NC STATE UNIVERSITY

Transforming denitrifying bioreactor research and applications: unveiling the inside of the black box

François Birgand[1], Bryan Maxwell[1], Louis Schipper[4], Laura Christianson[2], Matt Helmers[3], Mohamed Youssef[1], Shiying Tian[1], David Williams[5], George Chescheir[1,] Wenlong Liu[1]

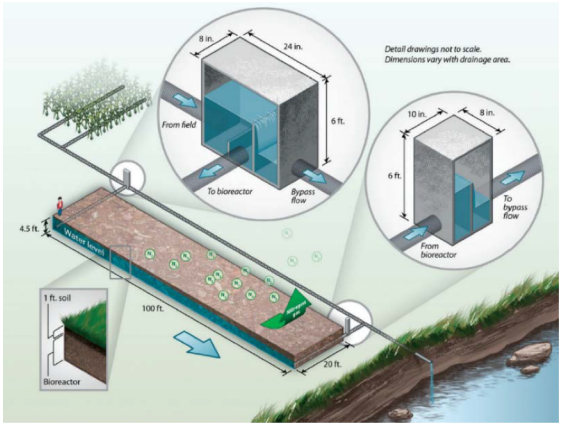
1 2 3 4 5

NIFA Award #: 2016-67019-25279

NC STATE UNIVERSITY

What are woodchip bioreactors?

- Agricultural BMP
- Intercept tile drainage
- Targets nitrate removal
- ~20 year lifespan
- NRCS approved
- 2-22 g N m^{-3} d^{-1} in field
- Mainly seen in Midwest



Christianson and Helmers, 2011

NC STATE UNIVERSITY

From the literature

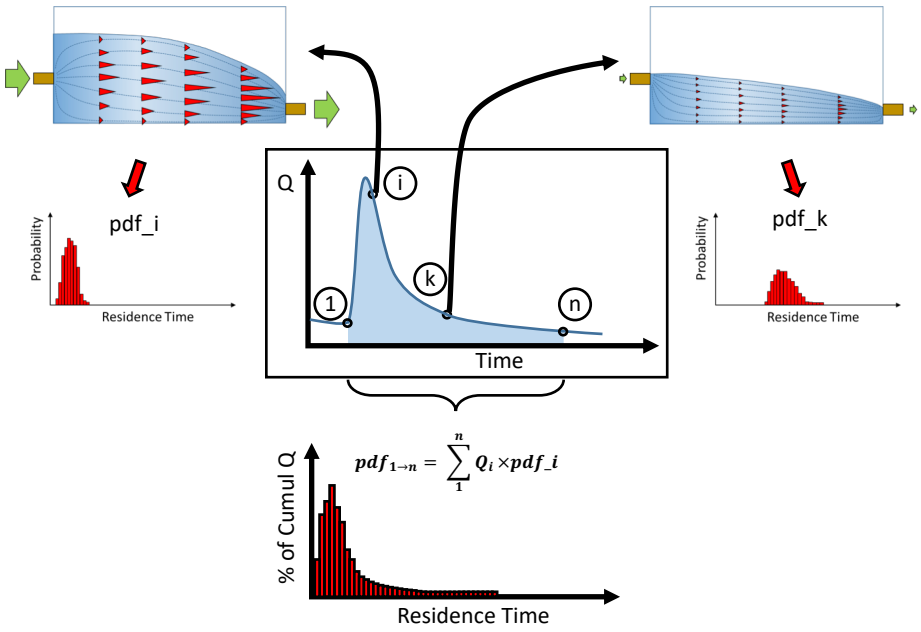
- Reported nitrate removal efficiencies varying from less than 10% to more than 90%
- Decrease of removal efficiency within one to five years from >60% to <20%

NC STATE UNIVERSITY

Research questions

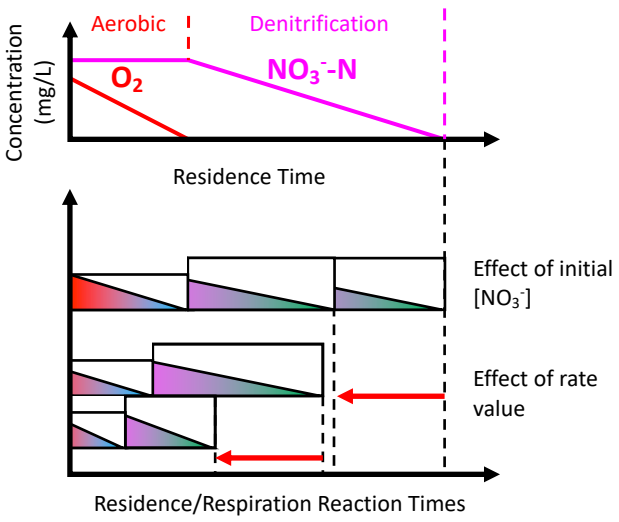
- Why are there so much discrepancies in the reported removal rates?
- What are the factors driving the nitrate removal efficiencies, and its decrease over time?
- What can we do to 'rejuvenate' bioreactor and maintain removal efficiency?
- Can we provide guidelines for maintaining and increasing nitrate removal efficiencies?

