The Potential of Using Biological Nitrogen Removal Technique for Stormwater Treatment

Yewei Sun, PhD Student
Zhi-Wu Wang, Assistant Professor
Sustainable Environment Research Laboratory

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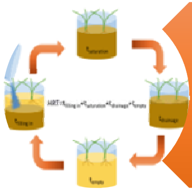
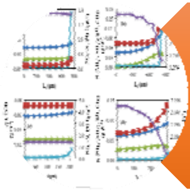
Agenda

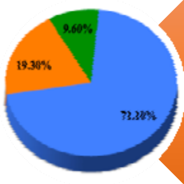
Introduction



Material and Methods



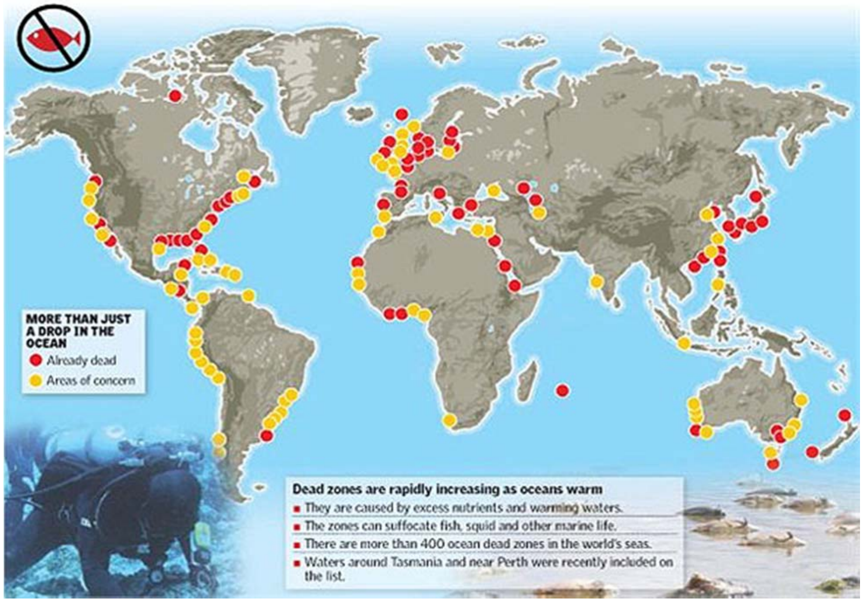
Results



Discussion

“Dead Zones”

What is “Dead Zones”? -----NO FISH!!



