Recent Progress in Mainstream Deammonification

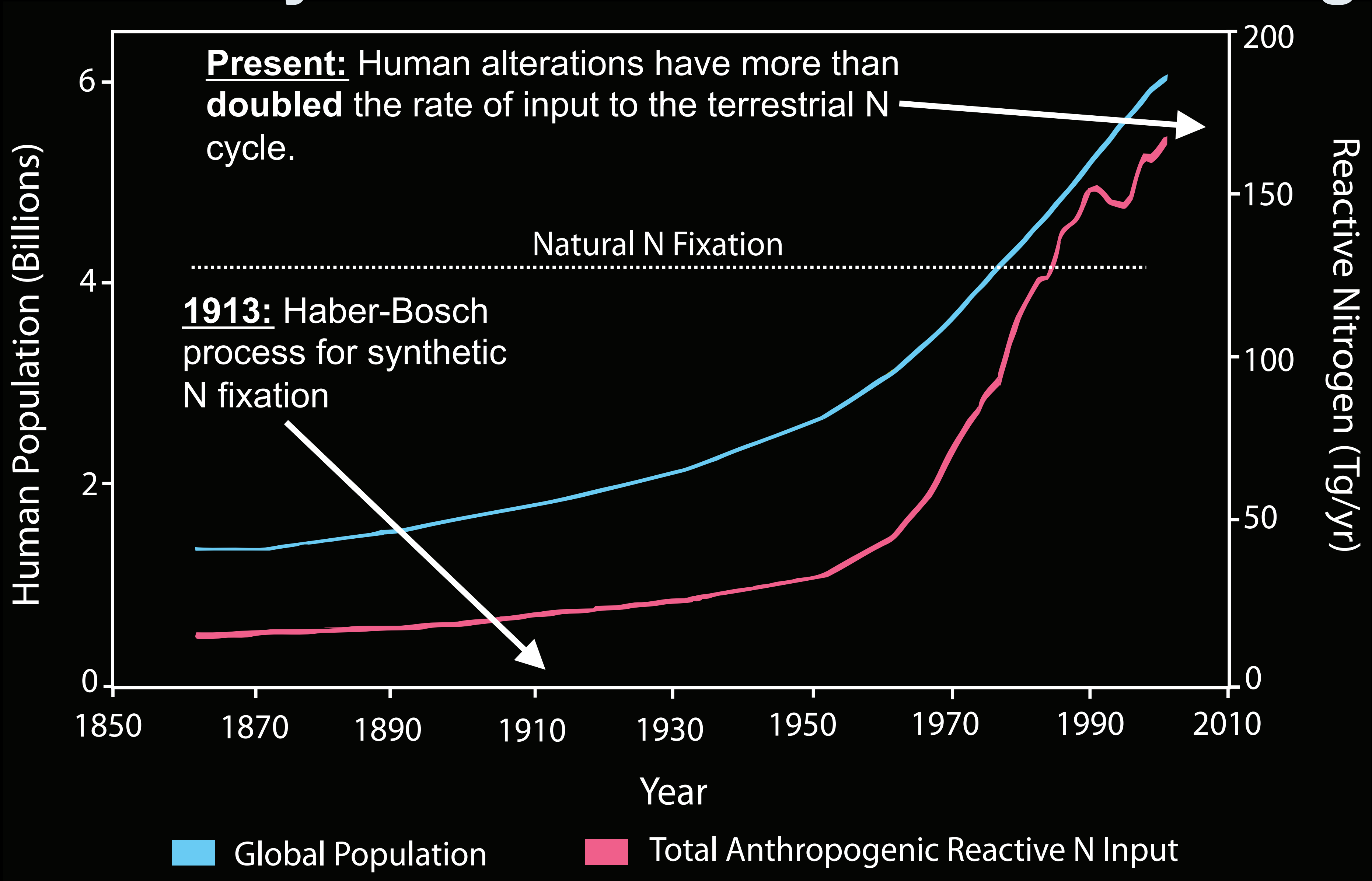
A Potential Low-Energy Option for Nitrogen Removal

George Wells

MWRDGC Monitoring and Research Department Seminar

31 July 2015

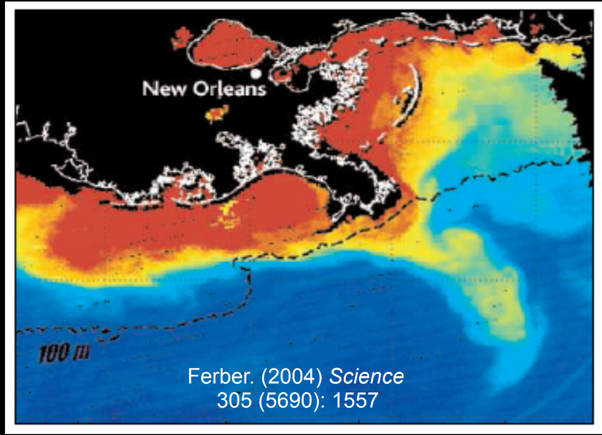
The N Cycle: Too Much of a Good Thing



Fields, S. 2004 "Global Nitrogen: Cycling out of Control." *Environmental Health Perspectives*. 112 (10): A556-A563.

Why control ammonia & reactive N levels?

- Ammonia toxicity to aquatic life
- High oxygen demand
- Eutrophication and resulting hypoxia in N-limited systems
- Emissions of the potent greenhouse gas N_2O
- Public Health Concerns:
  - Methemoglobinemia
  - Cyanobacterial toxins



Ferber. (2004) *Science* 305 (5690): 1557


www.nytimes.com, 8/3/14

GRAND CHALLENGES FOR ENGINEERING

Make solar energy economical

Provide energy from fusion

Develop carbon sequestration technologies

Manage the nitrogen cycle

Provide access to clean water

Restore and improve urban infrastructure

Advance health informatics

Engineer better medicines

Reverse-engineer the brain

Prevent nuclear terror

Secure cyberspace

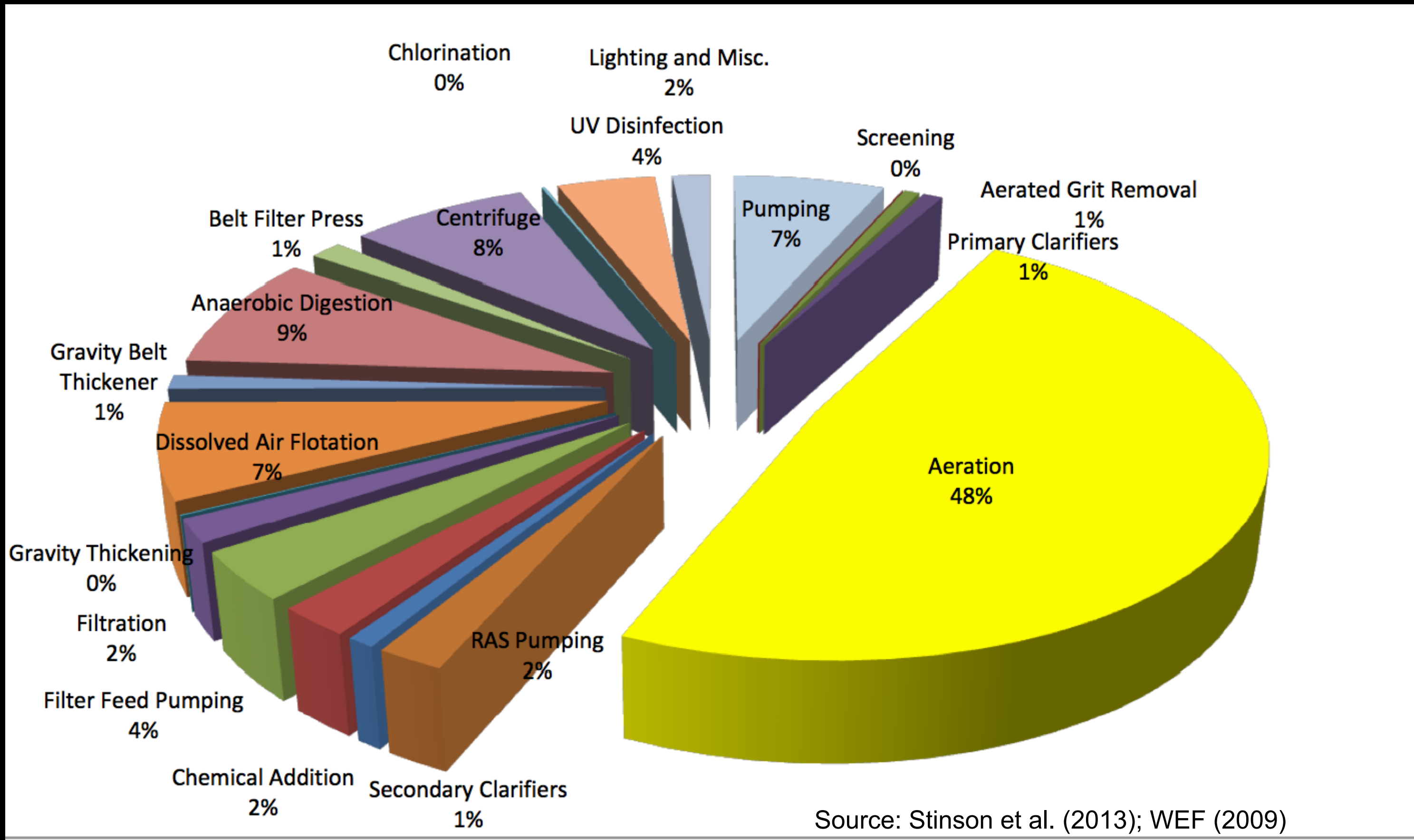
Enhance virtual reality

Advance personalized learning

National Academy of Engineering. (2008) *Grand Challenges for Engineering*. www.engineeringchallenges.org

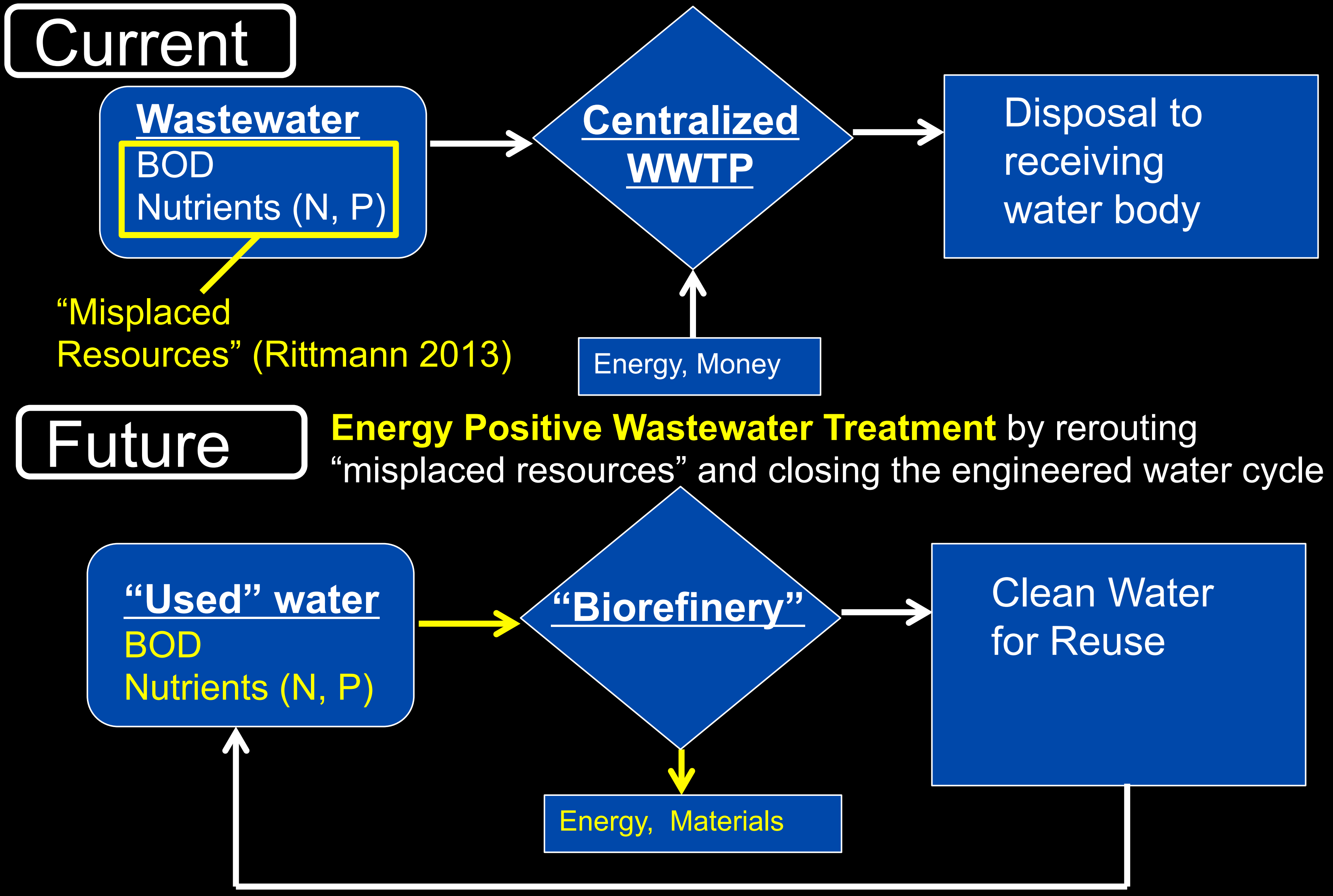
Conventional biological wastewater treatment (particularly N removal bioprocesses) are highly **energy intensive**

Wastewater treatment accounts for ~3% of nationwide electricity use (~15 GW)



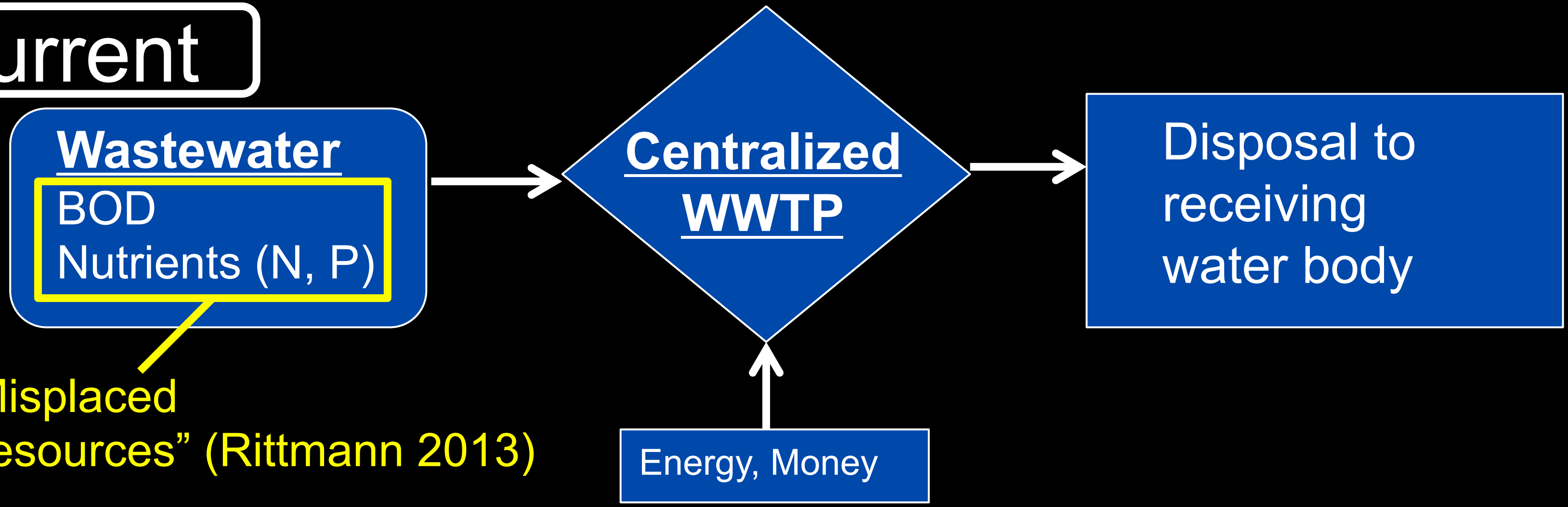
Conversely, organic-rich domestic, industrial, and animal wastewater contains potential energy equivalent to ~17 GW of power (Logan et al. 2012)

A Paradigm Shift towards Resource Recovery



A Paradigm Shift towards Resource Recovery

Current



Future

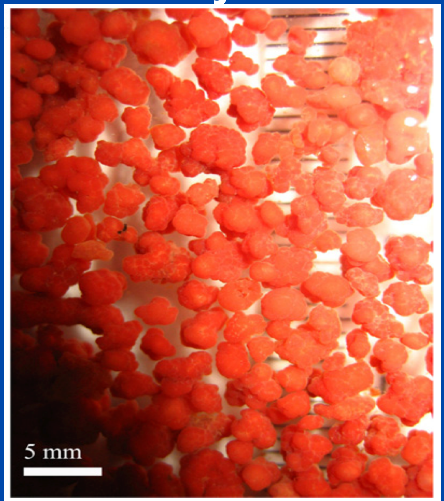
Energy Positive Wastewater Treatment by rerouting "misplaced resources" and closing the engineered water cycle