NC STATE UNIVERSITY



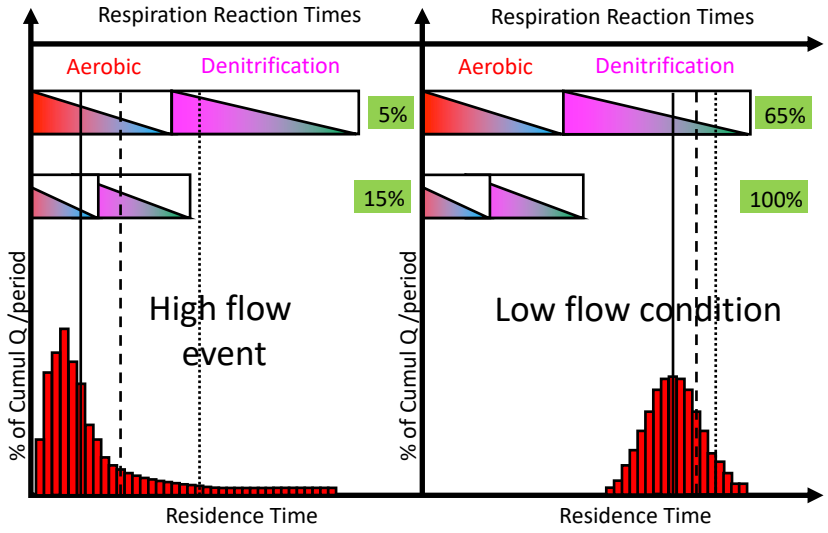
NC STATE UNIVERSITY

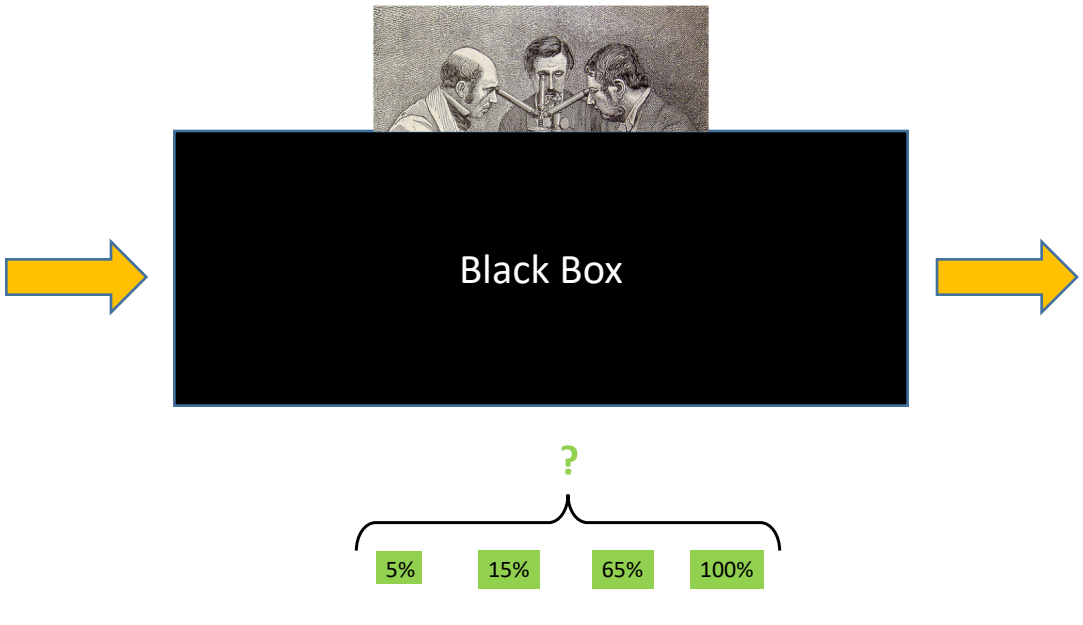
Respiration rates and residence time



NC STATE UNIVERSITY

Apparent removal rates





NC STATE UNIVERSITY

Objectives

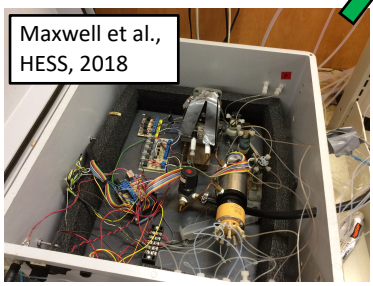
- Track and quantify the fate of water, nitrate, and DOC to reconstruct the apparent functioning
- Measure in the lab and in the field the aqueous and gaseous removals and emissions associated with the use of bioreactors
- Find solutions to 'rejuvenate' woodchip bioreactor
- Integrate this new knowledge into 2D biogeochemical computer models
- Use the models to explore and define novel and optimized design and management guidelines

NC STATE UNIVERSITY

Method

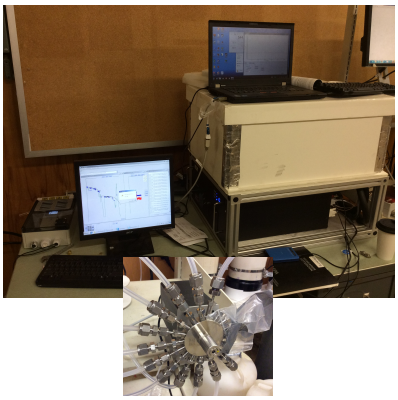
- Use high resolution instruments to measure gaseous and aqueous concentrations
- Lab column experiments
- 2-5 week long experiments in field bioreactors in North Carolina, Iowa, New Zealand
- Process-based modeling

NC STATE UNIVERSITY



Lab microvolume MPS

Field macrovolume MPS



15 min resolution on gaseous emissions of CO_2 and N_2O (+ isotopomers)

NC STATE UNIVERSITY

1. Effect of wetting and drying cycles to rejuvenate bioreactors: replicated column experiment in the lab

NC STATE UNIVERSITY

What are drying-rewetting cycles?

- Cycle between dry/wet conditions
- Gradient of conditions

Dry — Unsaturated — Wet — Saturated

- Based on literature:
  - Stimulates respiration
  - Increases mineralization of C & N
  - Changes in microbial community

NC STATE UNIVERSITY

Experimental Hypothesis

Do drying-rewetting cycles in woodchip bioreactors significantly improve treatment performance by increasing nitrate removal rates?

denitrification…

+ Carbon

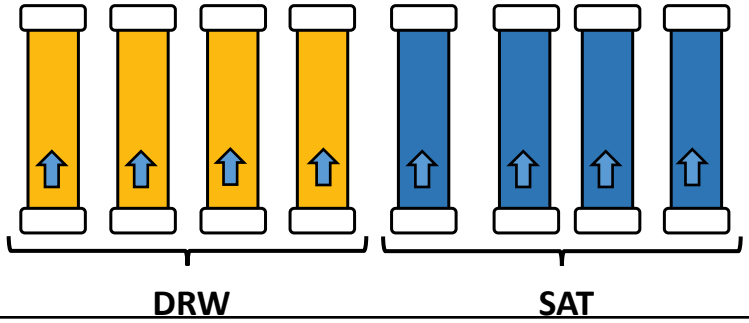
Aerobic breakdown increases available carbon

DENITRIFICATION!!!

NC STATE UNIVERSITY

Methods

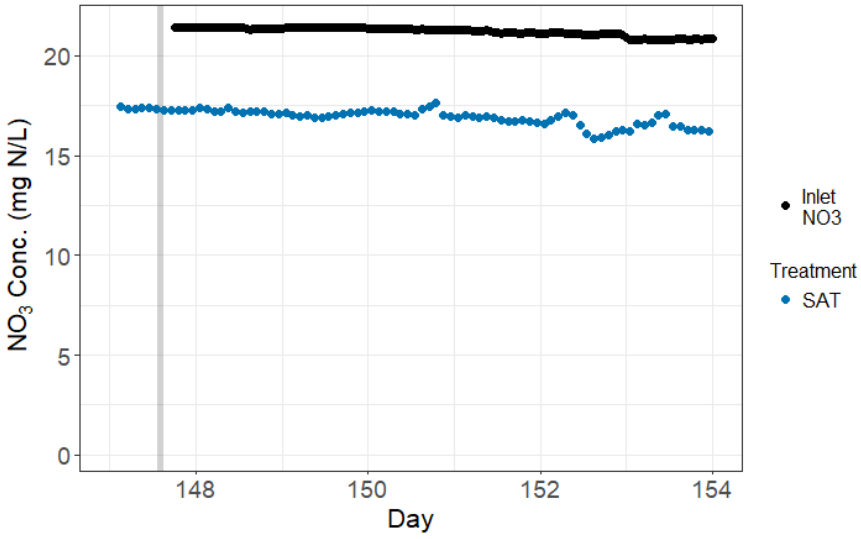
- Lab experiment with 8 woodchip-filled columns
- Continuous upflow (~8 hr HRT) for 10 months, ~20 mg NO3-N/L
- Two treatment groups
  - DRW – Drained once a week, unsaturated for 8 hr
  - SAT – Continuously saturated
  - Both columns received SAT treatment for first 3 weeks