https://nofishleft.wordpress.com/tag/marine-dead-zones/

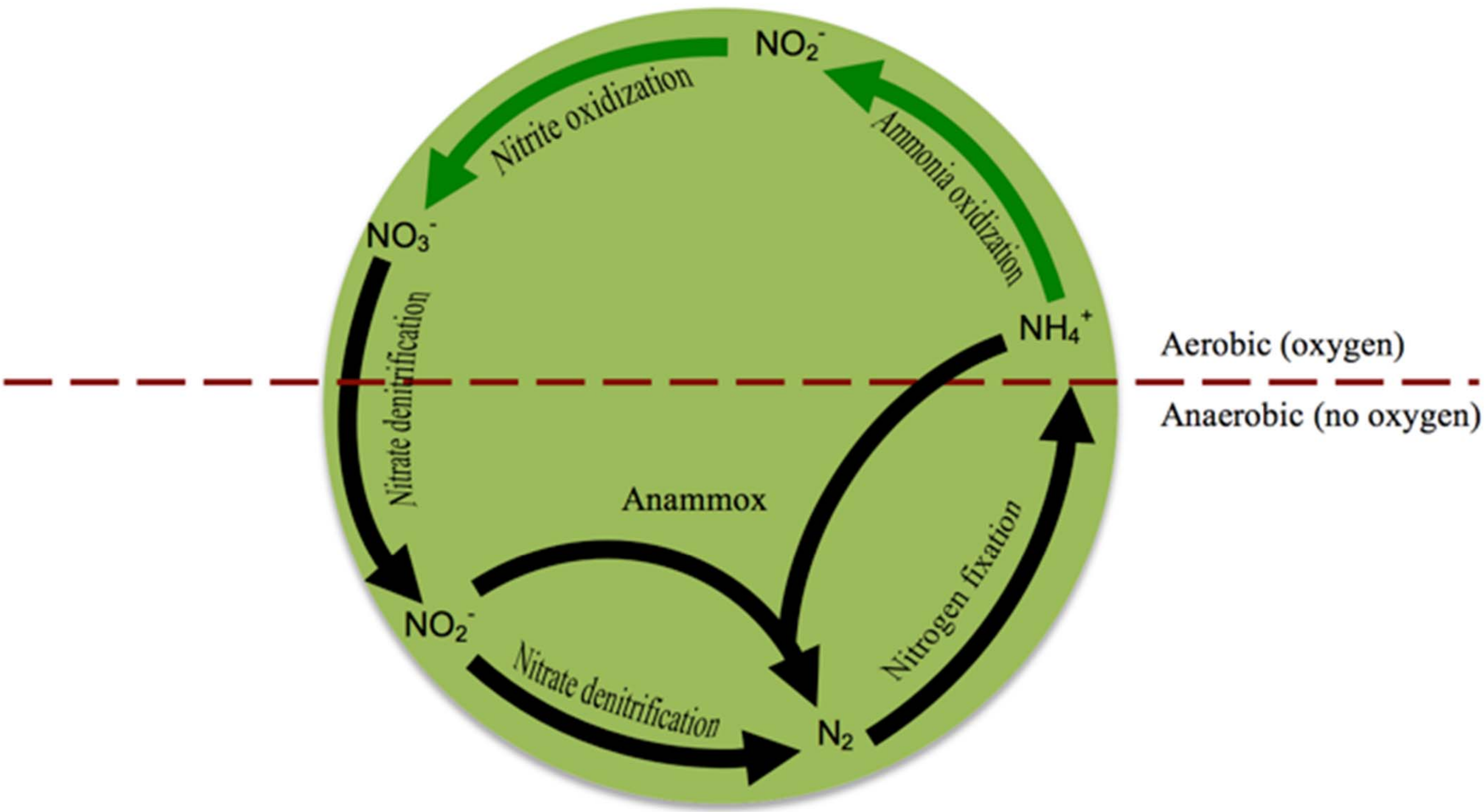
"Dead Zones" Formation

Increased
- Urbanization
- Climate Change

Increased
- Stormwater Runoff
- **Nitrogen Pollutant**

Formed
- "Dead Zones"

What is Biological Nitrogen Removal (BNR)?