Given that conventional nutrient removal processes are highly energy intensive, ***it is unlikely that energy positive wastewater treatment targeting resource recovery can be achieved without new innovations in N removal bioprocesses***

Our Agenda For Today

Anammox and the Quest for Mainstream Deammonification

I. New Microbial Players



Tang 2013 J of Haz Mat 250-251: 1-8

II. Innovative Bioprocesses for low energy N removal

Paque BV

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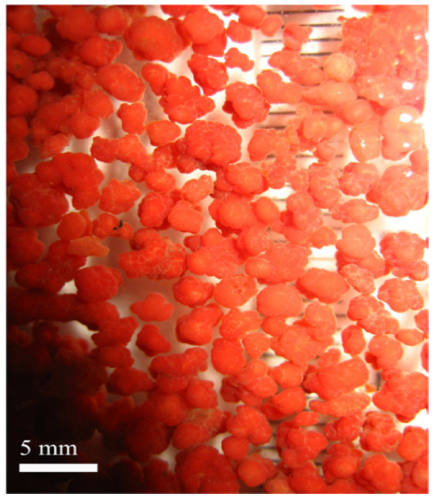
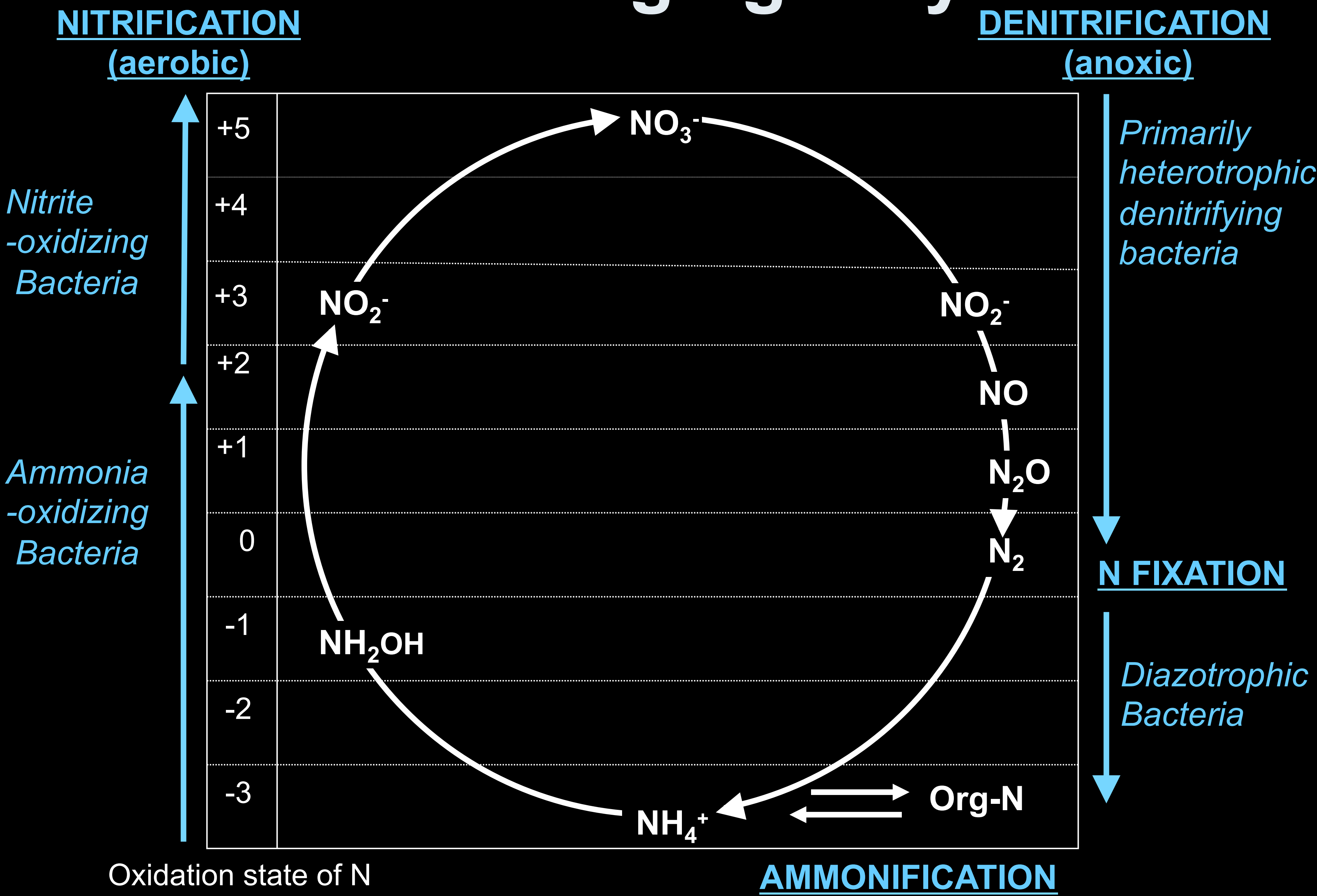


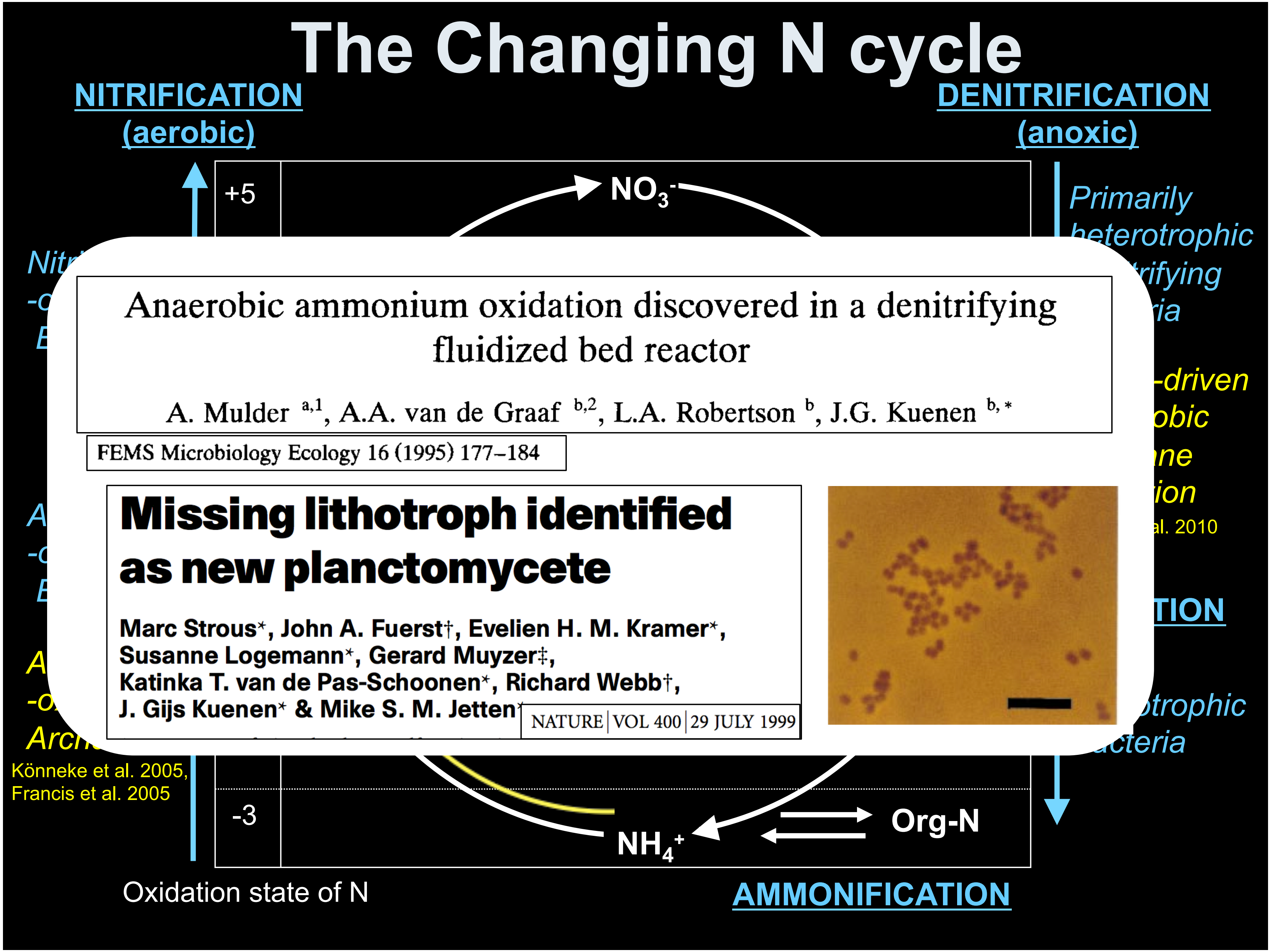
Tang 2013 J of Haz Mat 250-251: 1-8

II. Innovative Bioprocesses for low energy N removal

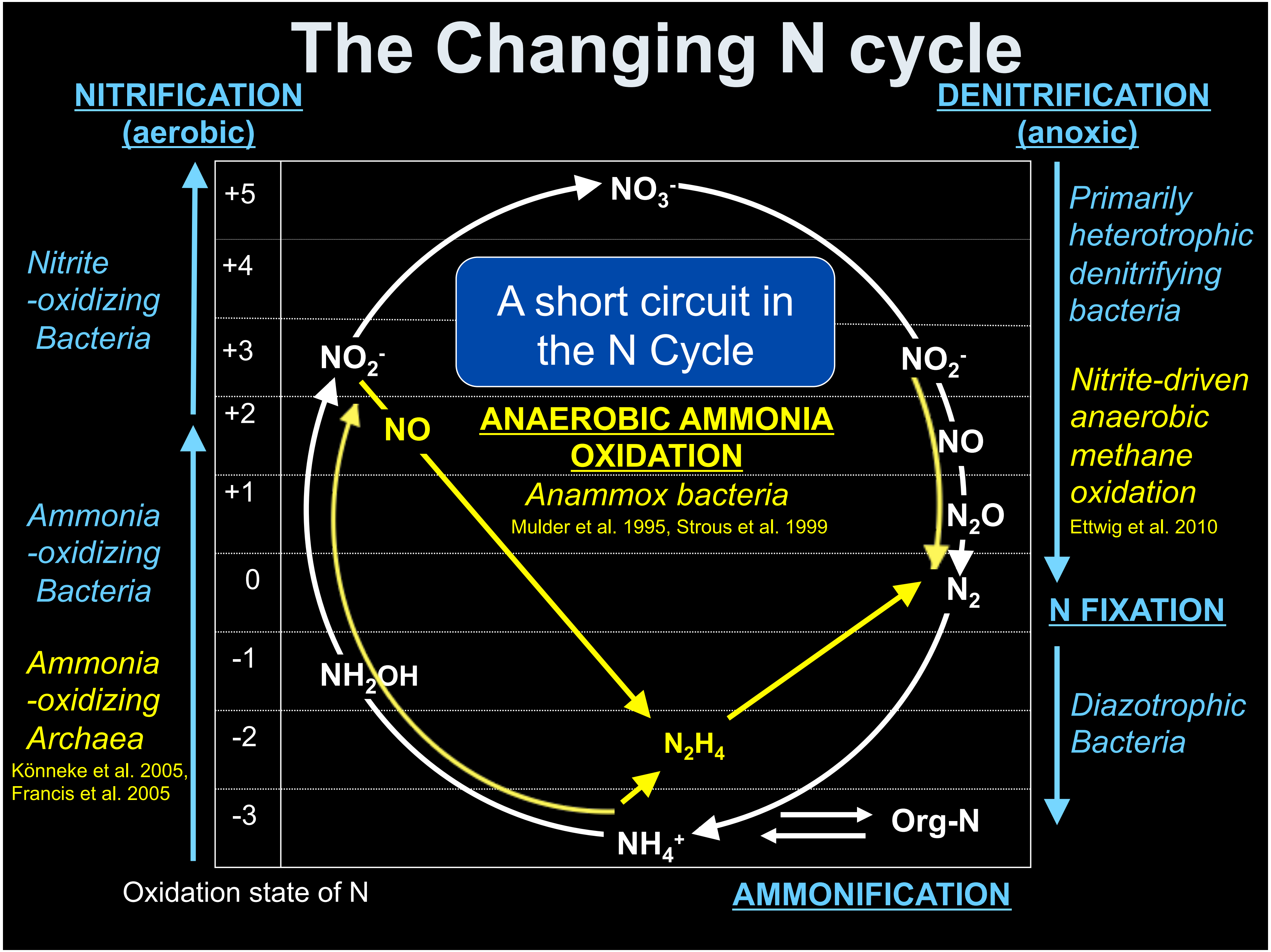
Paque BV

The Changing N cycle



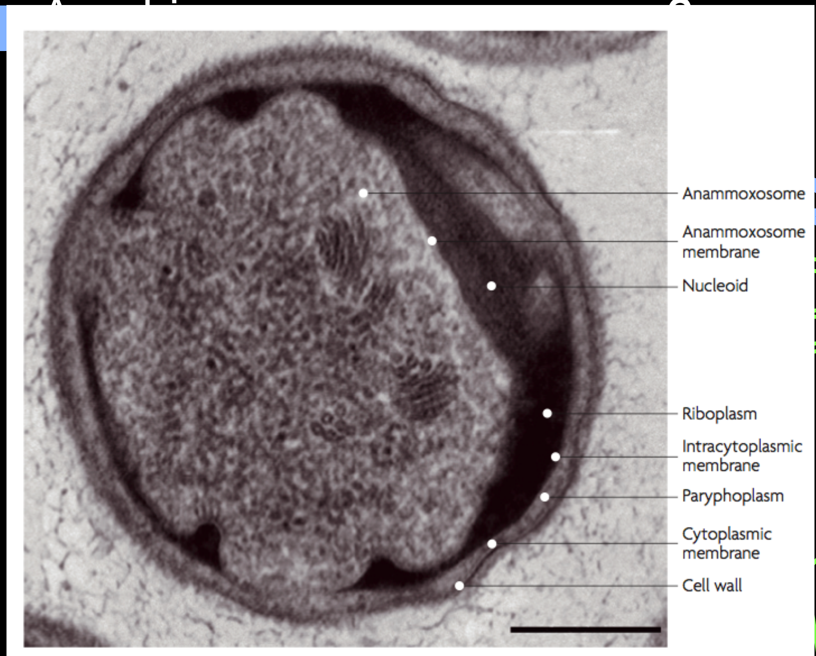


The Changing N cycle
NITRIFICATION
(aerobic)
DENITRIFICATION
(anoxic)
+5
NO3-
-3
NH4+
Org-N
Primarily
heterotrophic
Könneke et al. 2005,
Francis et al. 2005
Oxidation state of N
AMMONIFICATION
Anaerobic ammonium oxidation discovered in a denitrifying fluidized bed reactor
A. Mulder a,1, A.A. van de Graaf b,2, L.A. Robertson b, J.G. Kuenen b,*
FEMS Microbiology Ecology 16 (1995) 177–184
Missing lithotroph identified as new planctomycete
Marc Strous*, John A. Fuerst†, Evelien H. M. Kramer*, Susanne Logemann*, Gerard Muyzer‡, Katinka T. van de Pas-Schoonen*, Richard Webb†, J. Gijs Kuenen* & Mike S. M. Jetten*
NATURE | VOL 400 | 29 JULY 1999