NC STATE UNIVERSITY

Results : High frequency data

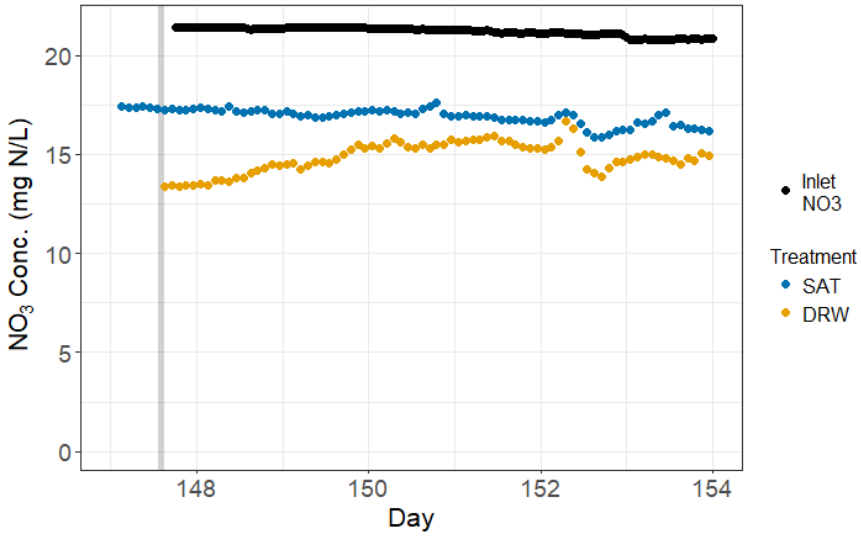
84 measurements per column per week



NC STATE UNIVERSITY

Results : High frequency data

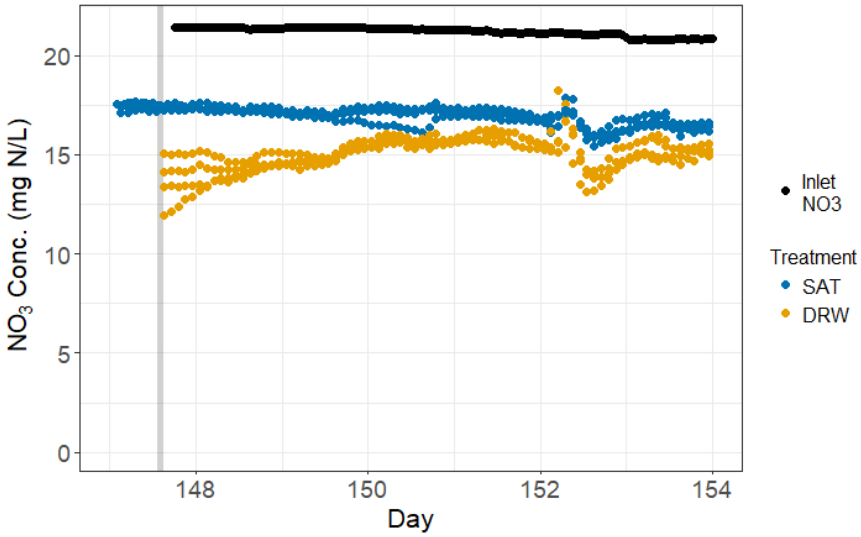
84 measurements per column per week



NC STATE UNIVERSITY

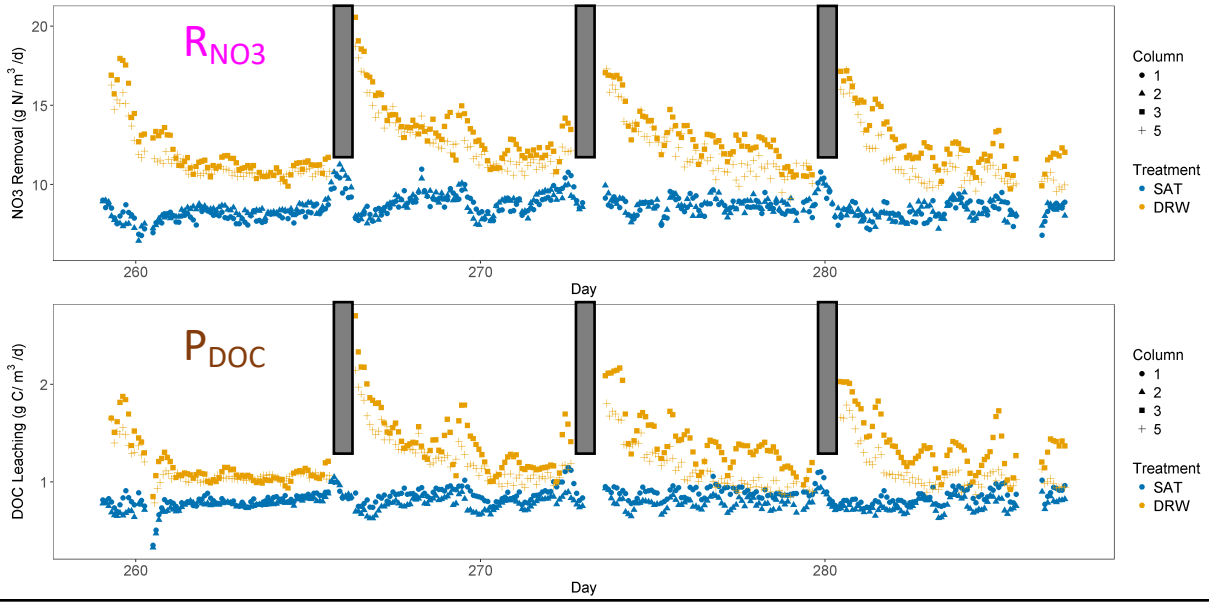
Results : High frequency data

640 measurements per week for all columns



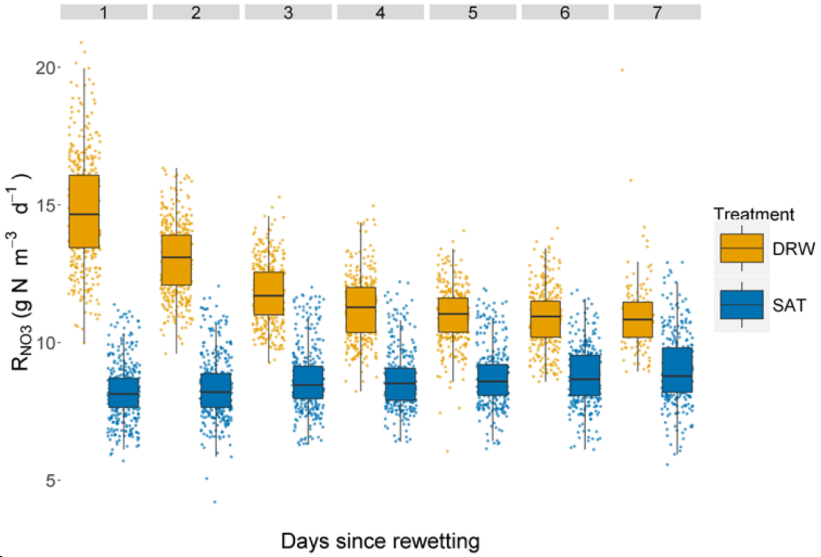
NC STATE UNIVERSITY

Rapid and Large response to DRW cycles



NC STATE UNIVERSITY

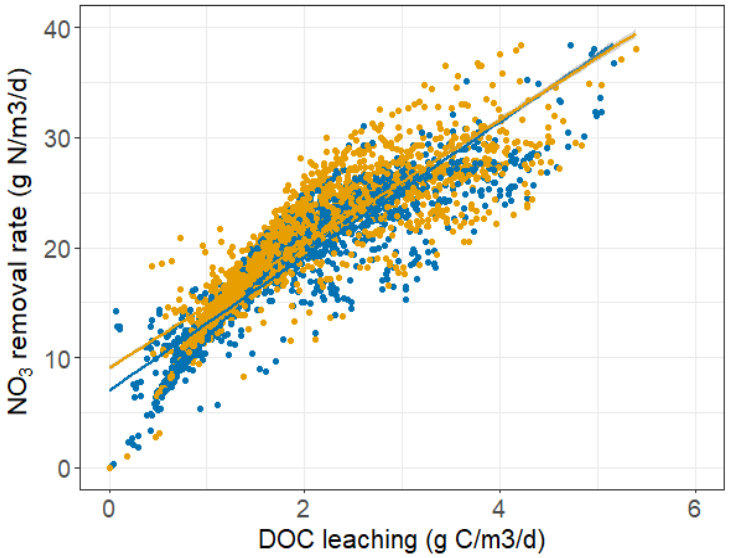
Nitrate response to DRW cycles



Removal rates in DRW columns decreased quickly within 3 days of rewetting, and were still significantly higher 7 days later

NC STATE UNIVERSITY

Does DOC production explain NO3 removal?



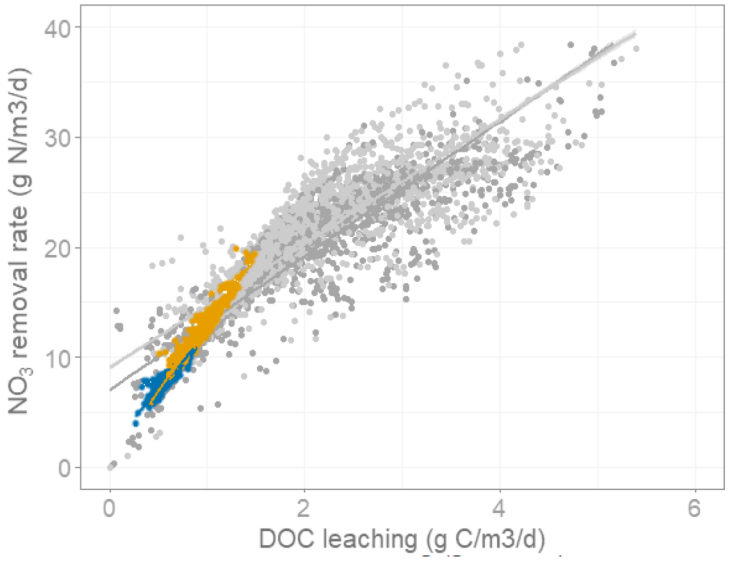
Days 20 - 100

Treatment
SAT
DRW

DOC production (leaching) rates explained most of variance in removal (R^2 : 0.90 – 0.97)

NC STATE UNIVERSITY

Does DOC production explain NO3 removal?



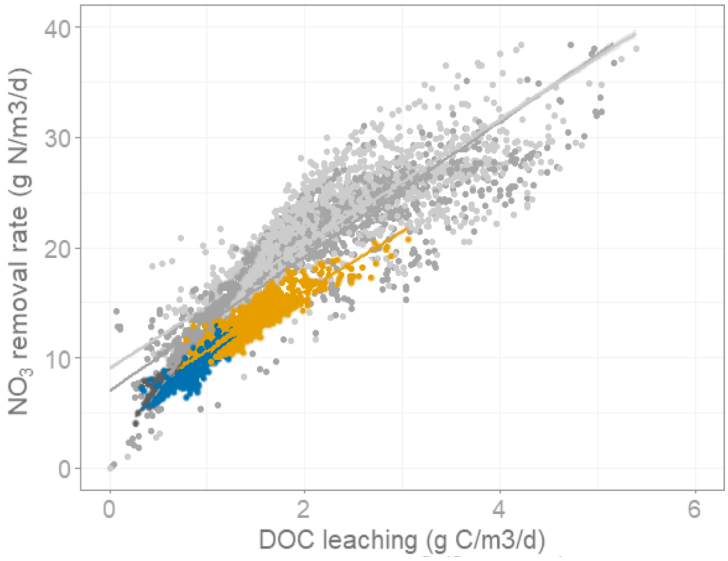
Days 140 - 180

Treatment
SAT
DRW

DOC production (leaching) rates explained most of variance in removal (R^2 : 0.90 – 0.97)

NC STATE UNIVERSITY

Does DOC production explain NO3 removal?



