic zone, alluvial aquifer, and floodplain/riparian complex. DON = dissolved organic nitrogen; PON = particulate organic nitrogen; NH_4^+ = ammonium; NO_3^- = nitrate; N_2 = dinitrogen gas; N_2O = nitrous oxide; DNRA = dissimilatory nitrate reduction to ammonium.

Temporal dynamics

Ignoring the seasonality of flows: underprediction of nitrogen removal during peak periods

- River flow is highly variable
- Variations in daily runoff influences denitrification patterns *(Wollheim et al. 2008 / Liu, Ji et al.)*
- Example of storms pulse *(Valett et al. 2005)*
- Dynamic hydrologic assumption > Steady state hydrologic assumption

(3) J. Liu, D. Tetzlaff, T. Goldhammer, S. Wu, and C. Soulsby, "Quantifying changes and trends of NO3 concentrations and concentration-discharge relationships in a complex, heavily managed, drought-sensitive river system," *Journal of Hydrology*, vol. 622, pp. 129750–129750, May 2023

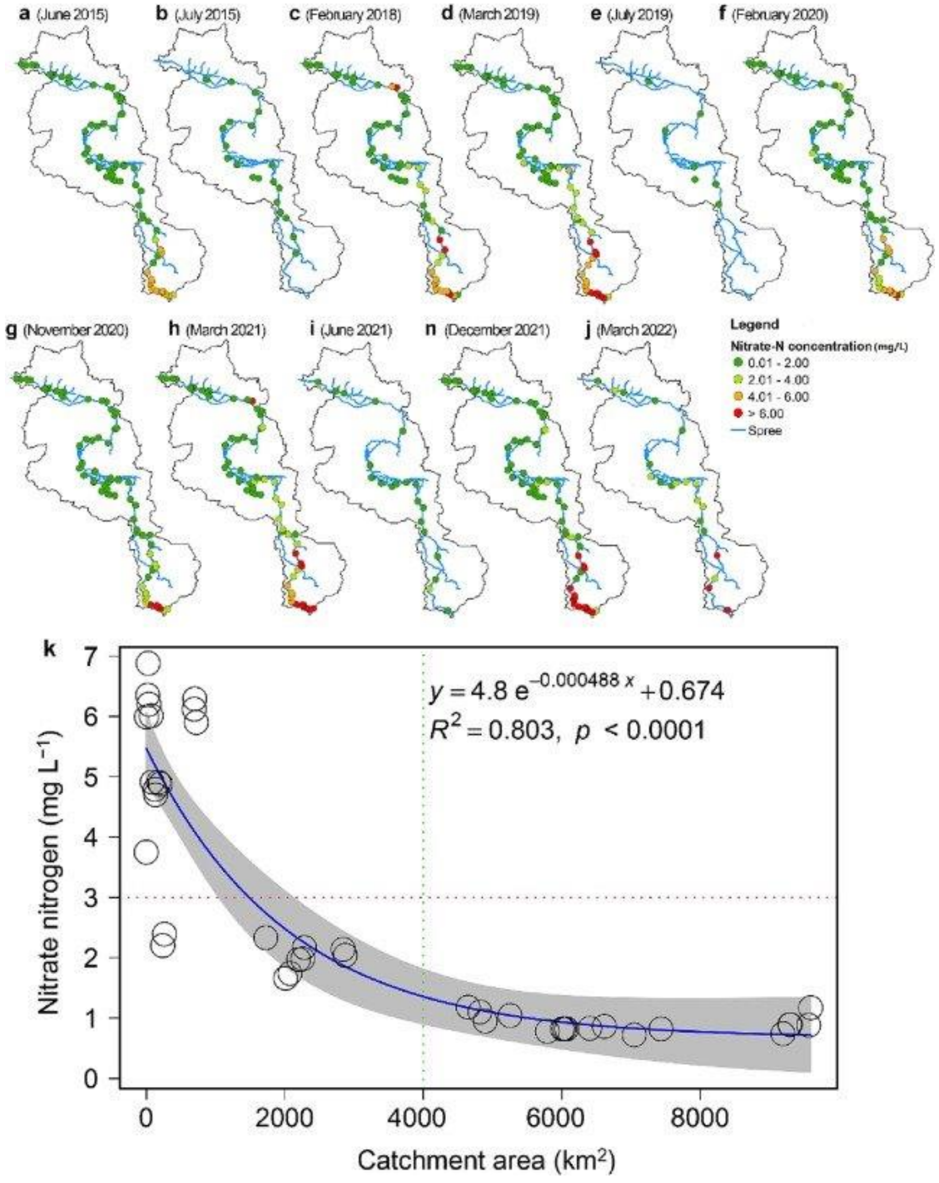


Fig. 3. Monthly spatial distribution of stream nitrate concentrations (upper plot) and relationship with catchment area over the main river channel

Conclusion

Do the assumptions used for current nitrogen exchange models in rivers provide coherent and reliable results?