Biological Nitrogen Removal

Wastewater →

Stormwater →

Applications

Models

ASM1
ASM2
ASM3
CWM1

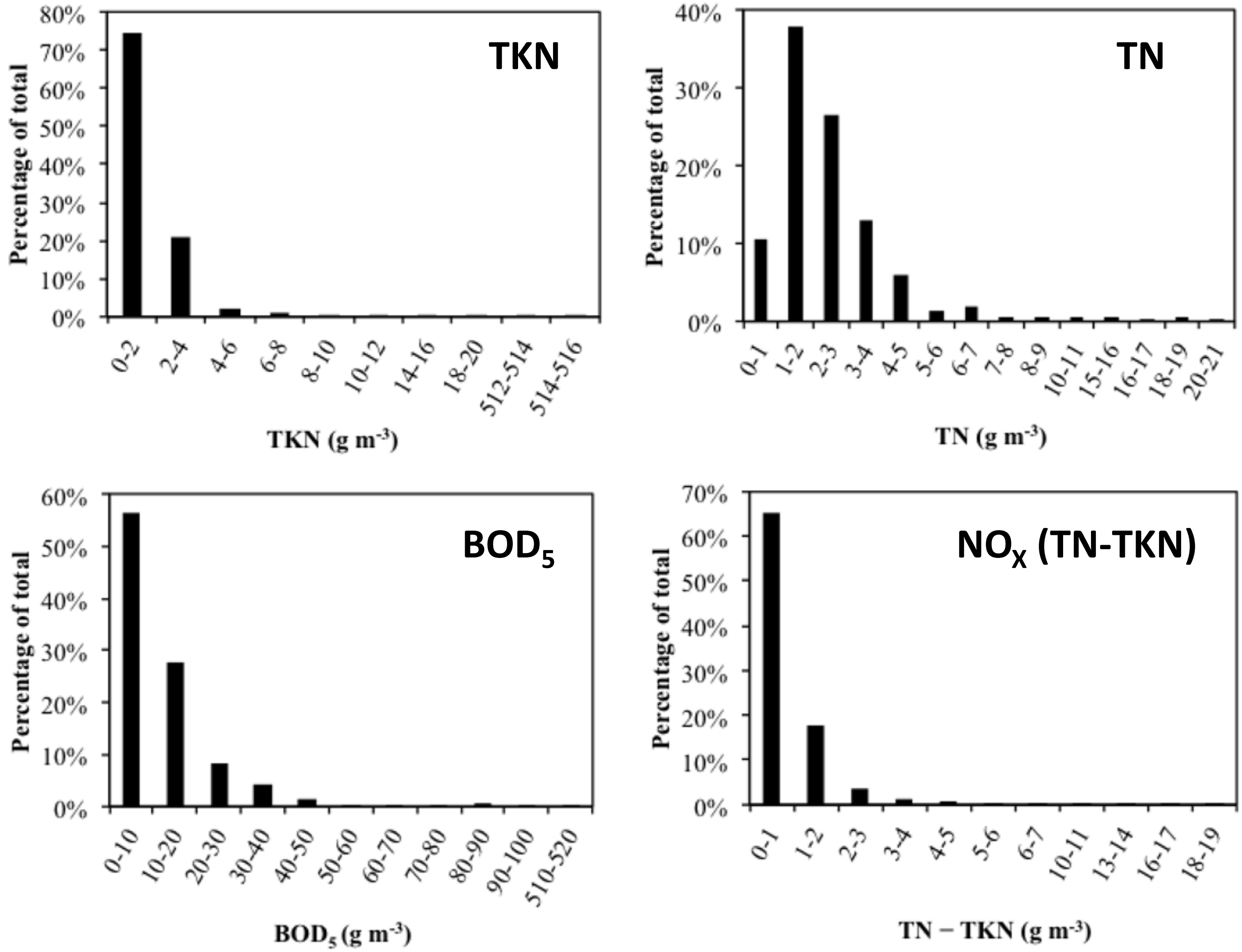
High affinity of BNR communities to nitrogen pollutants