Days 250 - 290

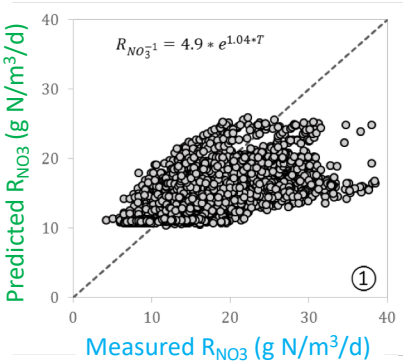
Treatment
SAT
DRW

DOC production (leaching) rates explained most of variance in removal (R^2 : 0.90 – 0.97)

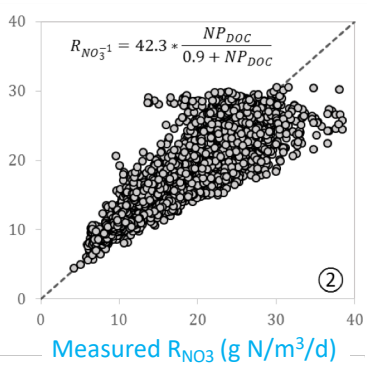
NC STATE UNIVERSITY

Column modeling insights

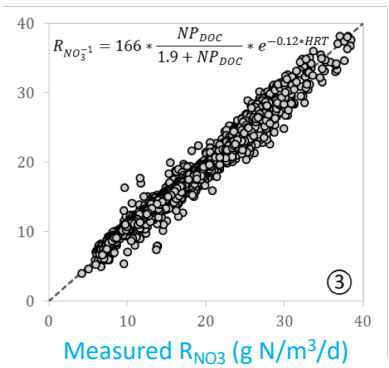
T°C effect



T°C effect + P_{DOC}



T°C effect + P_{DOC} + Negative HRT



NC STATE UNIVERSITY

Column Experiment Highlights

- Drying-rewetting cycles increased nitrate removal rates in woodchip bioreactors by 30-80%
- Aerobically-produced DOC is a main driver
- Long HRT result in building of inhibitory substances
- DRW have ~10x less N_2O emissions
- Microbial community shift
- Continuous saturation may not be best design for treatment systems relying on anaerobic processes!