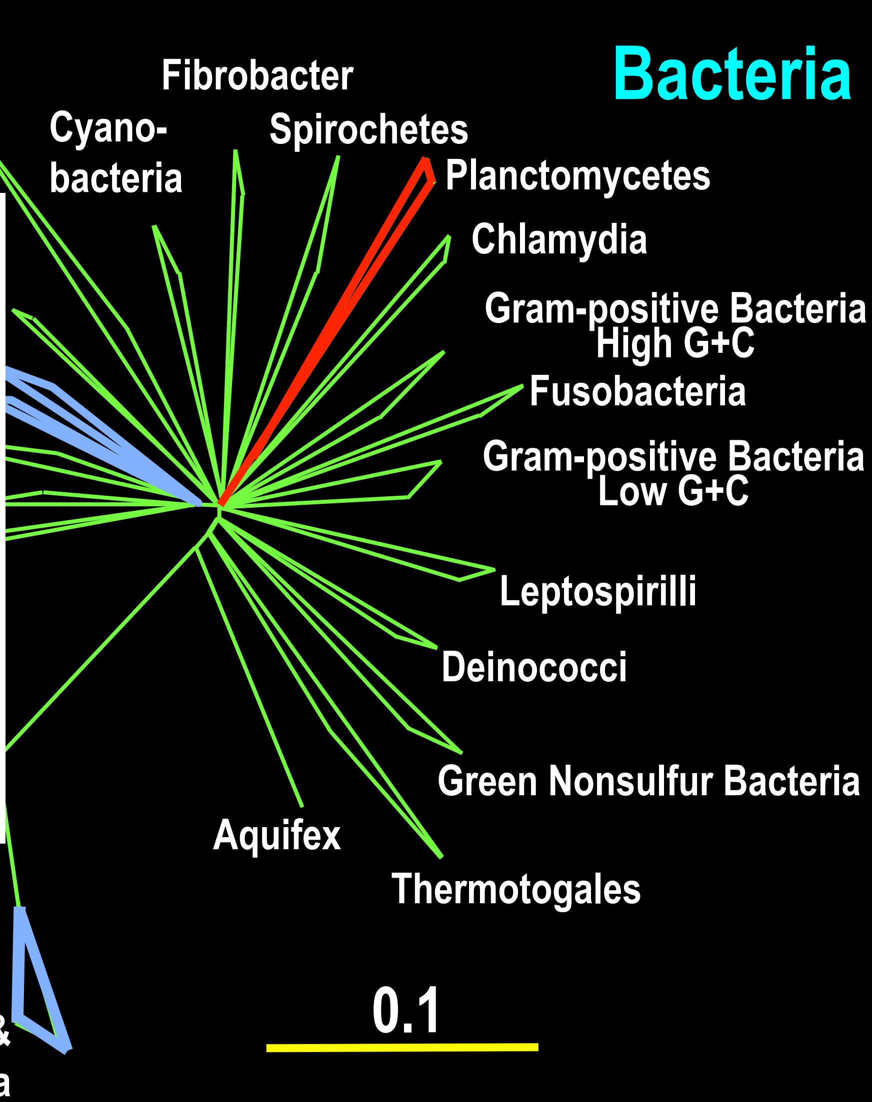

The Changing N cycle
NITRIFICATION
(aerobic)
DENITRIFICATION
(anoxic)
Nitrite
-oxidizing
Bacteria
Ammonia
-oxidizing
Bacteria
Ammonia
-oxidizing
Archaea
Könneke et al. 2005,
Francis et al. 2005
+5
+4
+3
+2
+1
0
-1
-2
-3
NO_3^-
A short circuit in
the N Cycle
NO_2^-
NO
ANAEROBIC AMMONIA
OXIDATION
Anammox bacteria
Mulder et al. 1995, Strous et al. 1999
NO_2^-
NO
N_2O
N_2
NH_2OH
N_2H_4
NH_4^+
Org-N
Primarily
heterotrophic
denitrifying
bacteria
Nitrite-driven
anaerobic
methane
oxidation
Ettwig et al. 2010
N FIXATION
Diazotrophic
Bacteria
Oxidation state of N
AMMONIFICATION

Anaerobic Ammonia Oxidation (Anammox)

$NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O$



From Kuenen 2005. Nature Rev Micro 6(4): 320-326.



(Amann et. al, 1995)

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Anammox and the Quest for Mainstream Deammonification

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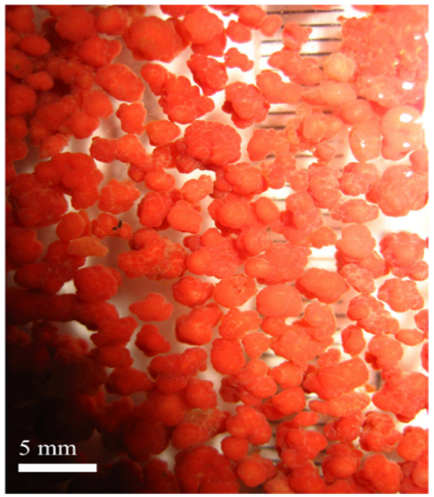


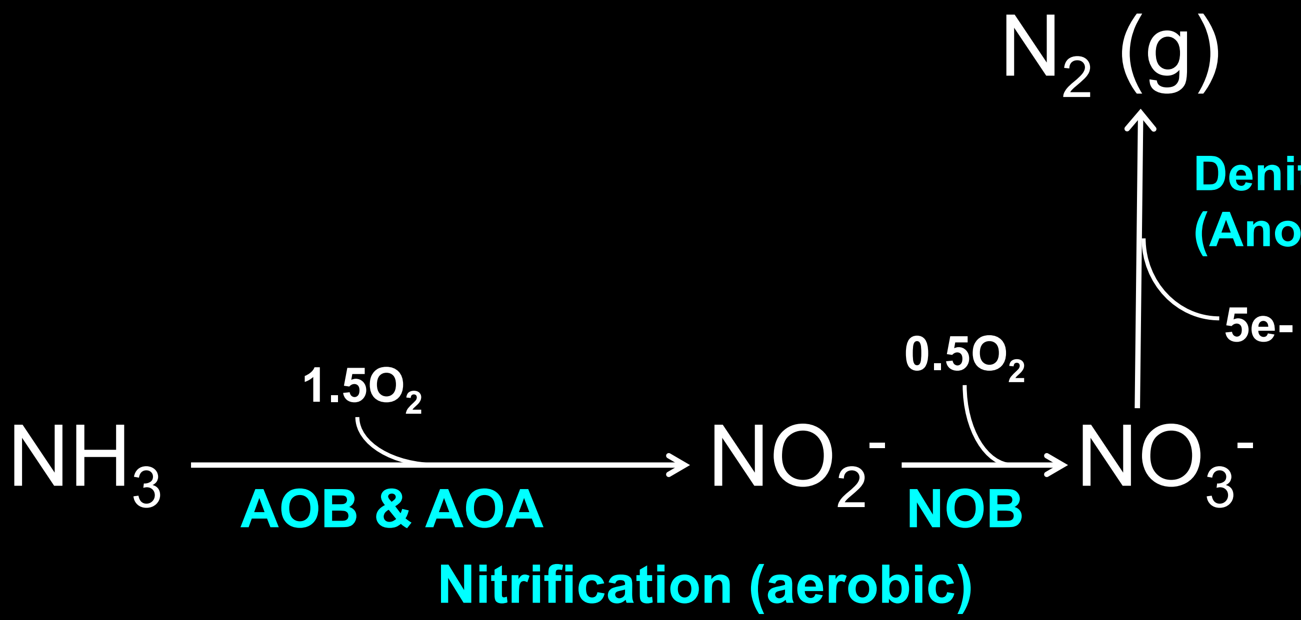
Tang 2013 J of Haz Mat 250-251: 1-8

II. Innovative Bioprocesses for Low Energy N removal

Paque BV

Anammox Bioprocesses: A Critical Opportunity for Sustainable Wastewater Treatment

Conventional Biological N Removal*



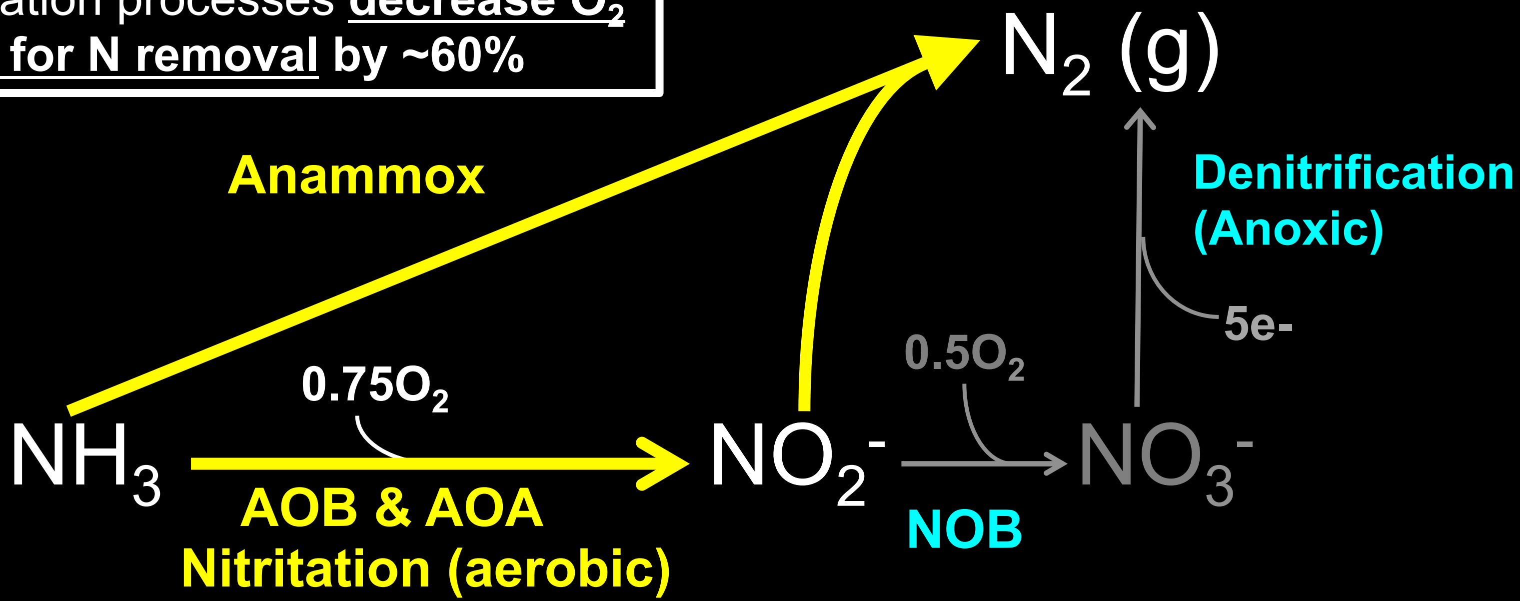
AOB: Ammonia-Oxidizing Bacteria
AOA: Ammonia-Oxidizing Archaea
NOB: Nitrite-Oxidizing Bacteria

**Neglecting biomass growth and decay*

Anammox Bioprocesses: A Critical Opportunity for Sustainable Wastewater Treatment

Deammonification*

Deammonification processes **<u>decrease O_2 requirement for N removal</u>** by ~60%



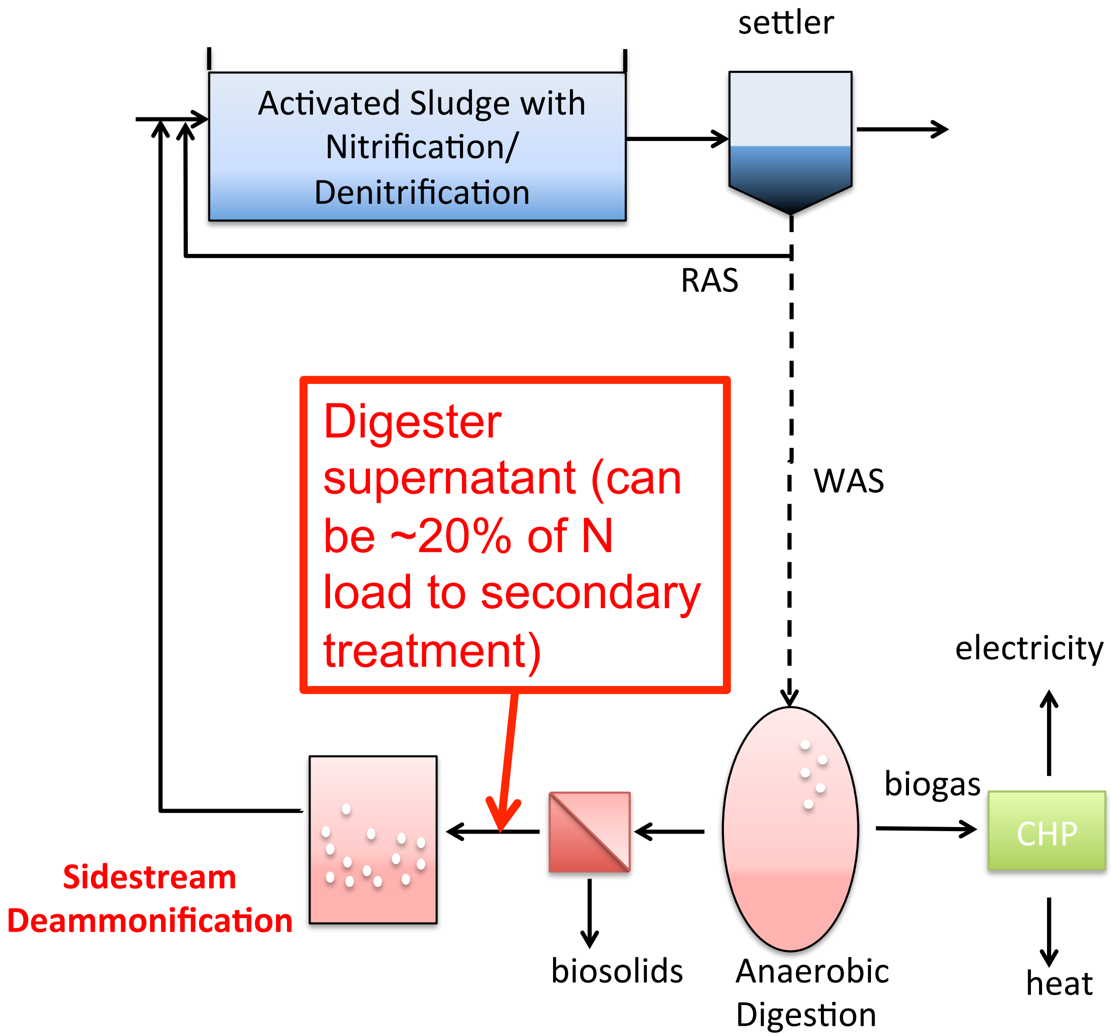
Deammonification processes ***<u>decouple C and N removal</u>***, thereby potentially enabling enhanced C removal as biogas or value-added products (bioplastics, platform chemicals, liquid biofuels, etc.)

**Neglecting biomass growth and decay*

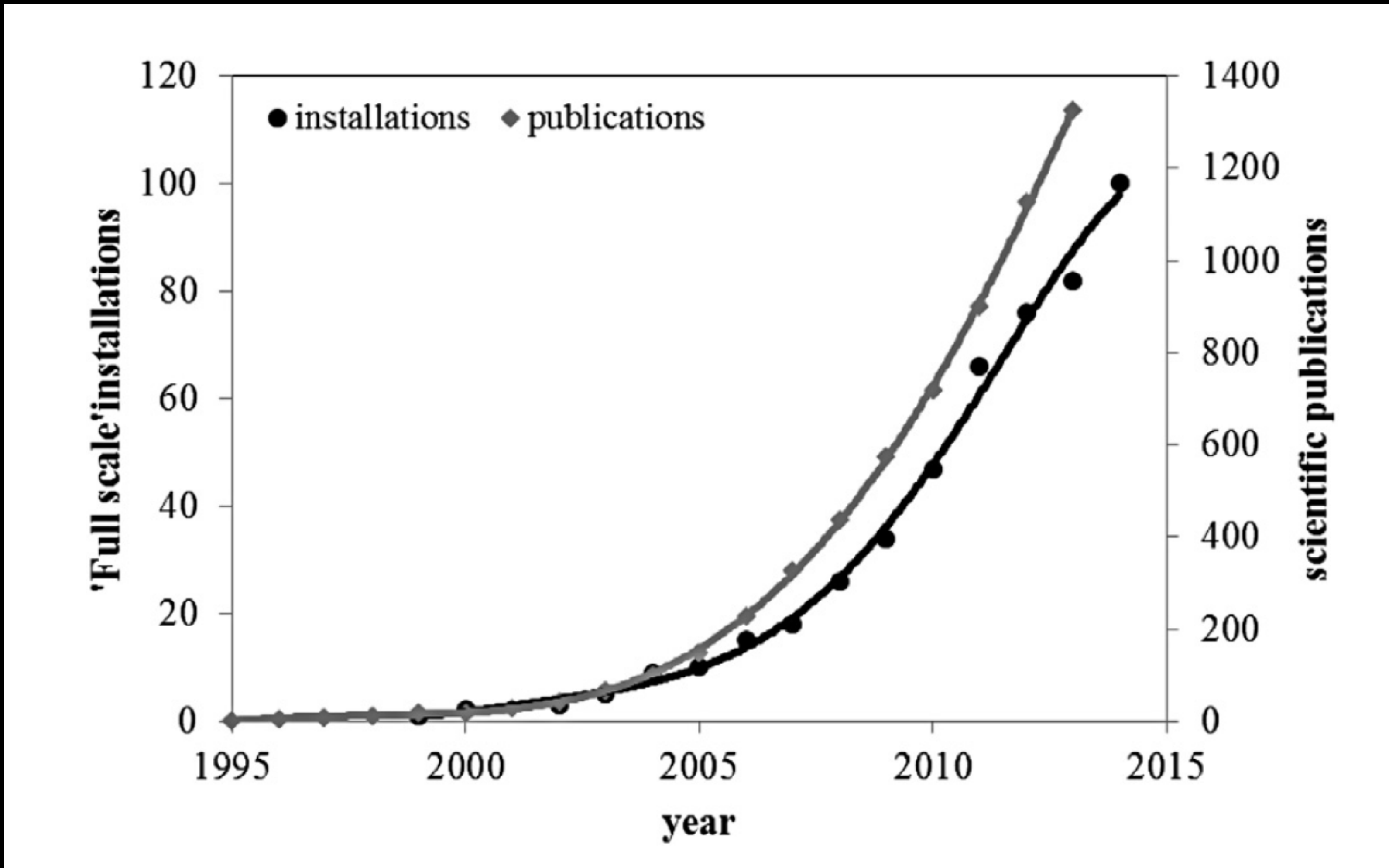
Initial Development of Deammonification Processes has focussed on *sidestream* treatment of anaerobic digester supernatant