Conventional **models are limited** when representing nitrogen dynamics across entire river networks

Incoherent results in most of the basins studied, due to the **simplistic hypotheses on the topography, morphology and one-way nitrogen cycling** of watercourses, and stationary hydrological regimes.

Non-channel areas, such as wetlands, hyporheic areas and floodplains, significantly **influence nitrogen cycles** but are often neglected in models.

→ Need to develop the model in order to predict **anthropogenic and environmental perturbations** on river-networks

Perspectives

Integration of river-network and catchment ecohydrologic models

→ Better estimate water and nutrient intake by taking into account spatial and temporal variations, and human influences

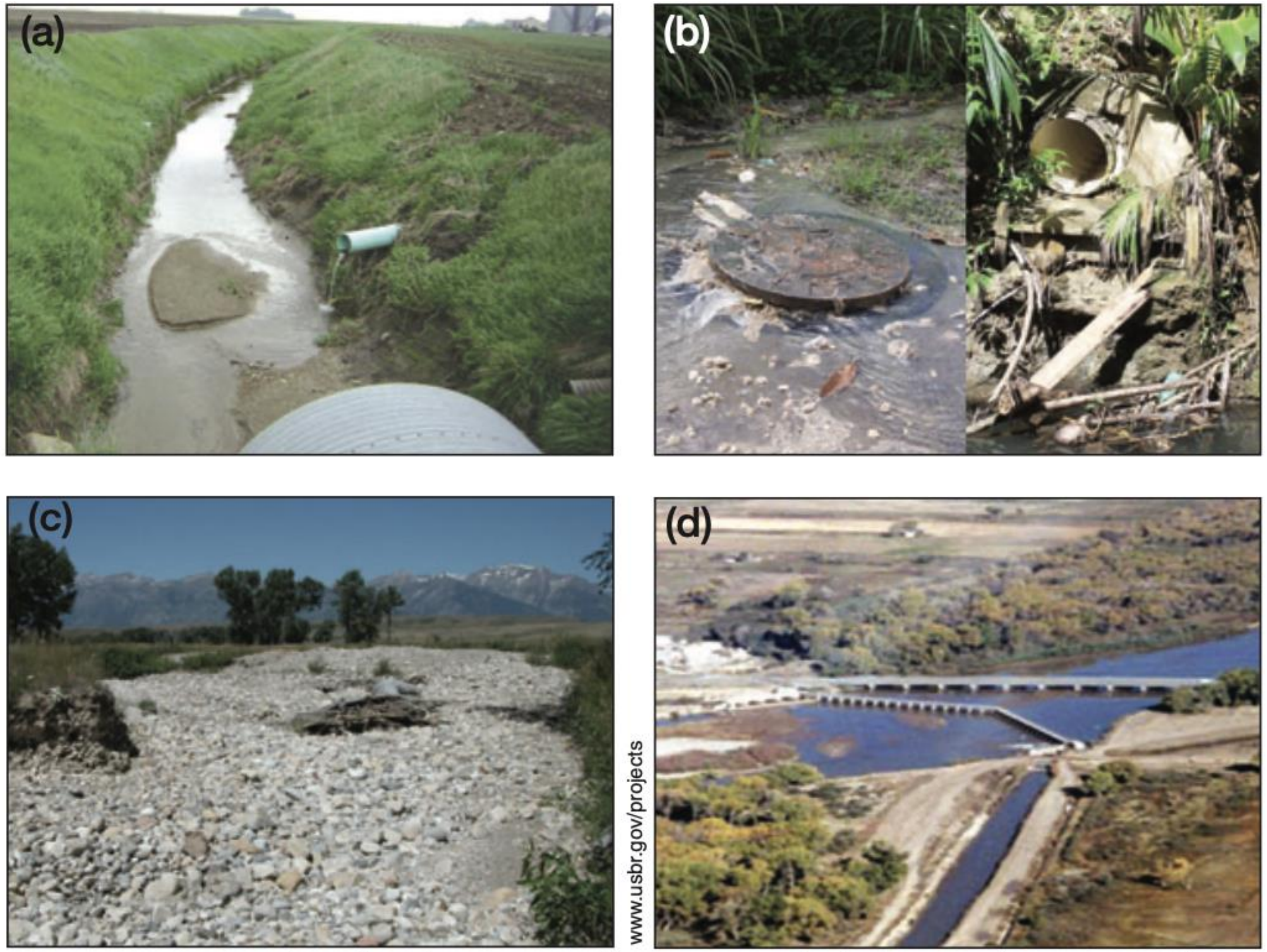


Figure 3. *Examples of anthropogenic alterations to hydrology and nitrogen delivery that deviate from assumptions within modeled catchments. (a) Agricultural tile