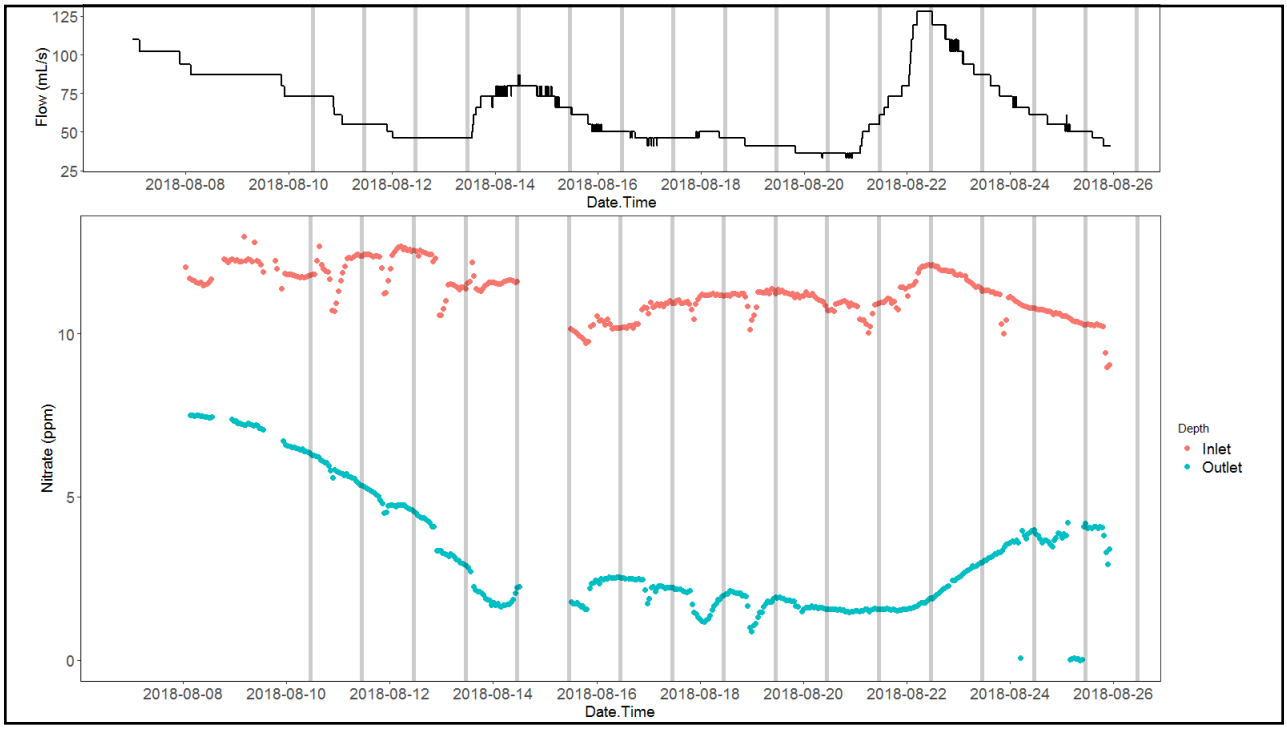
NC STATE UNIVERSITY

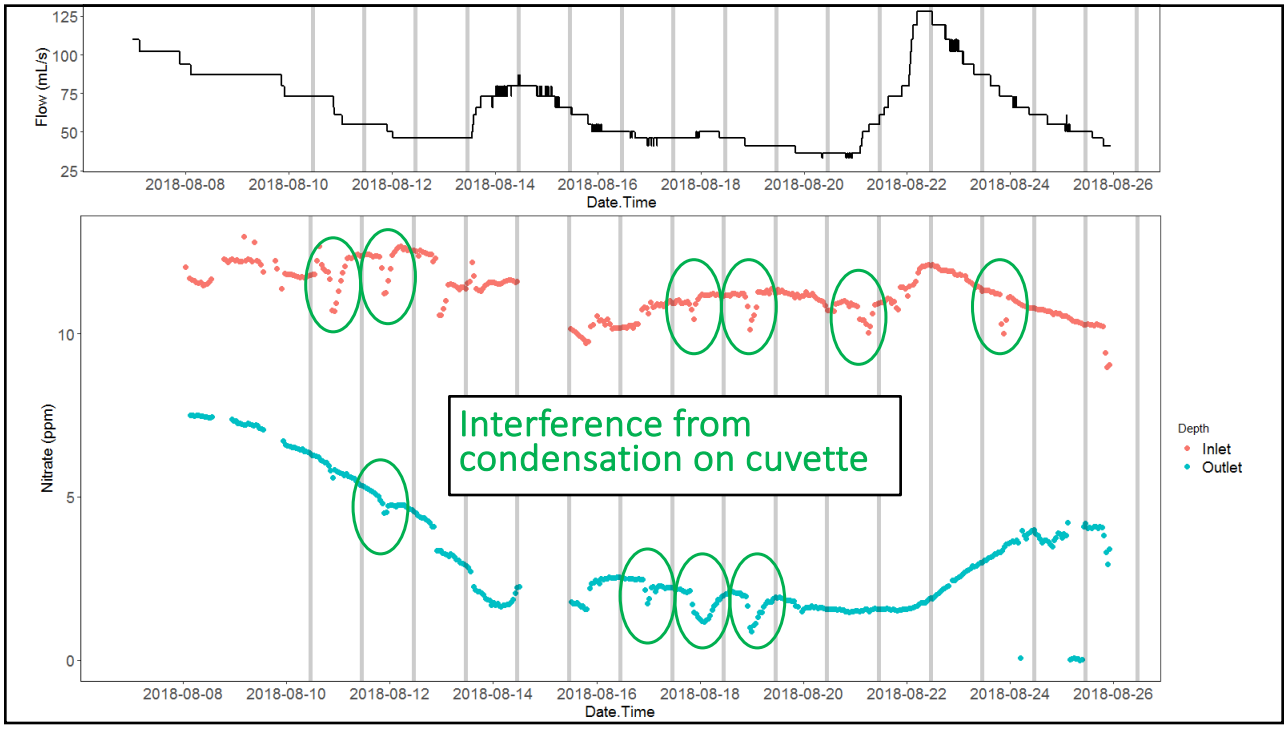
Results from the field

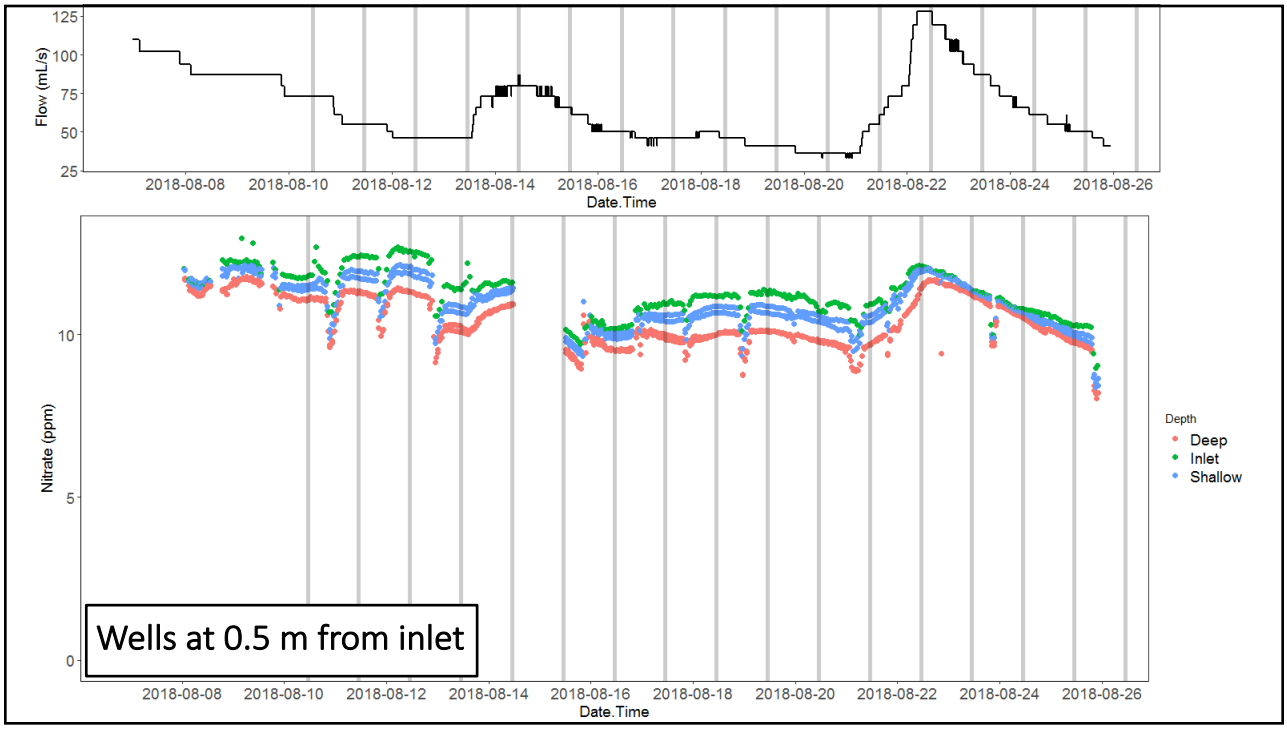