↓

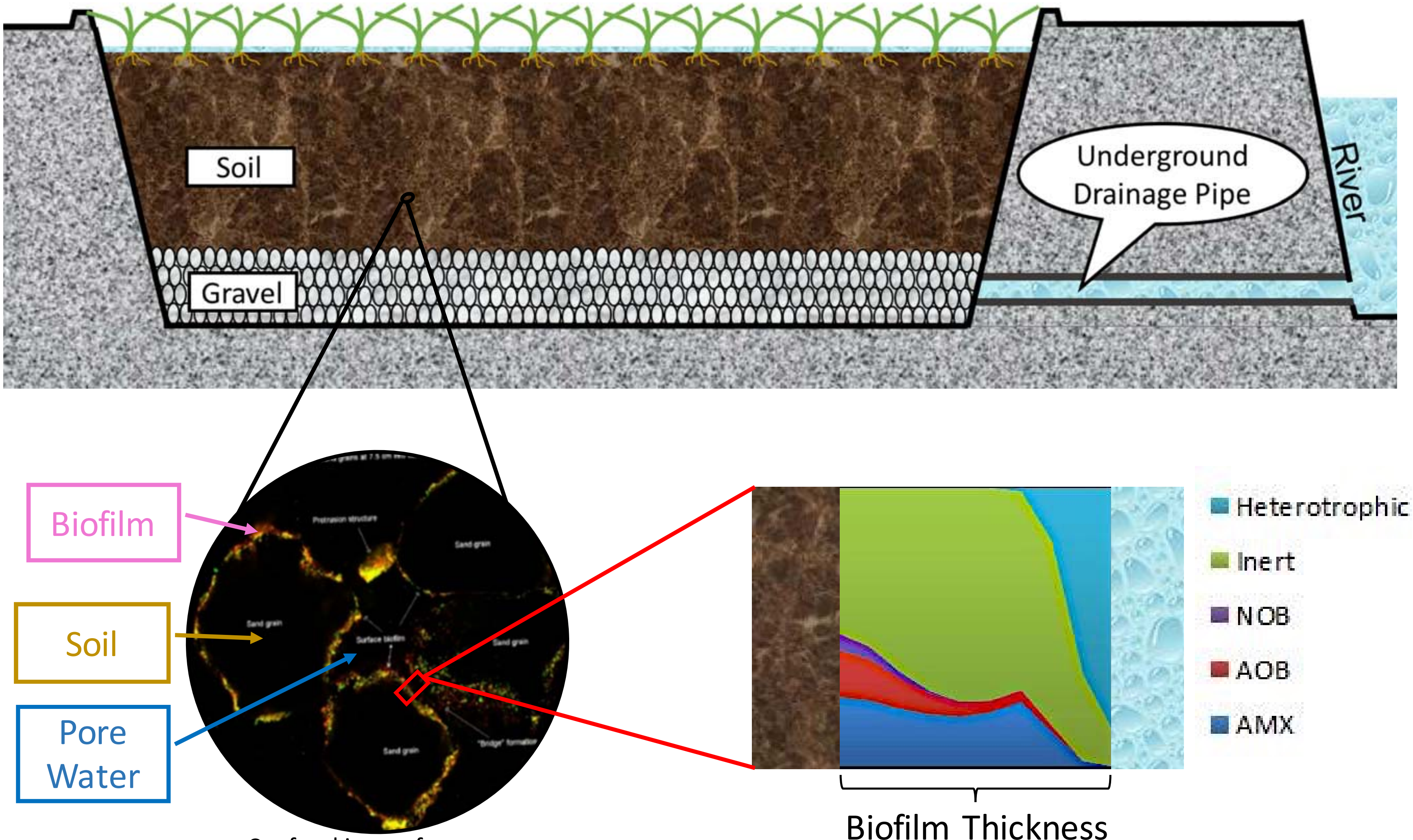
Applicability of wastewater BNR models to low nitrogen concentration environment

Introduction: BNR for stormwater

Stormwater Characteristics (National Stormwater Quality Database)



Bioretention System



Confocal image from Meherunnesha et al. (2008)

Bacterial Model

- **Five substrates in the liquid phase**
  - Dissolved oxygen (DO)
  - Nitrate (NO_3^-)
  - Nitrite (NO_2^-)
  - Ammonium (NH_4^+)
  - Biodegradable organic carbon source expressed as chemical oxygen demand (COD)
- **Three types of autotrophic bacteria**
  - Ammonia-oxidizing bacteria (AOB)
  - Nitrite-oxidizing bacteria (NOB)
  - Anammox bacteria (AMX)
- **Three types of heterotrophic bacteria**
  - Oxygen-respiring heterotroph (ORH)
  - Nitrite denitrifier (NID)
  - Nitrate denitrifier (NAD)