drains, Rabbit River, MI, catchment. (b) Sanitary sewer overflow (left) and straight-pipe sewer discharge (right), Río Piedras, PR, catchment. (c) Alluvial stream reach irrigated to dryness, Flat Creek, WY, catchment; (d) Water abstraction, Isleta diversion, Rio Grande, NM.*

Perspectives

Integration of connection with nitrogen retention areas (floodplains, riparian wetlands, and hyporheic areas)

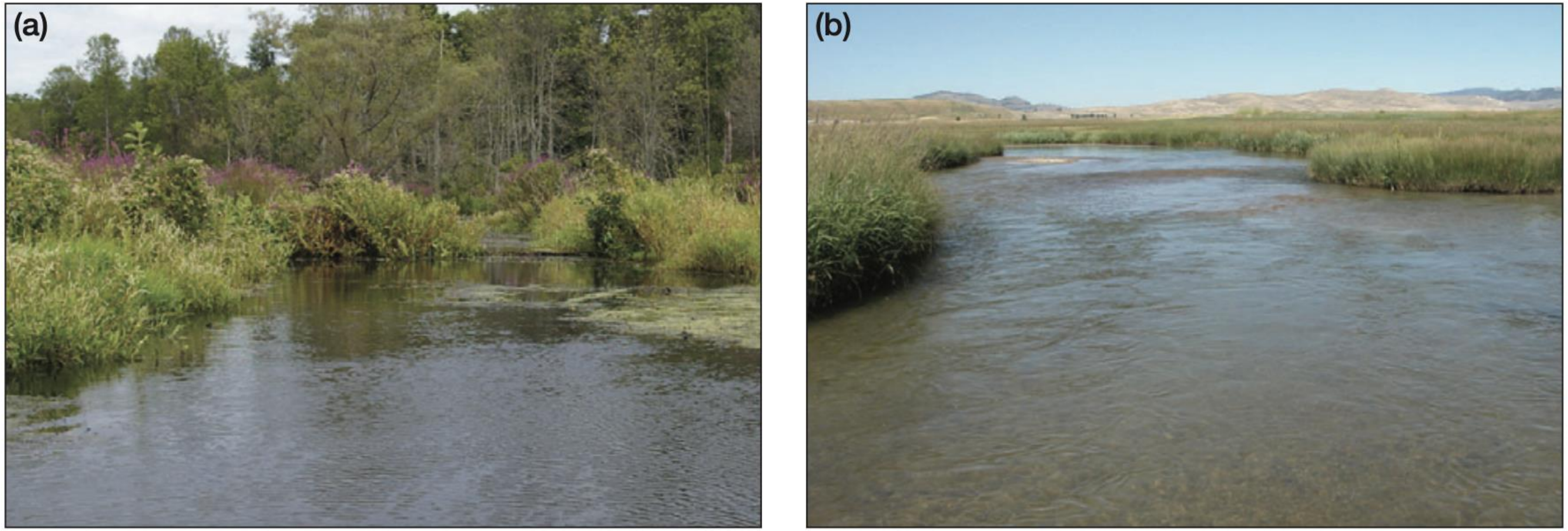
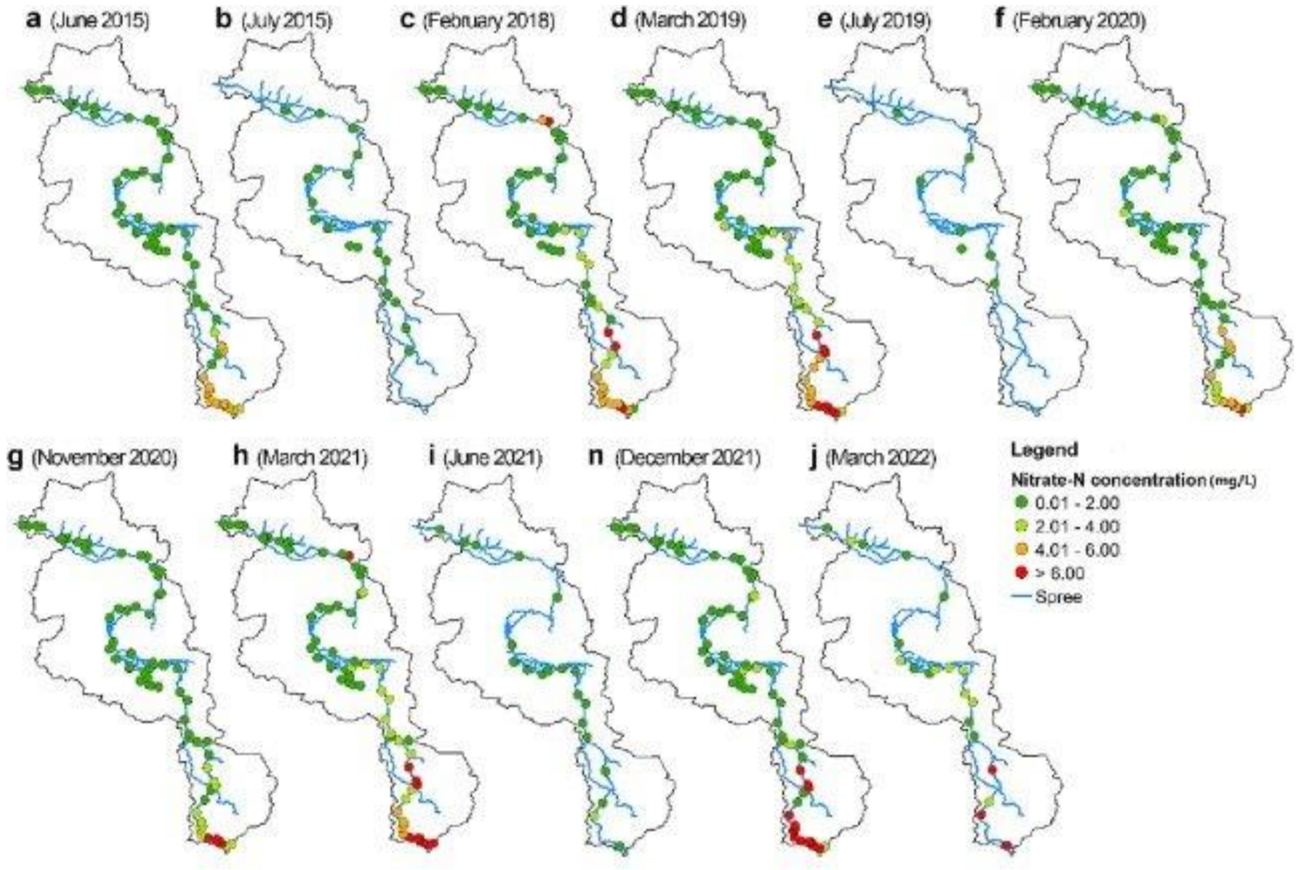


