Microbial Nitrogen Transformations in Regenerative Stormwater Conveyance Systems

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Outline

- 1. RSC for nitrogen treatment and stream restoration
- 2. Nitrogen cycle background
- 3. Town Creek Culvert Project
- 4. Nitrogen transformations in Town Creek RSCs

Microbes transform nitrogen in stormwater control measures



- Nutrient treatment relies heavily on microscopic organisms
- Nitrogen fixation vs. denitrification
 - Microbes importing and exporting N
- Domestic and industrial activities increase N inputs

Urbanization impairs stream health

A. Symptoms



B. Hydrologic Drivers



- Increased N inputs
- Decreased time/space for denitrification
- Degraded stream morphology

Regenerative Stormwater Conveyance (RSC) for stream restoration

Series of pools, riffle weirs, media beds

- Hydrologic restoration (Cizek et al., 2017. ASCE)
 - Infiltration
 - Increase HRT
 - Evapotranspiration

- Denitrification environment
- Variable nitrogen treatment
 - 16-37% decrease (Duan et al., 2020. Sci Tot Env)

Hawkey, J. 2013. University of Maryland.

Why does RSC nitrogen treatment vary?

> Is it because of environmental controls on denitrification?



Hawkey, J. 2013. University of Maryland.

Could stagnant in-stream RSC pools support nitrogen fixation (N fix)?

Evidence of N fix in stormwater ponds Goeckner et al., 2024 Gold et al., 2017 N fix not yet measured in RSC pools

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Nitrogen cycle highlights

- Major microbial processes to emphasize:
 - Nitrogen fixation ($N_2 \rightarrow NH_3$)
 - Nitrification (NH₃ \rightarrow NO₃⁻)
 - Denitrification (NO₃⁻ \rightarrow N₂O \rightarrow N₂)
- Nitrogen processes commonly measured in stormwater infrastructure
- Denitrification responsible for complete N removal and drives N treatment

Simplified nitrogen cycle

Atmosphere is major reservoir

- 78% of atmosphere
- N₂ is highly stable
- Reactive N
 required for all
 life



Biological Nitrogen Fixation (BNF)

- Energetically demanding
- Conditions:
 - Soil
 - Water
 - Stormwater ponds
 - Low O₂
 - Rely on C source (or photosynth)



Human sources of fixed nitrogen



- Haber-Bosch process (synthetic fertilizers)
- Agricultural BNF (legumes: soybeans, clover)
- Fuel combustion

Atmospheric transport moves fixed N



- Short-range transport (reactive N)
- Nonpoint source pollution

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Fowler et al., 2013. Philos Trans R Soc Lond B Biol Sci.

Nitrogen deposition hotspot in ENC

- Livestock waste in open-air lagoons
- Albemarle-Pamlico Sound within transport range
- ~100,000 t NH₃ yr⁻¹ from Coastal Plain



Nitrogen exported in watersheds



- Reactive N (NO₃⁻, NH₄⁺) transported in water
- Accumulation of N in receiving water (e.g., estuaries)

Basu et al., 2022. Nature Geoscience

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Transformations of reactive nitrogen

- Processes in "forward" and "reverse" directions
- Nitrification
 - O₂ (aerobic)
 - Water column (well mixed)
 - Soil/sediment



Returning reactive N to atmosphere



- Denitrification removes reactive N and returns to atmosphere
- Controls on denitrification (carbon, nitrate, oxygen)

Fowler et al., 2013. Philos Trans R Soc Lond B Biol Sci.

Breathing with oxygen

Why do humans use oxygen?