Sidestreams are characterized by:

- *High temperature (~30^{o}C)*
- *High NH_4^+ (~500-1000 mgN/L)*



While challenges remain to be addressed, particularly regarding process stability, sidestream deammonification is a rapidly maturing technology



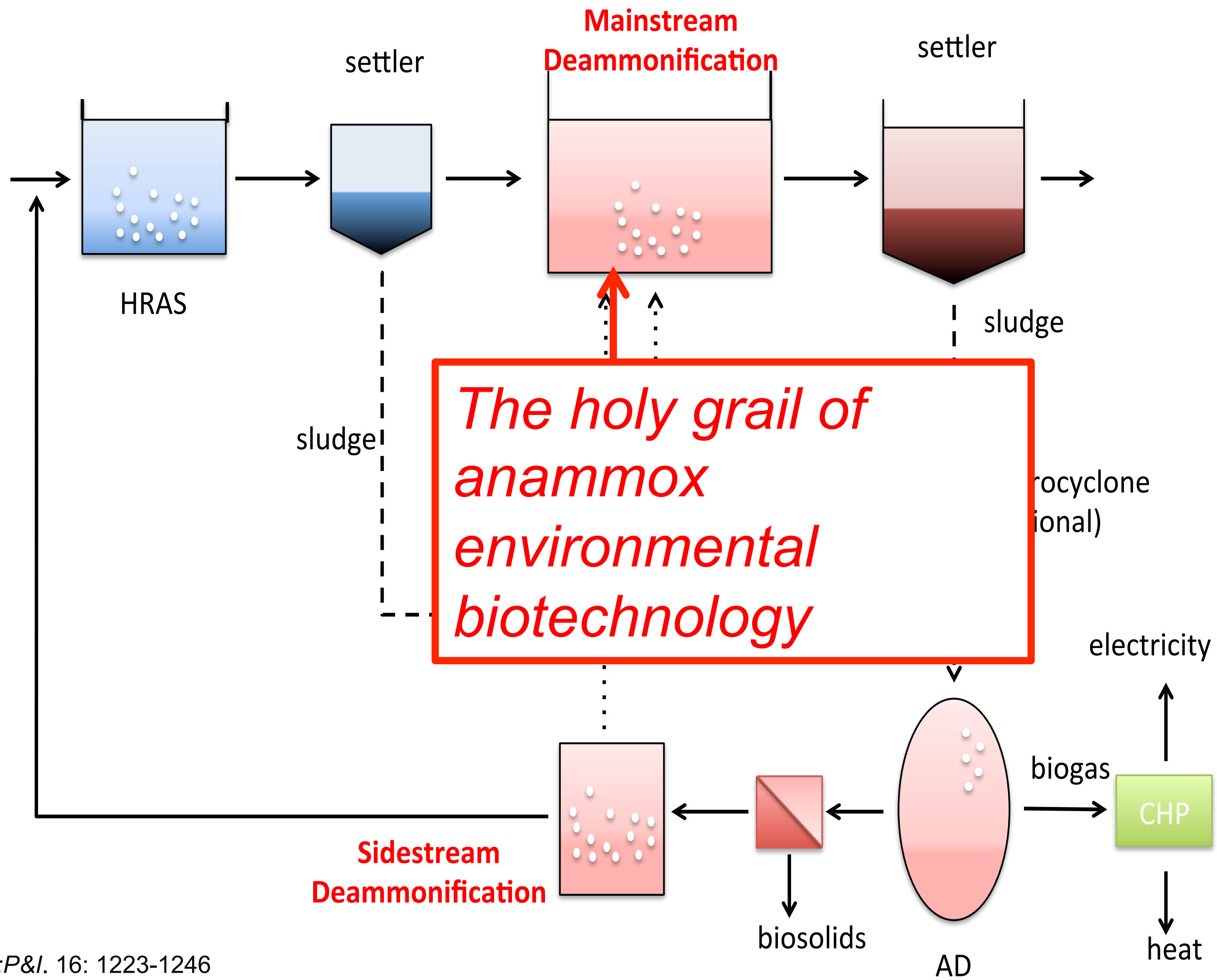
Source: Lackner et al. 2014. *Water Research*, 55 (2014) 292-303.

Pushing the envelope:

Can we apply deammonification bioprocesses in the **mainstream**?

The mainstream is characterized by:

- *Low temperatures*
- *Low NH_4^+*



Source: Gao, Scherson, & Wells (2014) *ES:P&I*. 16: 1223-1246

Critical Challenges to (Mainstream) Deammonification

1. ***Process stability and reliability*** under dynamic conditions expected in the mainstream

2. Robust and stable ***outcompetition of NOB***

3. Maintenance of ***high levels of anammox biomass and activity*** under low temperature, low substrate conditions

4. Coupled deammonification and ***biological P removal***

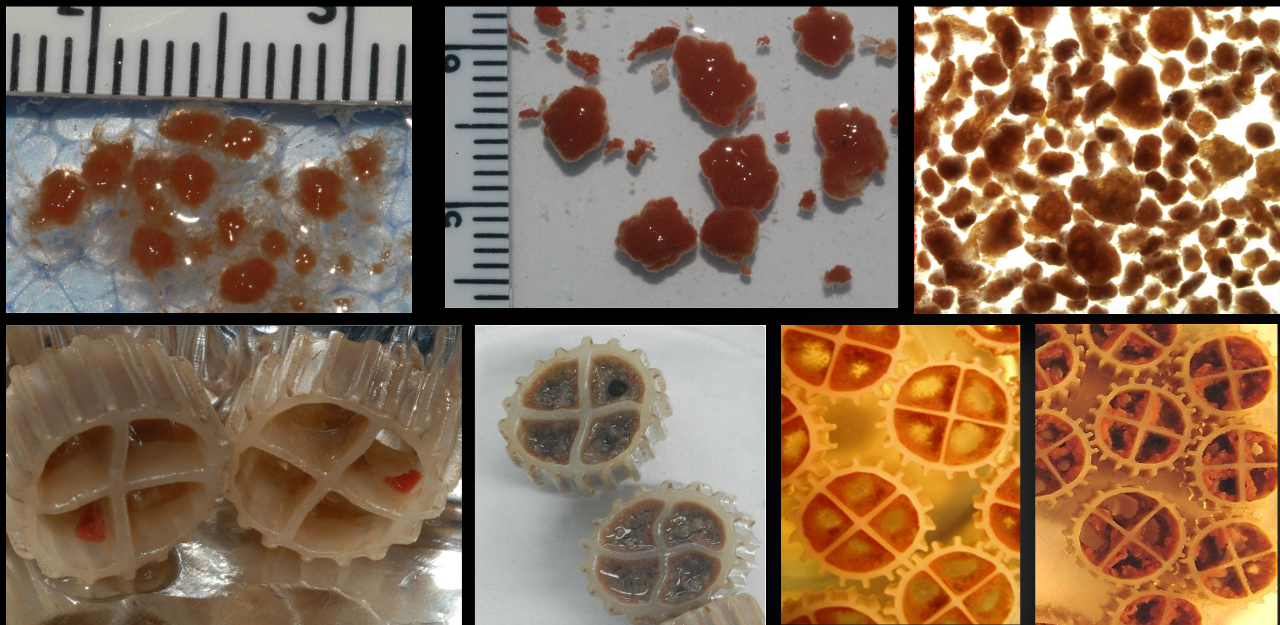
Impact of **Aggregate Architecture** on Deammonification Process Stability

Alex
Rosenthal

David
Weissbrodt

Eberhard
Morgenroth

Adriano
Joss



eawag
aquatic research

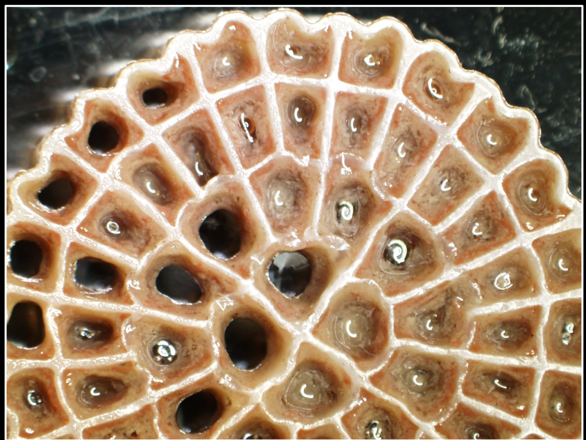
NORTHWESTERN
UNIVERSITY

Our Hypothesis

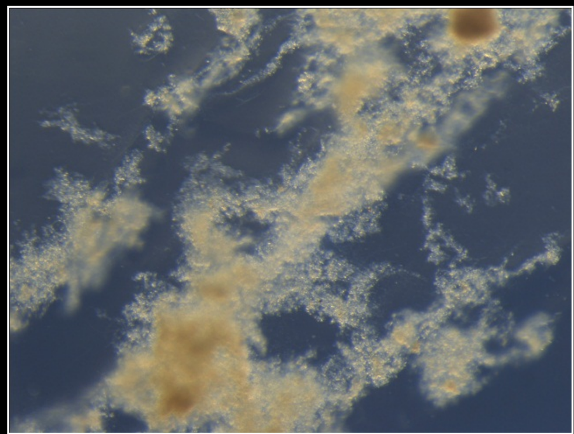
Mass transport limitations and aggregate structure in deammonification processes impact **process performance and stability**

Approach: Side-by-side comparison between two common process variations employing different aggregate types:

Biofilm Carriers (MBBR)



Suspended Growth Biomass



Flocs

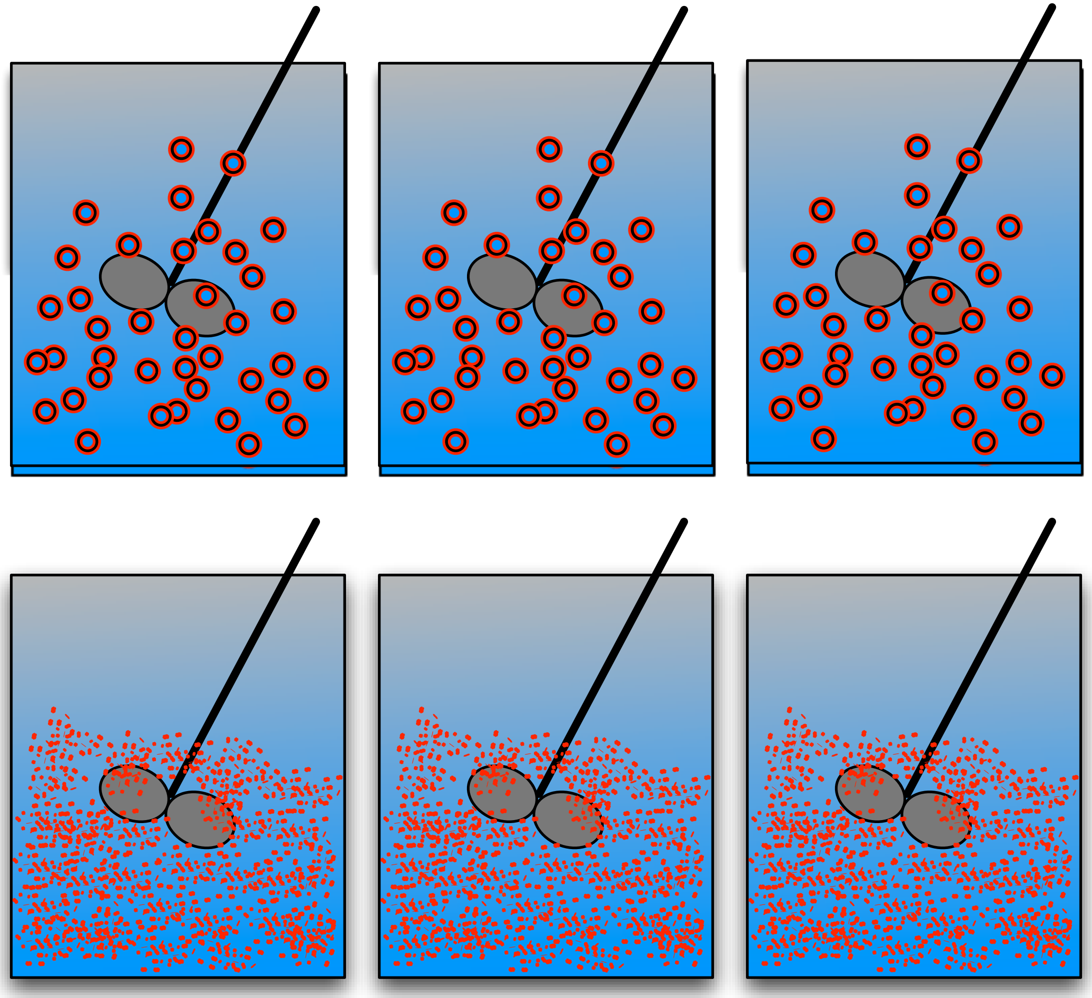
Granules

Process Performance and Stability in Replicated Lab-Scale Reactors

Process Performance and Stability in Replicated Lab-Scale Reactors

3x MBBRs (Reactors R1, R2, R3)

3x Suspended Growth (Reactors R4, R5, R6)