Plymouth, NC

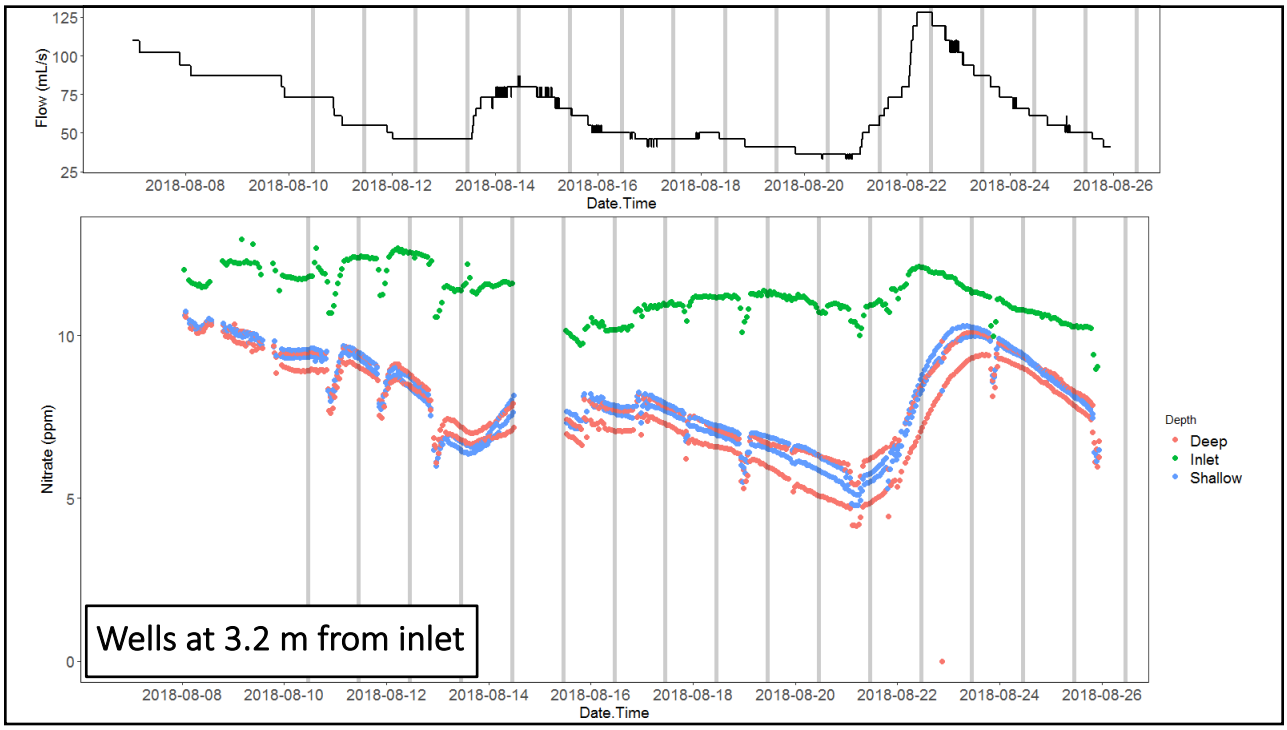
Nashua, IA

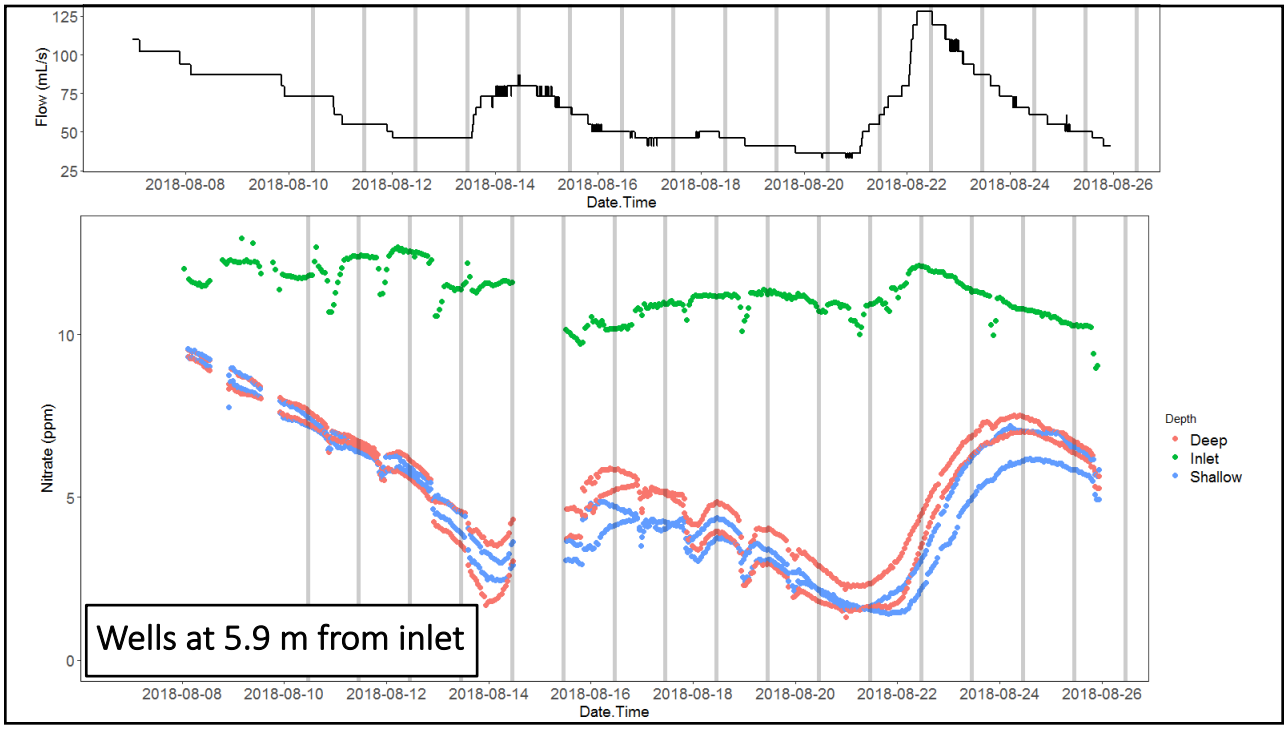
Tatanui, NZ

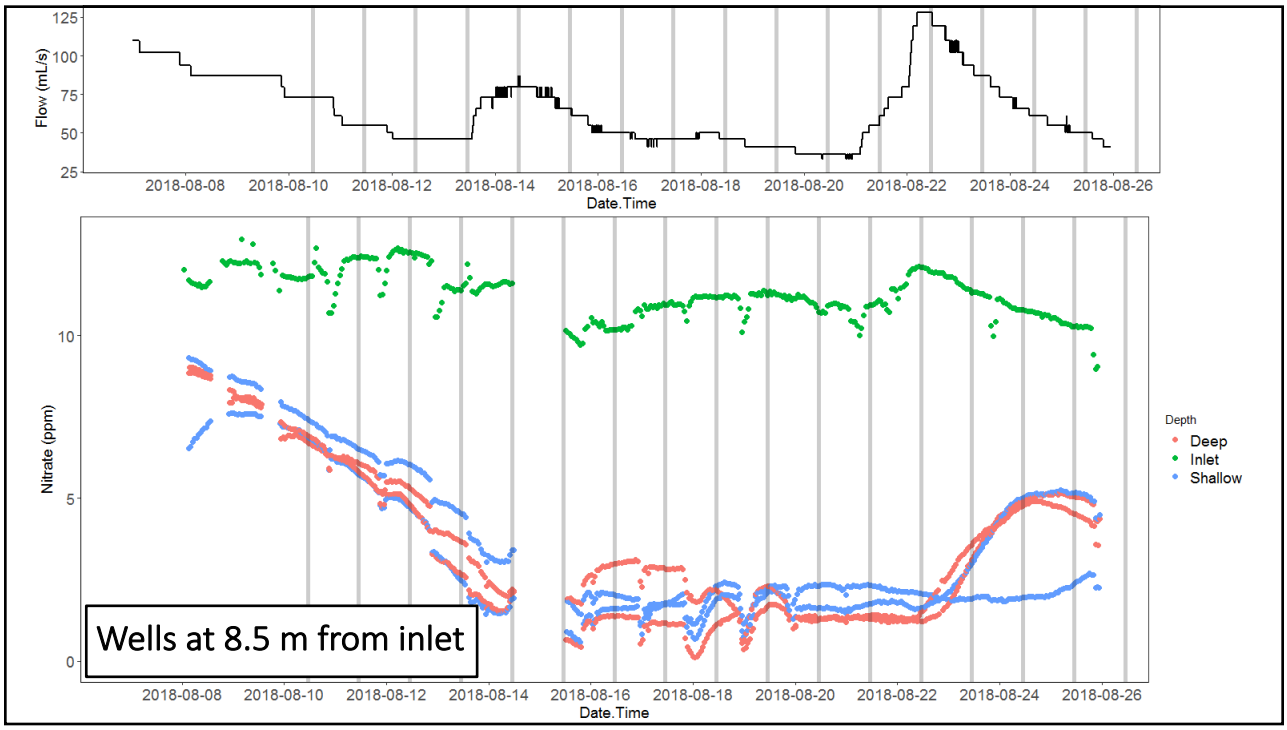

Flow (mL/s)
125
100
75
50
25
2018-08-08
2018-08-10
2018-08-12
2018-08-14
2018-08-16
2018-08-18
2018-08-20
2018-08-22
2018-08-24
2018-08-26
Date.Time
Nitrate (ppm)
10
5
0
Depth
Inlet
Outlet