Figure 4. *Examples of river hydrogeomorphology that deviate from assumptions within modeled catchments. (a) Riverine wetlands, Ipswich River, MA, catchment. (b) Spring-fed alluvial stream reach with high hyporheic exchange, Flat Creek, WY, catchment.*

Perspectives

Integrate variable hydrological regimes and temporary connections between canals and surrounding areas, to reflect seasonal variations and extreme hydrological events.



(3) J. Liu, D. Tetzlaff, T. Goldhammer, S. Wu, and C. Soulsby, “Quantifying changes and trends of NO3 concentrations and concentration-discharge relationships in a complex, heavily managed, drought-sensitive river system,” *Journal of Hydrology*, vol. 622, pp. 129750–129750, May 2023

Perspectives

Taking into account microbial biomass, respiration, and ecological stoichiometry, with couplings between nitrogen cycles and other elements

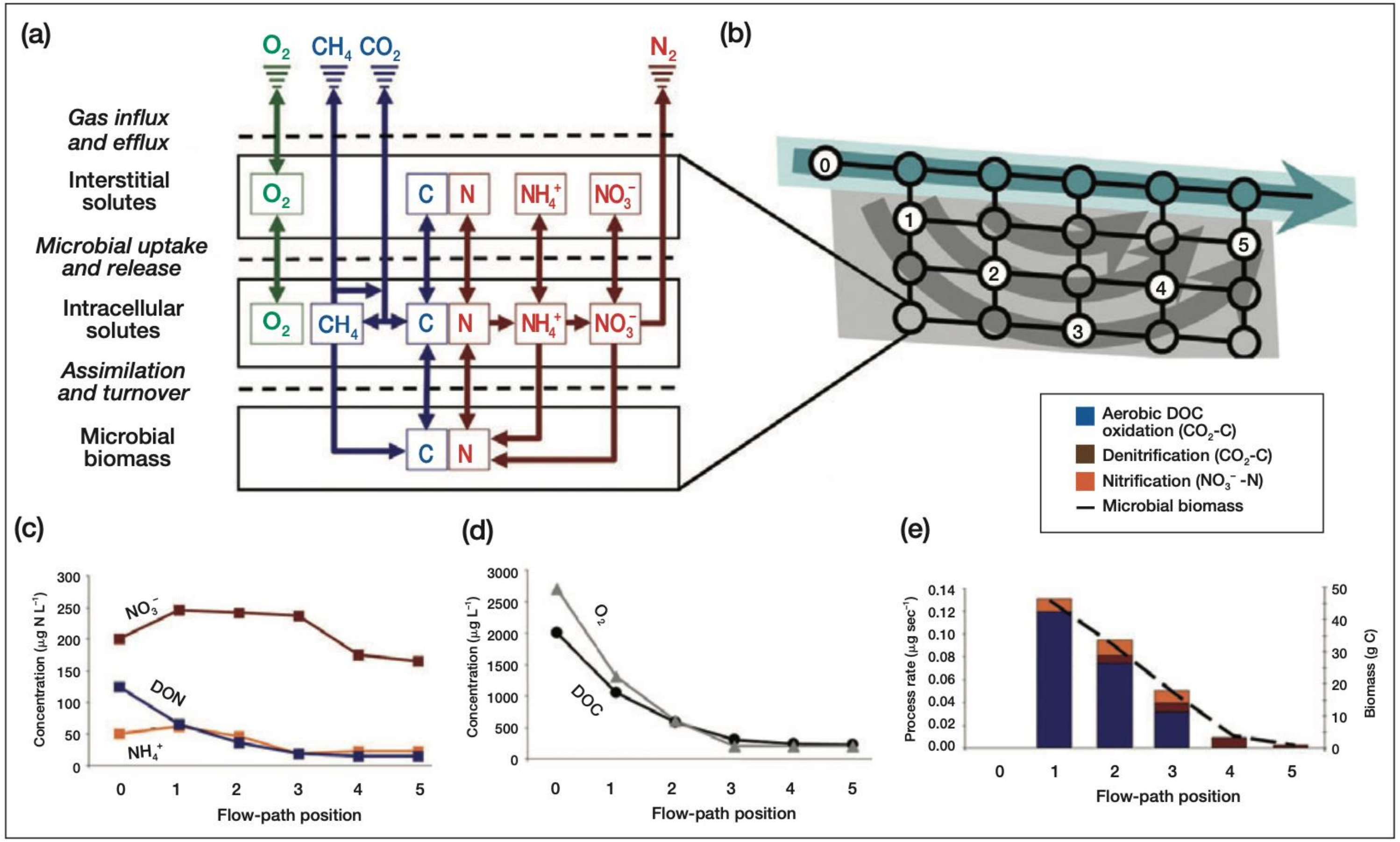


Figure 6. Simulation of multi-element biogeochemical cycles along a hyporheic flow path. (a) Schematic of a prototype biogeochemical model (AM Helton et al. unpublished) that simulates microbial uptake and utilization and/or production of dissolved organic matter, oxygen, nitrate, ammonium, and methane. The model operates by assuming that microbial assemblages will use the suite of metabolic pathways that will maximize microbial growth, as co-limited by the availability of carbon, nitrogen, and oxygen as electron donors/acceptors and the stoichiometric ratio of carbon and nitrogen required for building biomass. (b) Simulated hydrologic flow paths in a simple two-dimensional implementation of a mechanistic model of surface water flow and hyporheic exchange (hydrology model described by Poole et al. 2006). We combined the two models to simulate hydrologic solute flux and (c) concentrations of different nitrogen forms (DON = dissolved organic nitrogen), (d) dissolved oxygen and dissolved organic carbon (DOC), and (e) microbial activity and biomass along an idealized hyporheic flow path (numbered circles in [b]).

Questions ?

Bibliography

(1) Grimvall, Anders & Sundblad, Eva-Lotta & Sonesten, Lars. (2017). *Mitigating marine Eutrophication in the presence of strong societal driving forces*.

(2) T. Maavara *et al.*, "River dam impacts on biogeochemical cycling," *Nature Reviews Earth & Environment*, vol. 1, no. 2, pp. 103–116, Feb. 2020

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