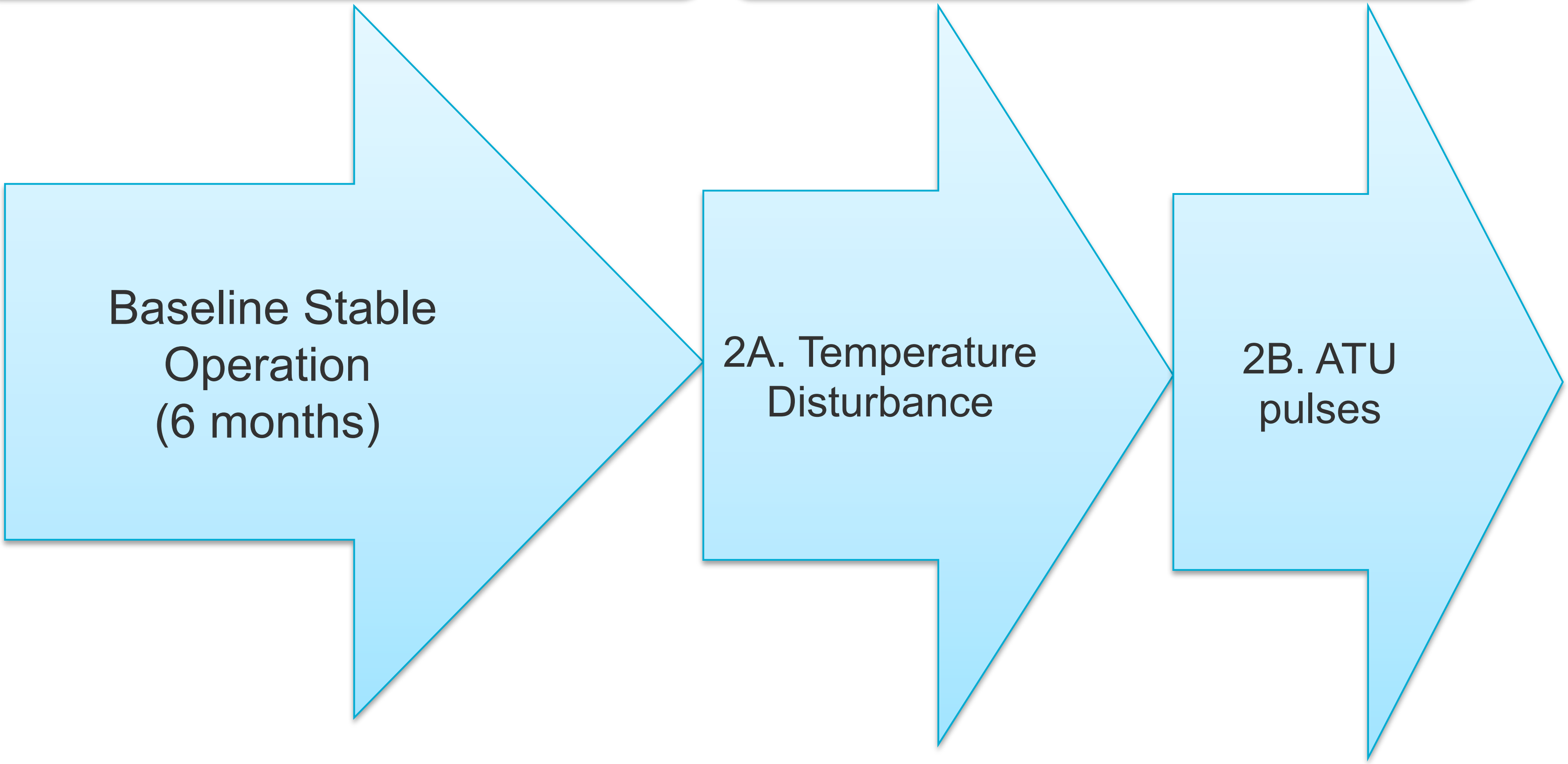


Deammonification Bioprocesses

Phases of Operation

1. Baseline

2. Transient Perturbation Scenarios



Feed: anaerobic digester centrate

Deammonification Bioprocesses

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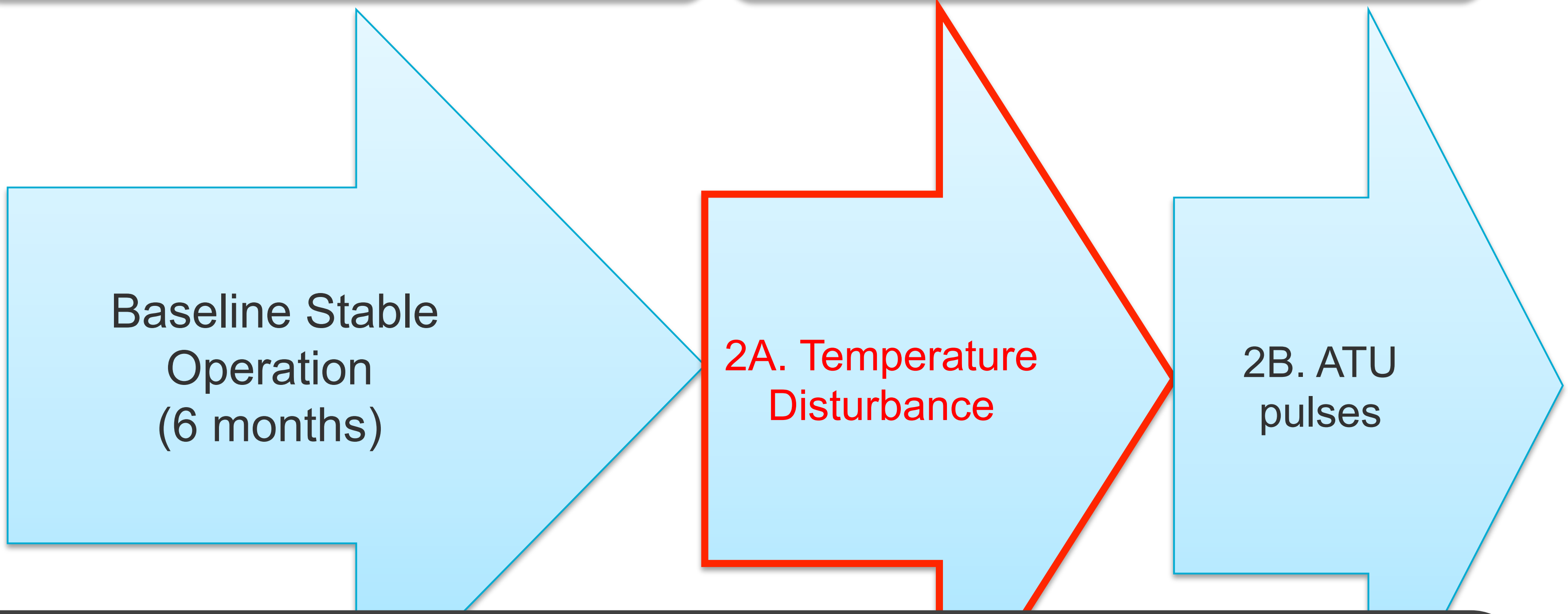
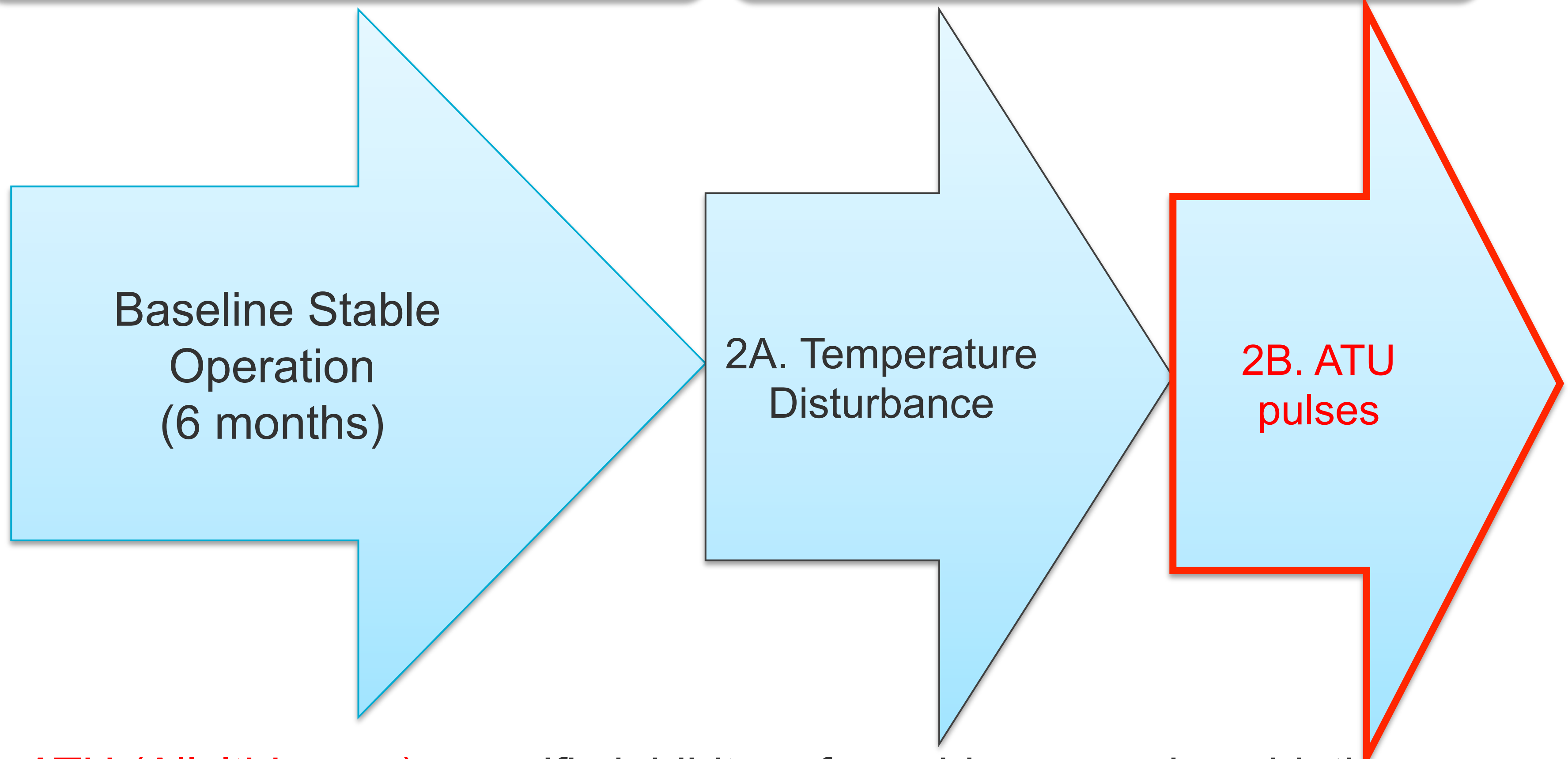


- **MBBRs:** Strong decline in performance (NH_4^+ depletion rate), no accumulation of the key intermediate NO_2^-
- **Suspended Growth:** Moderate decline in performance (NH_4^+ depletion rate), with substantial NO_2^- accumulation

Deammonification Bioprocesses

Phases of Operation

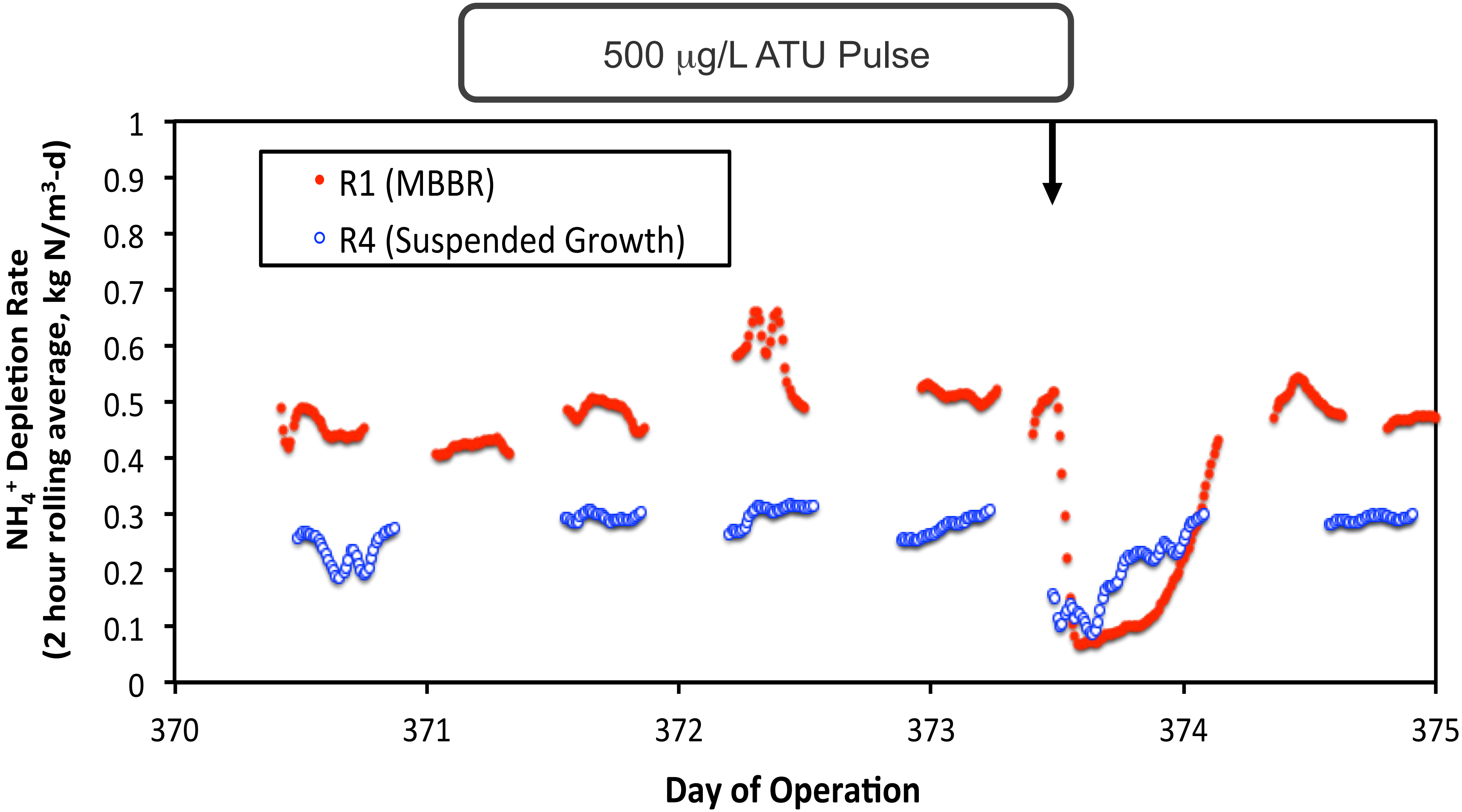
1. Baseline | **2. Transient Perturbation Scenarios**



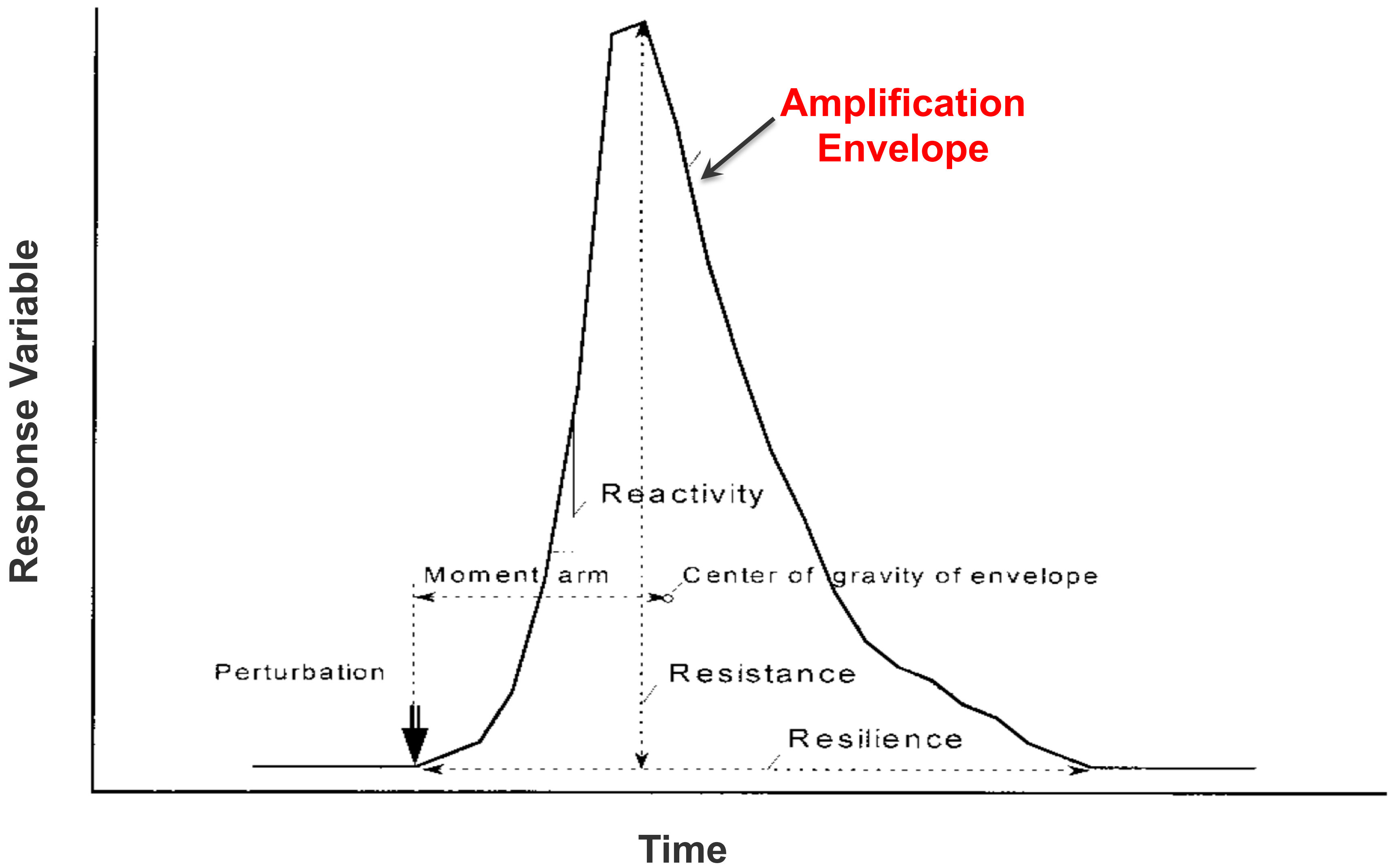
- ATU (Allylthiourea): specific inhibitor of aerobic ammonia oxidation (AOB and AOA)
- Dose: 500-1100 μg/L, expected to only partially inhibit activity

Deammonification Bioprocesses

Response to Pulse of Inhibitor of Aerobic Ammonia Oxidation



The Amplification Envelope: Borrowing from Ecology to Quantify Stability



Modified from Hashsham et al. 2000 Applied and Env. Micro. 66(9): 4050-4057.