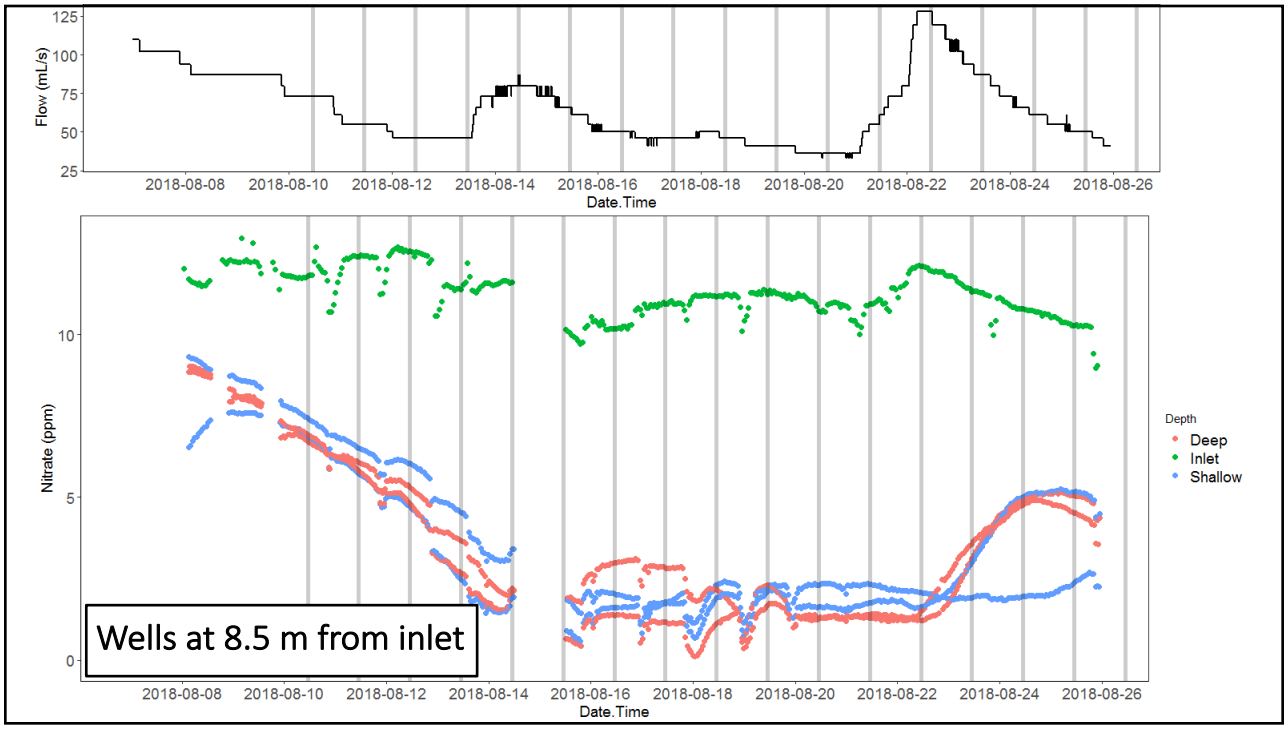

Flow (mL/s)
125
100
75
50
25
2018-08-08
2018-08-10
2018-08-12
2018-08-14
2018-08-16
2018-08-18
2018-08-20
2018-08-22
2018-08-24
2018-08-26
Date.Time
Nitrate (ppm)
10
5
0
Interference from condensation on cuvette
Depth
Inlet
Outlet


Flow (mL/s)
125
100
75
50
25
2018-08-08
2018-08-10
2018-08-12
2018-08-14
2018-08-16
2018-08-18
2018-08-20
2018-08-22
2018-08-24
2018-08-26
Date.Time
Nitrate (ppm)
10
5
0
Depth
Deep
Inlet
Shallow
Wells at 0.5 m from inlet


Flow (mL/s)
125
100
75
50
25
2018-08-08
2018-08-10
2018-08-12
2018-08-14
2018-08-16
2018-08-18
2018-08-20
2018-08-22
2018-08-24
2018-08-26
Date.Time
Nitrate (ppm)
10
5
0
Depth
Deep
Inlet
Shallow
Wells at 3.2 m from inlet


Flow (mL/s)
125
100
75
50
25
2018-08-08
2018-08-10
2018-08-12
2018-08-14
2018-08-16
2018-08-18
2018-08-20
2018-08-22
2018-08-24
2018-08-26
Date.Time
Nitrate (ppm)
10
5
0
Depth
Deep
Inlet
Shallow
Wells at 5.9 m from inlet


Flow (mL/s)
125
100
75
50
25
2018-08-08
2018-08-10
2018-08-12
2018-08-14
2018-08-16
2018-08-18
2018-08-20
2018-08-22
2018-08-24
2018-08-26
Date.Time
Nitrate (ppm)
10
5
0
Depth
Deep
Inlet
Shallow
Wells at 8.5 m from inlet



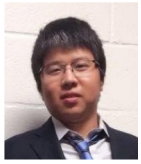
NC STATE UNIVERSITY

2. Field results highlights

- Able to capture the concentration and flow variability
- High resolution measurements have to be accompanied with particle tracking modeling
- MultiplexÔ: available for reseachers

NC STATE UNIVERSITY

Impacts


- 2 awarded Ph.D. students: Bryan Maxwell + Wenlong Liu
- 1 postdoc: Shying Tian
- 1 undergraduate student research + results used in 2 courses
- Papers
  - A small volume multiplexed pumping system for automated, high frequency water chemistry measurements in volume-limited applications. B. Maxwell, et al. HESS. https://doi.org/10.5194/hess-2018-220, 2018
  - Impact Of Drying-rewetting Cycles On Nitrate Removal Rates In Woodchip Bioreactors. B. Maxwell, F. Birgand, L. Schipperb, L.E. Christianson, S. Tian, M. J. Helmers, D. J. Williams, G. M. Chescheir, M. A. Youssef. JEQ. (*In revision*)
  - 3+ in prep.
- 13 Presentations and posters
- Startup company: MultiplexÔ
  - François Birgand, Sam Garvey

NC STATE UNIVERSITY

Looking inside the blackbox?

- Do we really have the choice not to look in there?
- Challenges include:
  - Data acquired forces new hypotheses
  - Microbial response probably a lot faster than perceived before
  - Models have to take into account the production of DOC as affected by rapidly changing redox conditions
  - Coupling modeling-high resolution data is key

NC STATE UNIVERSITY

Looking forward

- Why and how DOC production quantity and quality vary in woodchip bioreactor?
- How can we predict/model the DRW cycles on DOC production?
- What are the roles of inhibitory substances in anaerobic bioreactors?
- What is the optimal DRW management of bioreactor?

NC STATE UNIVERSITY

Acknowledgements

USDA NIFA → Funding Source

NC STATE UNIVERSITY Bio&Ag ENGINEERING → Facilities and Lab Analysis

STROUD WATER RESEARCH CENTER → Microbial Analysis