- Harvest energy from (organic) carbon compounds
 - Eat carbon (carbs, fats, proteins)
 - Inhale O₂
 - Exhale CO₂



Nitrate as an alternative to oxygen

- O₂ provides largest energy payoff
 - Reason why animals are large and can do expensive metabolic processes
- BUT what happens if O₂ isn't around?
 - Microbes can still thrive there
- NO₃⁻ is next most efficient option



Denitrification (breathing w/o oxygen)



Humans:

- Eat: carbon
- Inhale: O₂
- Exhale: CO₂



carbon source (woodchips)

Denitrifiers (microbes):

- "Eat": carbon
- "Inhale": NO_3^-
- Exhale: N_2O , N_2 , CO_2

Hotspots and hot moments

- O₂, NO_{3⁻}, and C are heterogenous in space and time
- Denitrifiers can use O₂ if available and switch to NO₃⁻ when O₂ is no longer available
- Consequence for observed denitrification
 - Large variation in hot spots/moments
 - Contributes to wide range of treatment performance in RSC



Bernard-Jannin et al., 2017. Ecological Engineering

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Can denitrification be restored?

- Denitrification must balance reactive N inputs
- Targeted restoration in high NO₃⁻ areas



Town Creek Culvert Project



MOVING FROM GRAY → GREEN



Photos: M. O'Driscoll & City of Greenville

Impervious cover and nutrient impairment

Town Creek, Greenville, North Carolina

- High proportion of impervious area (~66%)
- ~75% buried stream
- Town Creek and Tar River, nutrient impaired (NCDEQ, 303(d))
- Flood risk prompted daylighting and green stormwater infrastructure installation (2018-2020)



Robbins, J. 2017. Geol. Sciences (M.S. Thesis). East Carolina University.

Daylighting Town Creek





BEFORE (TOWN CREEK CULVERT)





DURING (DAYLIGHTED TOWN CREEK CULVERT)





AFTER (REGENERATIVE STORMWATER CONVEYANCE)

Two RSCs, different designs

- In-stream
 RSC
 - Baseflow
 and
 stormflow
- Dry RSC
 - Stormflow
 - Smaller volume



Research Questions

- How do seasons and storms influence N cycling processes in RSCs that process stormwater only compared to in-stream RSCs that treat baseflow and stormflow?
- How do RSC denitrification rates compare across space?
 - Dry vs. in-stream RSC
 - Upstream vs. downstream sampling locations

Dry RSC



How do RSC denitrification rates compare across space?

Submerged sediment vs. unintentional sediment island



How does stormflow N treatment compare to baseflow?



Optimal Nutrient Treatment Conditions

Minimal Nutrient Treatment Conditions

O'Driscoll et al., 2022

Pre- vs. Post-Restoration: RSC denitrification potential



Denitrification Enzyme Assay







Greater denitrification potential post-RSC

- RSC > pre-RSC
 - Seasonal variation in RSC data
- Dry RSC similar to pre-RSC stream sediment



Sample Type and Restoration Status

Denitrification potential: in-stream > dry, greatest in summer





In-stream RSC

Regenerative Stormwater Conveyance (RSC) Type

Nitrate & nitrite decline along instream RSC



Nitrogen balance: source vs. sink



Net denitrification vs. N-fixation



Net denitrification vs. N-fixation



Dry RSC: greatest sediment denitrification

- All sediment net denitrifying, none net N-fixing
- Greatest denitrification rate in dry RSC
 - Hot spots of N in dry RSC?



Water column: no net denitrification



Sample Location

Upstream

Downstream

What about stormflow?

- Tropical Storm
 Ophelia
- Sep 22-23, 2023
- Landfall near Emeral Isle, NC



Tropical Storm Ophelia

- 4.52" rain in Greenville
- Significant flooding along Green Mill Run



RSC water levels during TS Ophelia



Sample Location 📥 Upstream 🔻 Downstream

N concentrations, TS Ophelia

In-stream RSC

Dry RSC





N concentrations, TS Ophelia

In-stream RSC

Dry RSC







Summary

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GlaxoSmithKline

Questions?

microbial ecology

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https://www.peraltalab.com/

https://github.com/colfin/Denitrification_Enzyme_Assays https://github.com/colfin/TownCreekWater

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Link to data and code repositories Colin Finlay Department of Biology East Carolina University