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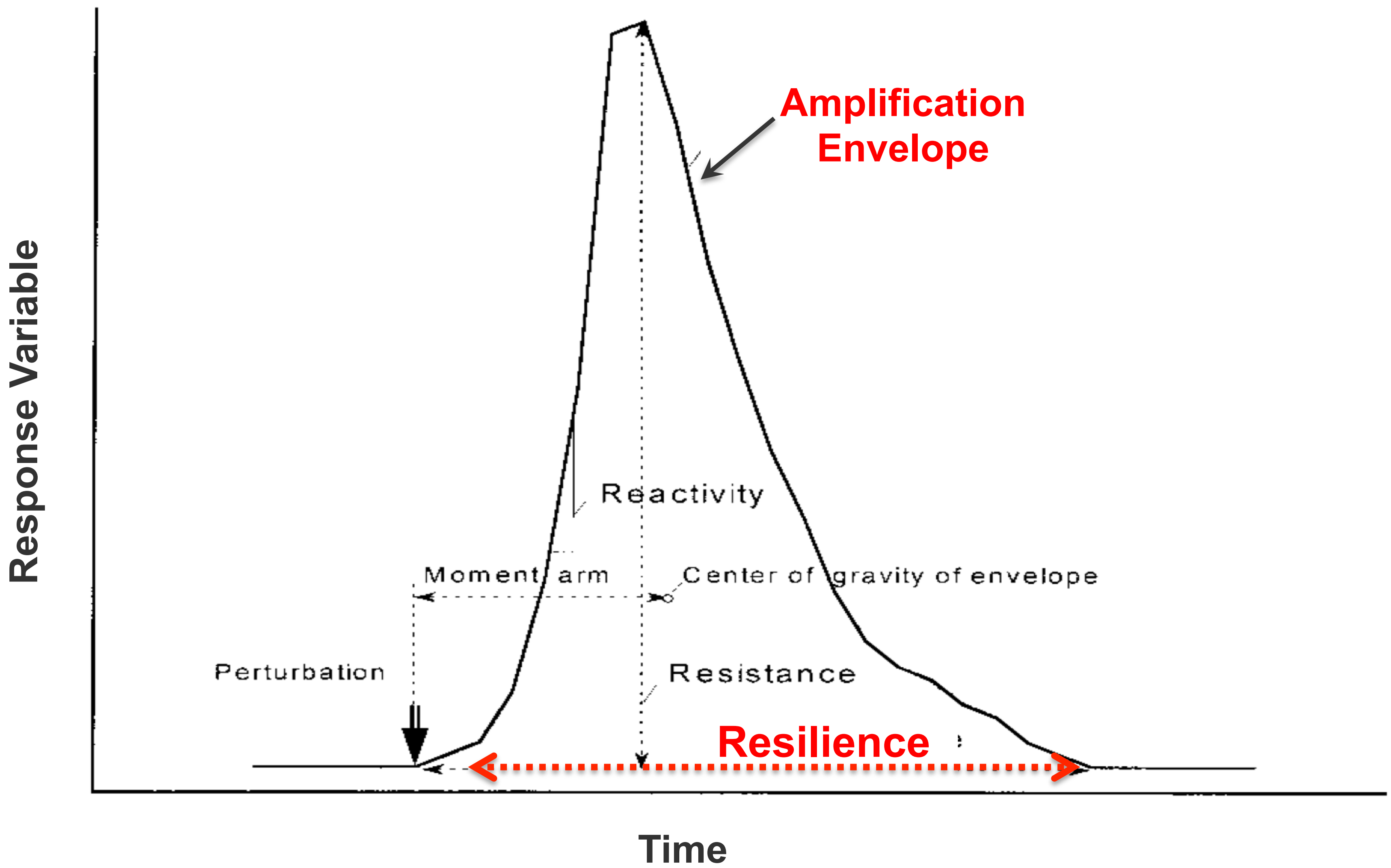

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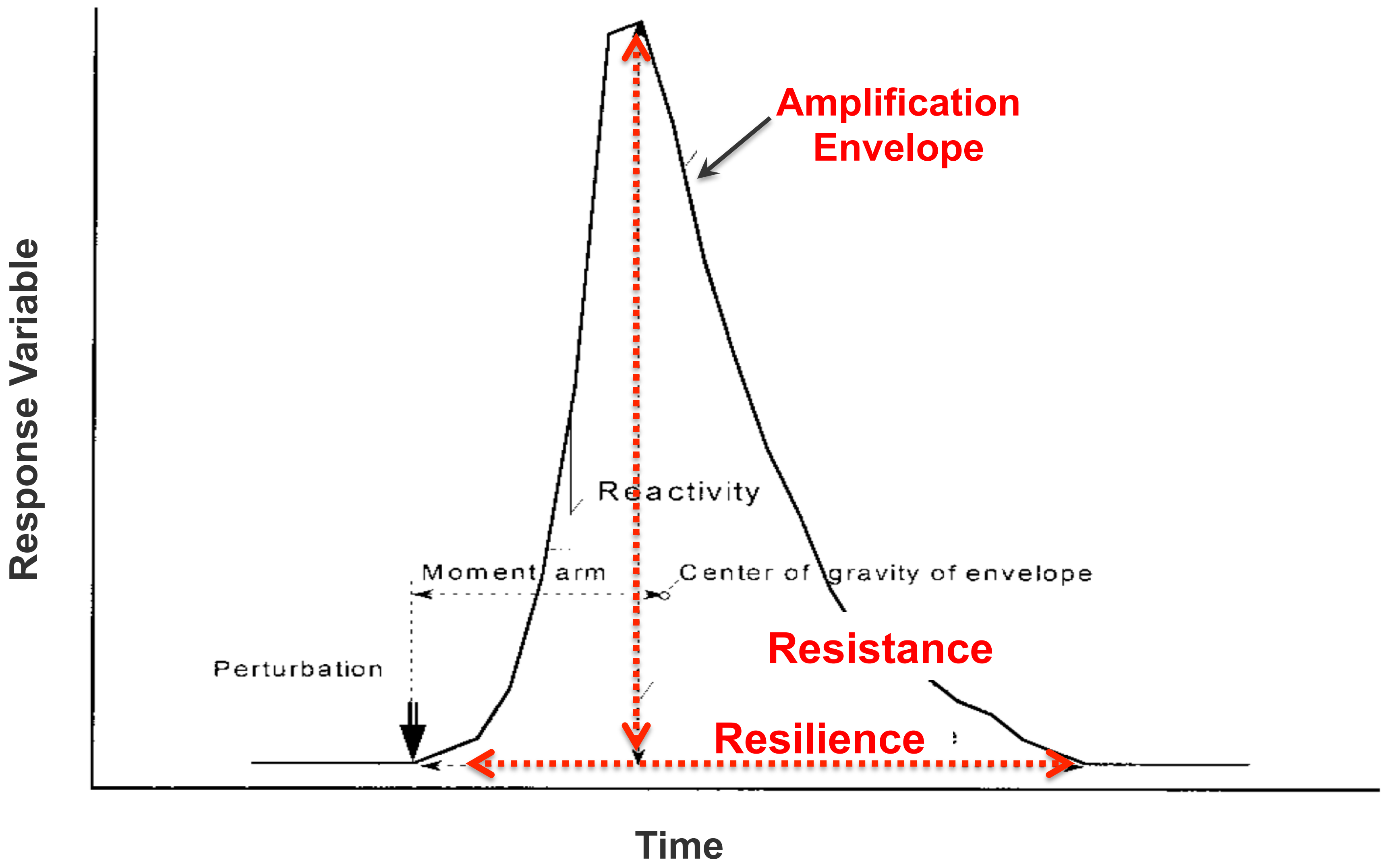

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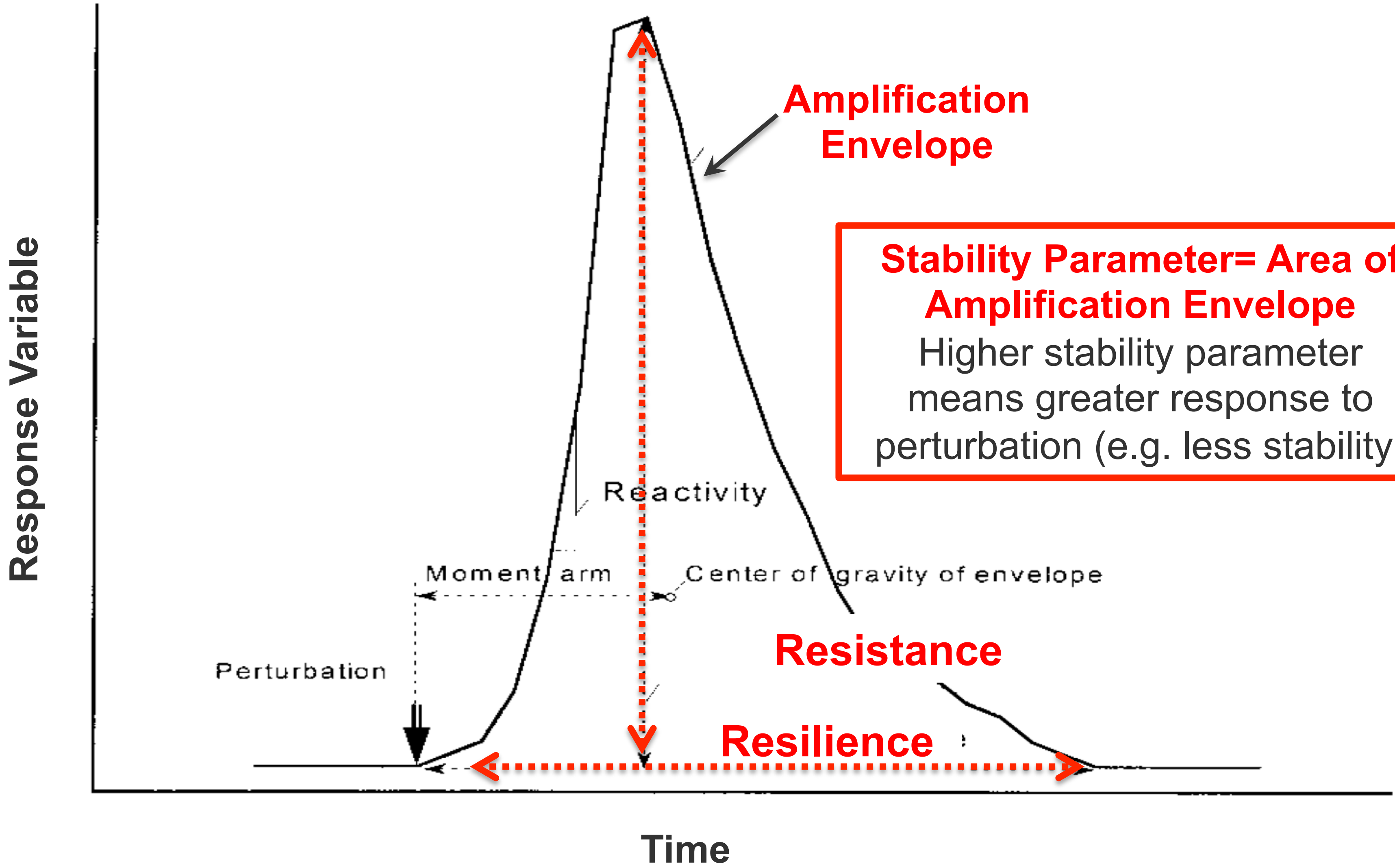
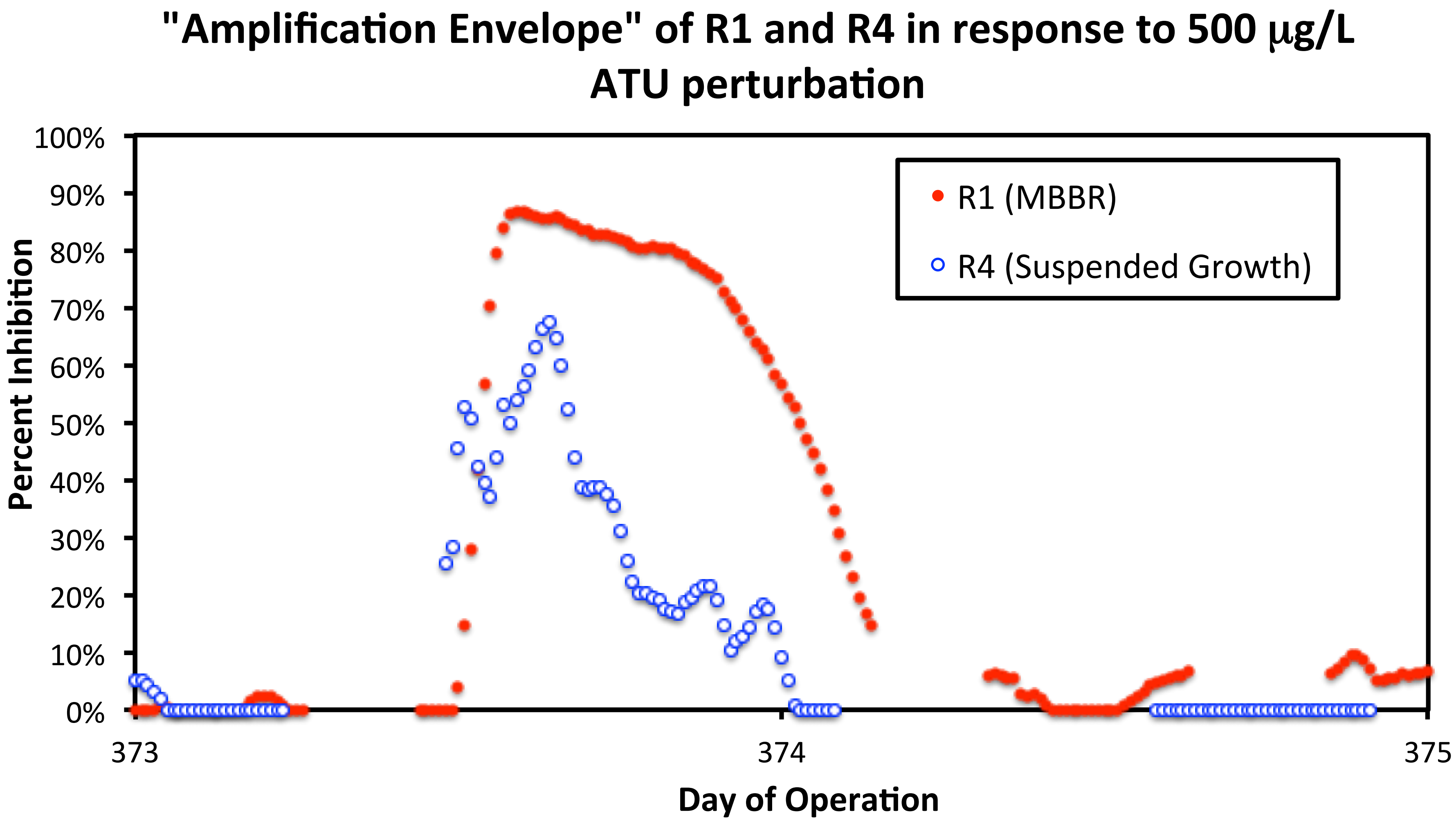


Stability Parameter= Area of Amplification Envelope
Higher stability parameter means greater response to perturbation (e.g. less stability)

Modified from Hashsham et al. 2000 Applied and Env. Micro. 66(9): 4050-4057.

Deammonification Bioprocesses

Response to Pulse of Inhibitor of Aerobic Ammonia Oxidation



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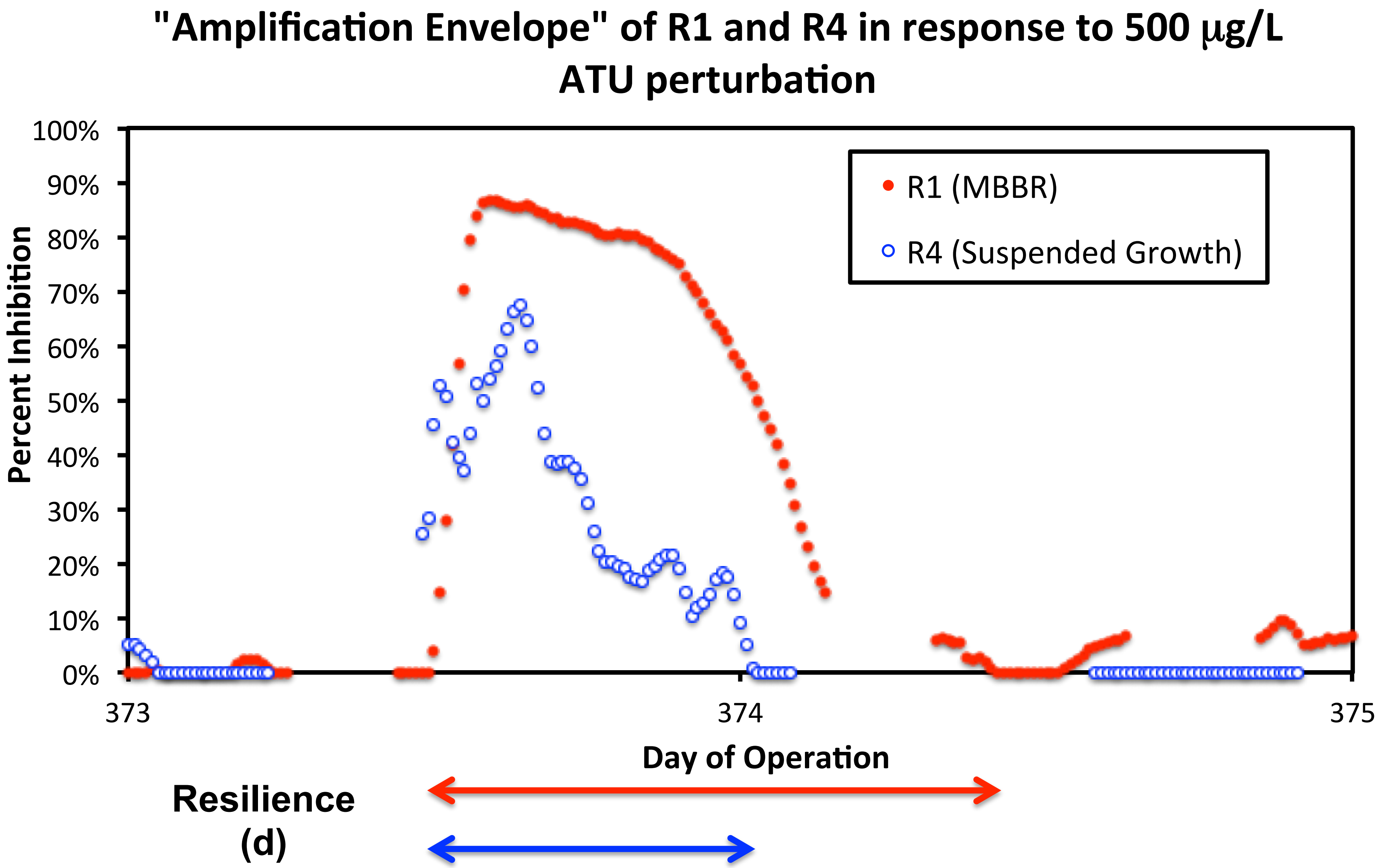

Deammonification Bioprocesses

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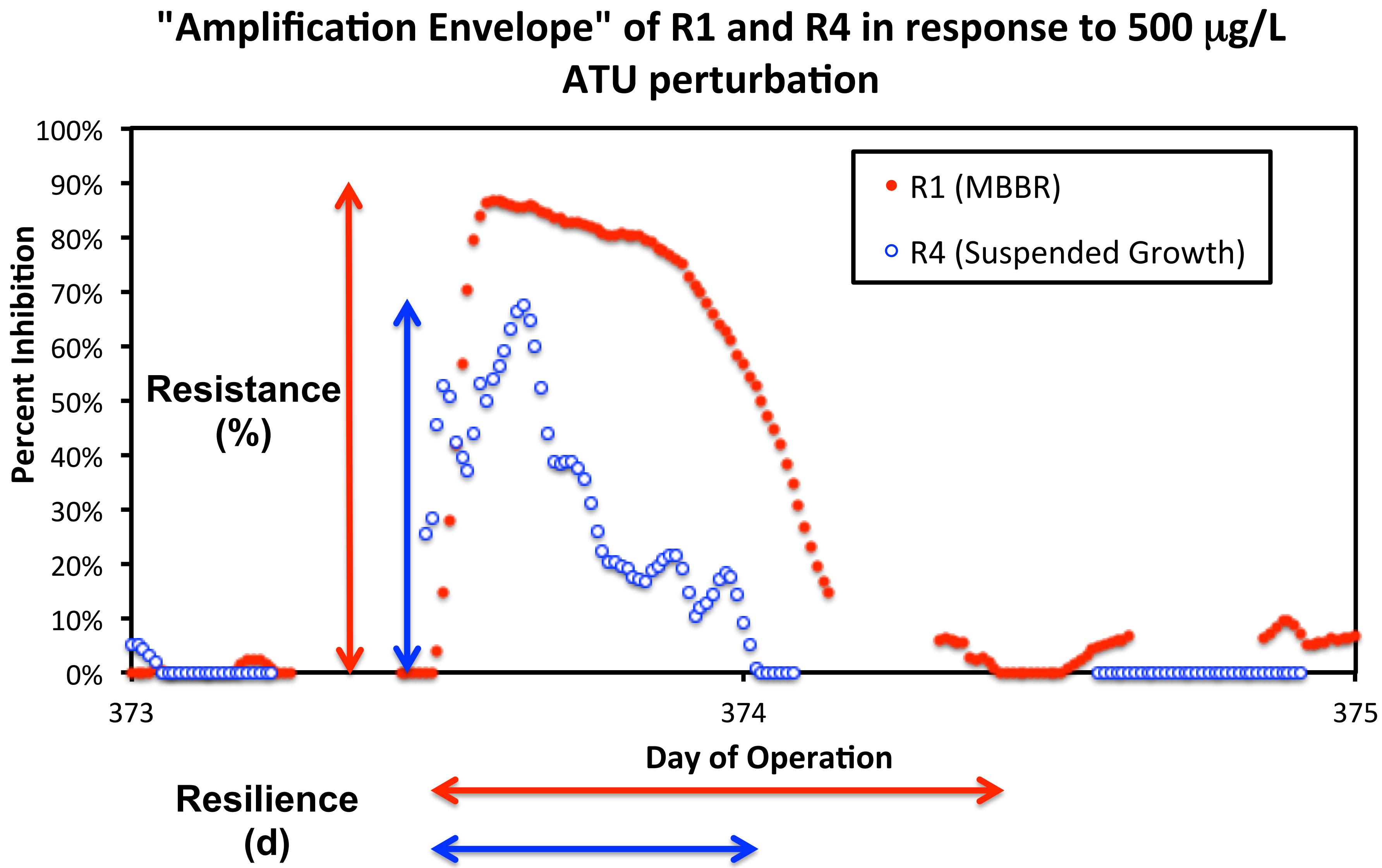

Deammonification Bioprocesses

Response to Pulse of Inhibitor of Aerobic Ammonia Oxidation

500 μg/L ATU Pulse

Reactor	Resilience (d)	Resistance (%)	Stability Parameter (d-%)
R1	0.67	0.86	0.41
R2	0.77	0.92	0.39
R3	0.66	0.96	0.35
R4	0.54	0.68	0.17
R5	0.48	1.00	0.30
R6	0.49	0.94	0.12

- **MBBRs (biofilm systems)** displayed significantly ***increased response to perturbation*** (higher stability parameter, $p<0.05$) relative to **suspended growth reactors**.

Synthesis of Response to Transient Perturbations

- In response to transient temperature and ATU disturbances, we observed:

MBBR (biofilm)
No excess NO_2^- Accumulation
Strong decrease in NH_4^+ depletion rate

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- Our results suggest that the **MBBR**s in this study may be **strongly limited by AOB activity**– and thus may maintain an excess anammox capacity…
- While **suspended growth** systems exhibited an **apparent excess AOB capacity** that muted the impact of variations in nitrification activity

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Suspended growth systems may be more resistant to fluctuations in aerobic ammonia oxidation activity, while **MBBR systems** may be more resistant to perturbations that predominantly impact anammox activity.

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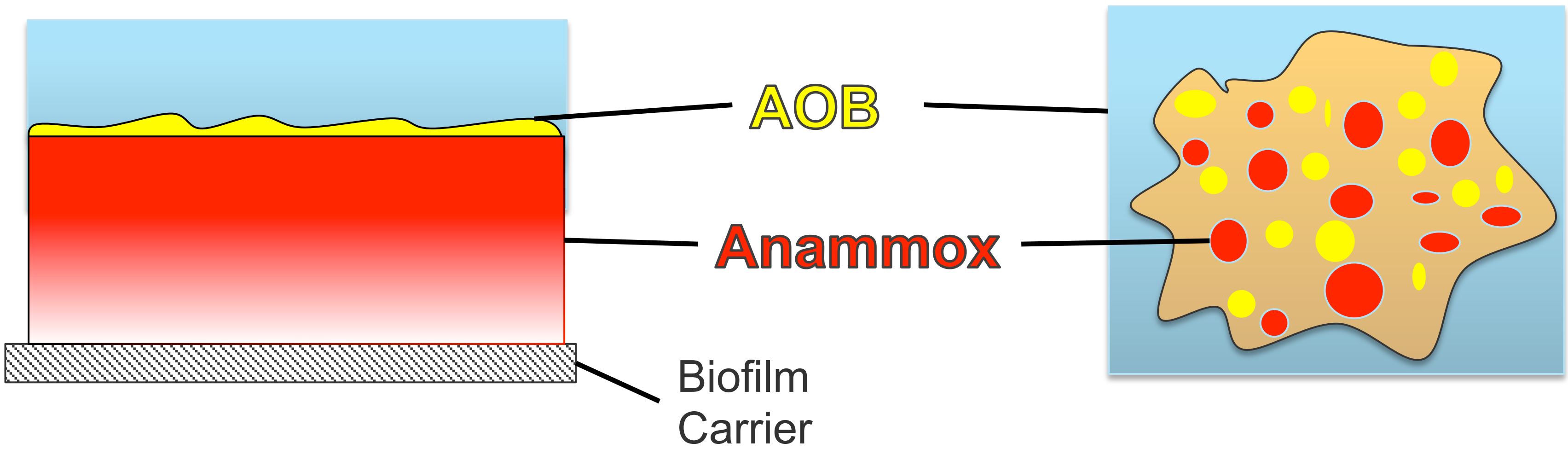
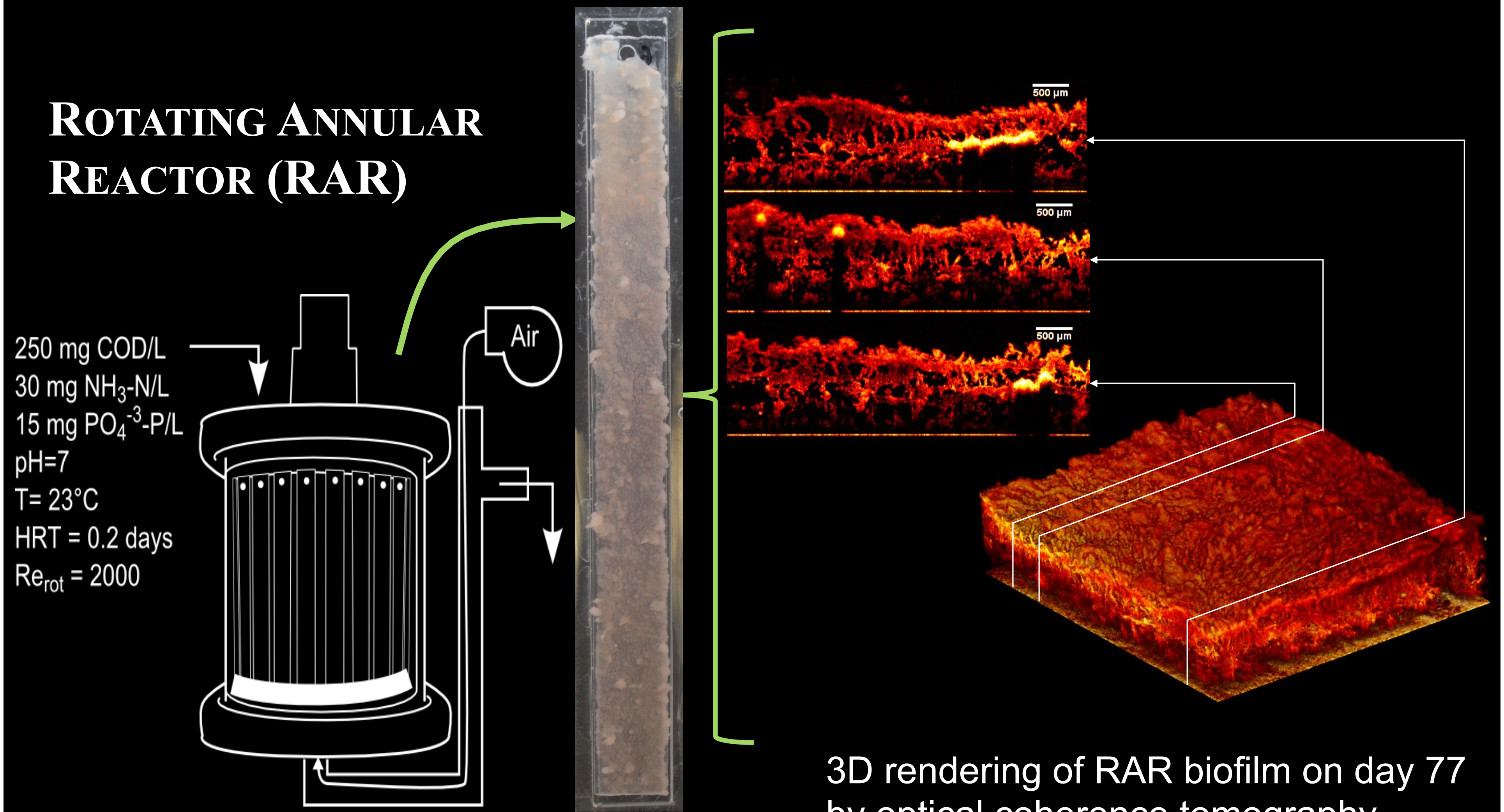


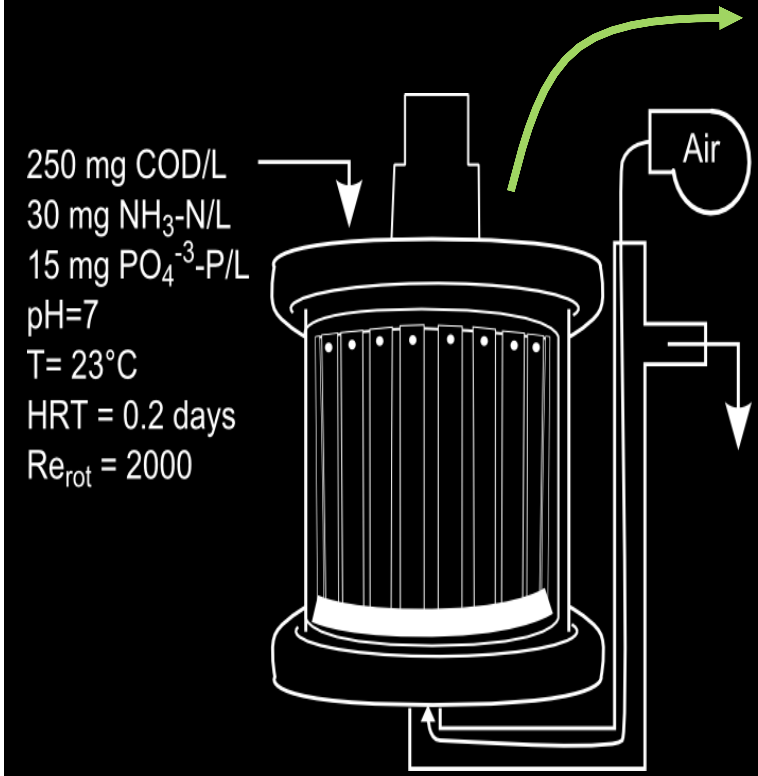
Ongoing Work: Enrichment of Deammonification Biofilms under Mainstream Conditions- Linking **Mesoscale Aggregate Structure** to Emergent Function



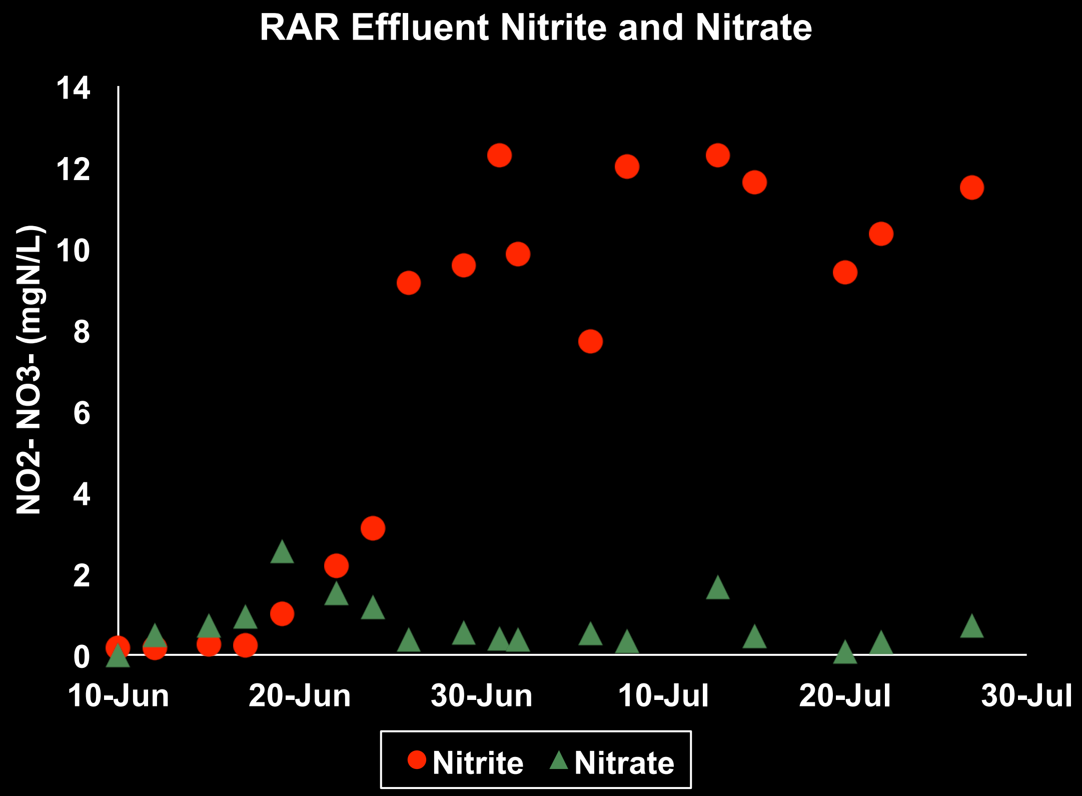
3D rendering of RAR biofilm on day 77 by optical coherence tomography

Ongoing Work: Enrichment of Deammonification Biofilms under Mainstream Conditions: Linking **Mesoscale Aggregate Structure** to Emergent Function

ROTATING ANNULAR REACTOR (RAR)



Sustained NOB outcompetition and putative (but low) anammox activity under mainstream conditions

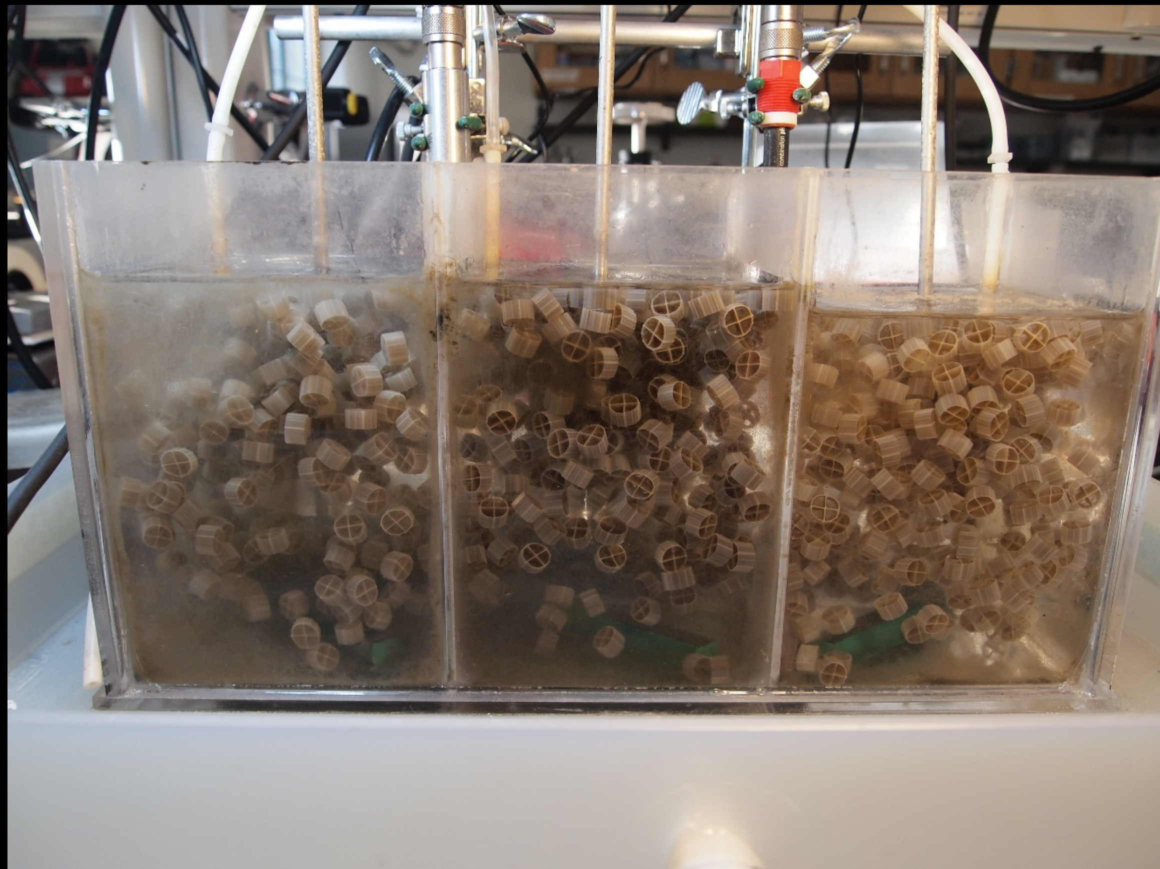


Ongoing Work: Can deammonification be coupled to C removal in mainstream MBBRs?

MBBR:
3 Compartments in Series
Loaded with real primary effluent from the O'Brien WRP

Initial Target:
- Sustained partial nitritation (NOB outcompetition)

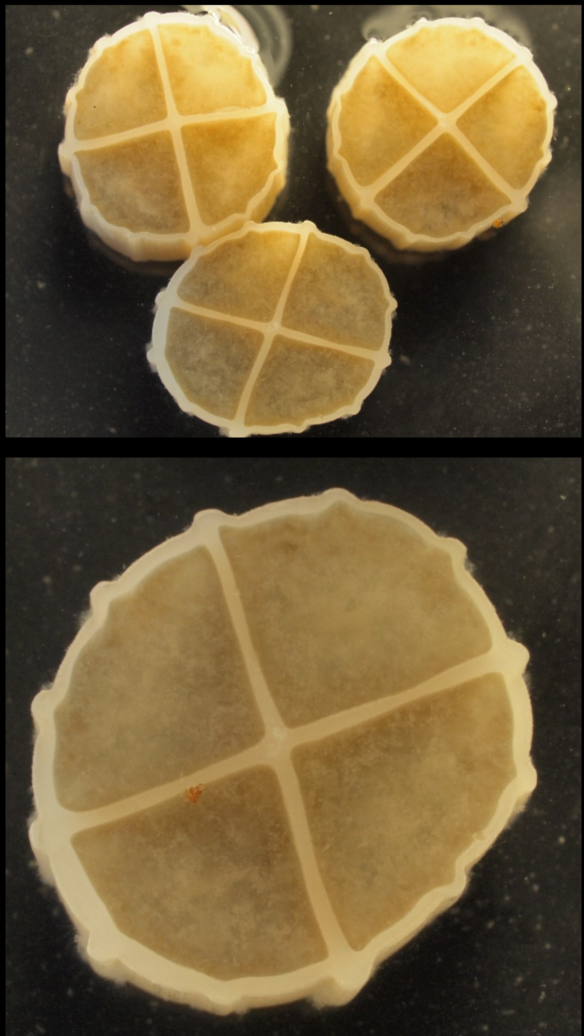
Final Target:
- COD removal/ Nitritation in Tank 1
- Full deammonification in Tank 2
- Anammox in Tank 3



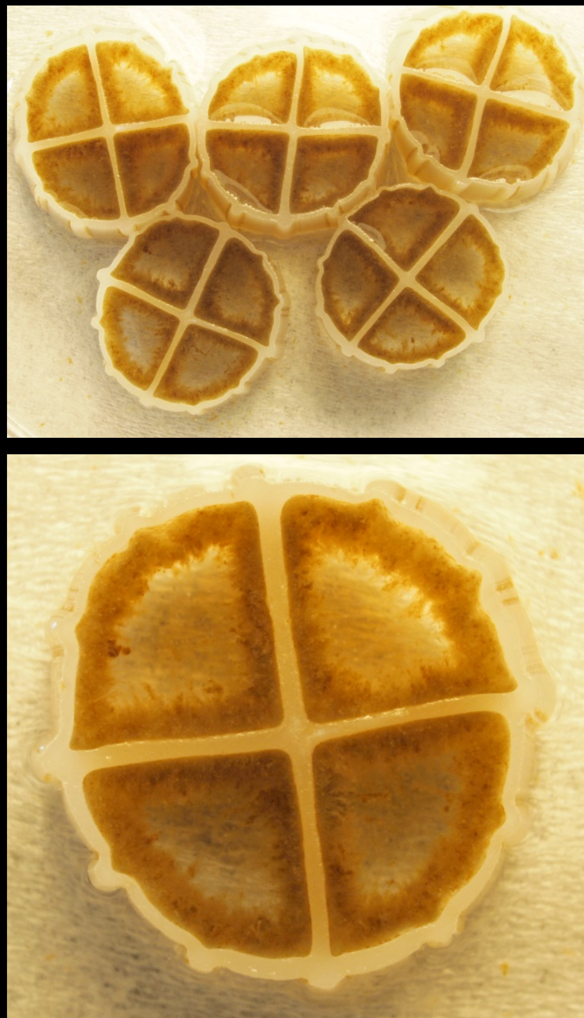
M1 M2 M3

Ongoing Work: Can deammonification be coupled to C removal in mainstream MBBRs with real wastewater?

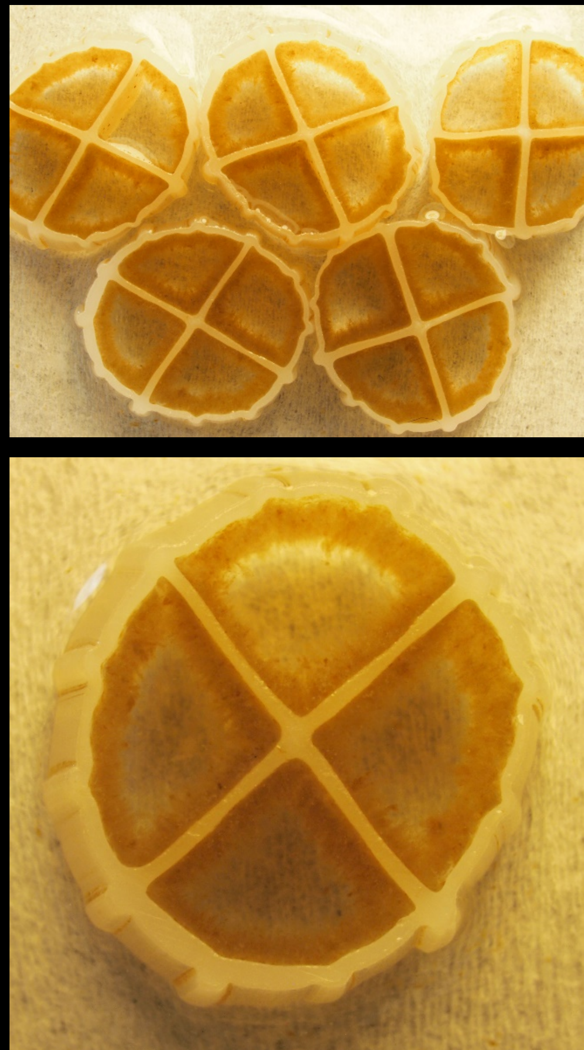
Compartment 1



Compartment 2

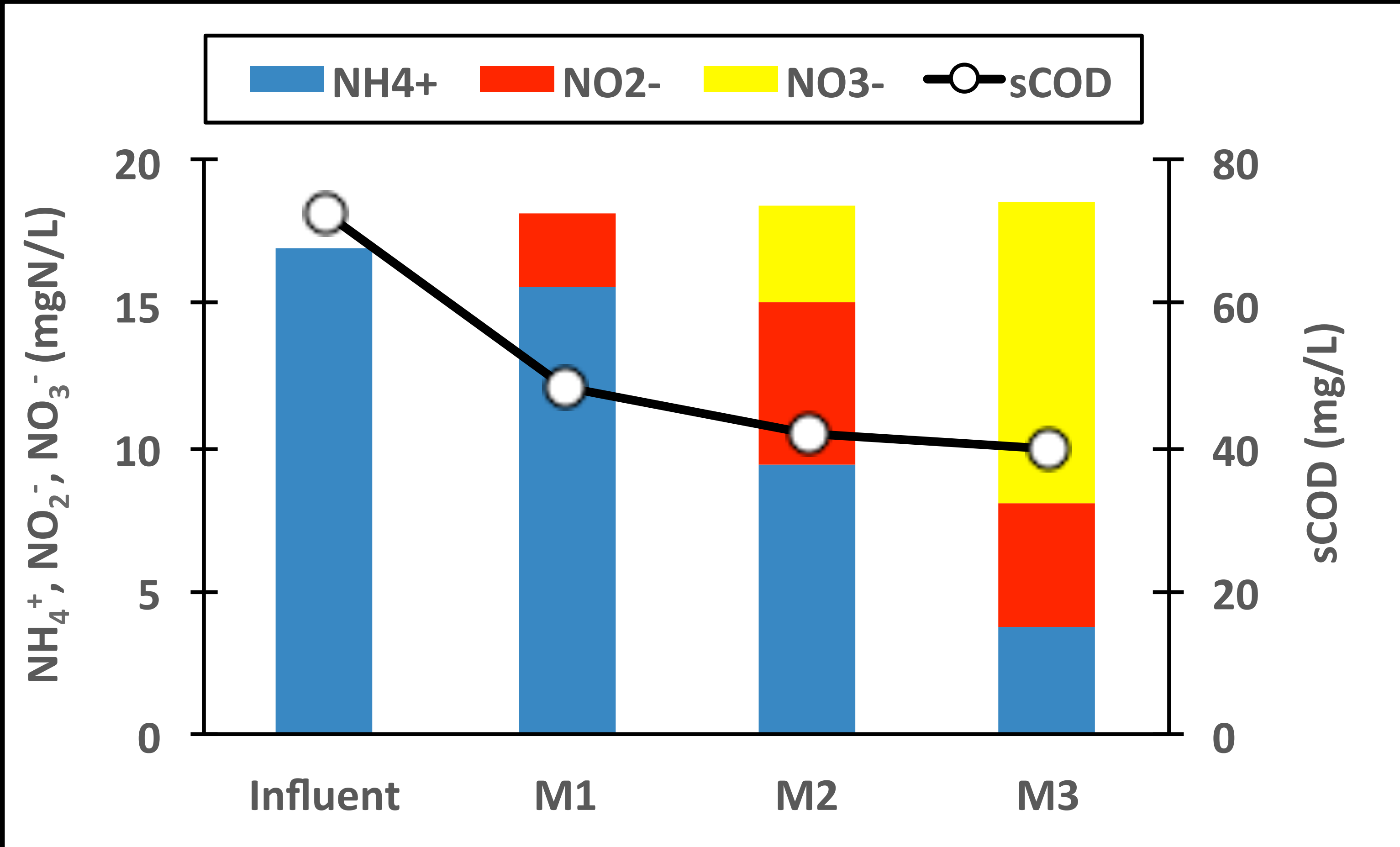


Compartment 3



Ongoing Work: Can deammonification be coupled to C removal in mainstream MBBRs with real wastewater?

MBBR Performance Snapshot 7/28/2015-7/29/2015

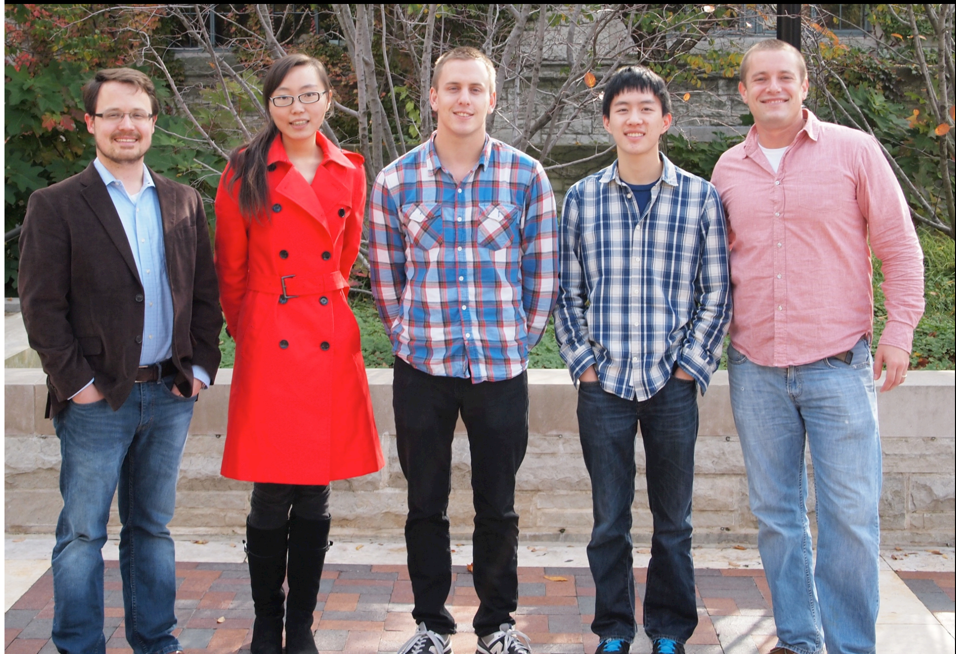


Initial results suggest successful NOB outcompetition in a biofilm system (compartments M1 and M2) under mainstream conditions

Take Away Points

- New understanding of N cycle microbial ecology is leading to emerging sustainable bioprocesses for nutrient removal and recovery of “misplaced resources”
- Mainstream deammonification has extraordinary promise, but is in its infancy, with key remaining challenges to be addressed
- Deammonification process variations harboring different aggregate types display starkly different patterns of performance and stability

Acknowledgements



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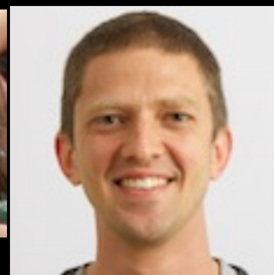

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