Plant Model

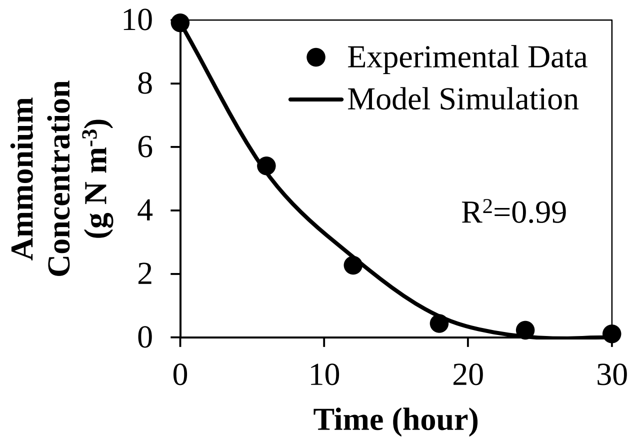
- Capability of assimilating both NH_4^+ and NO_3^-
- Nitrogen is only temporarily stored in plant and will be eventually released back to the downstream water at their death and decay.
- **Since this study focused on biological nitrogen removal and plant assimilation will reach its limit soon, plant nitrogen uptake was only considered in model calibration and validation.**

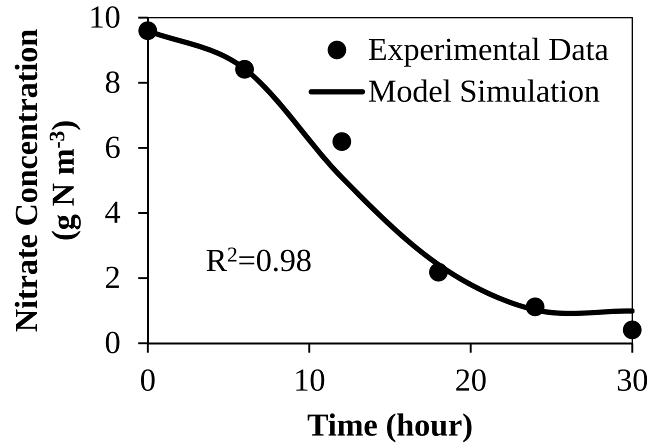
Material and Methods: Model kinetics

Process	Process Rate	Reference
Autotrophic Bacteria		
Growth of X_{AOB}	$\mu_{max,AOB}X_{AOB}\frac{S_{NH_4^+}}{K_{NH_4^+,AOB}+S_{NH_4^+}}\frac{S_{O_2}}{K_{O_2,AOB}+S_{O_2}}$	(Jubany et al. 2008)
Decay of X_{AOB}	$b_{AOB}X_{AOB}\frac{S_{O_2}}{K_{O_2,AOB}+S_{O_2}}$	(Volcke et al. 2010)
Growth of X_{NOB}	$\mu_{max,NOB}X_{NOB}\frac{S_{NO_2^-}}{K_{NO_2^-,NOB}+S_{NO_2^-}}\frac{S_{O_2}}{K_{O_2,NOB}+S_{O_2}}$	(Jubany et al. 2008)
Decay of X_{NOB}	$b_{NOB}X_{NOB}\frac{S_{O_2}}{K_{O_2,NOB}+S_{O_2}}$	(Volcke et al. 2010)
Growth of X_{AMX}	$\mu_{max,AMX}X_{AMX}\frac{S_{NH_4^+}}{K_{NH_4^+,AMX}+S_{NH_4^+}}\frac{S_{NO_2^-}}{K_{NO_2^-,AMX}+S_{NO_2^-}}\frac{K_{O_2,AMX}}{K_{O_2,AMX}+S_{O_2}}$	(Volcke et al. 2010)
Decay of X_{AMX}	$b_{AMX}X_{AMX}\frac{S_{O_2}}{K_{O_2,AMX}+S_{O_2}}$	(Volcke et al. 2010)
Heterotopic Bacteria		
OB Growth	$\mu_{max,H}X_H\frac{S_S}{K_{S,H}+S_S}\frac{S_{O_2}}{K_{O_2,H}+S_{O_2}}$	(Henze et al. 2000)
Decay of X_H	b_HX_H	(Henze et al. 2000)
DEN_3 Growth	$\mu_{max,N}X_N\frac{S_{NH_4^+}}{K_{NH_4^+,N}+S_{NH_4^+}}\frac{S_{NO_3^-}}{K_{NO_X^-,N}+S_{NO_3^-}}\frac{K_{O_2,N}}{K_{O_2,N}+S_{O_2}}\frac{S_S}{K_{S,N}+S_S}$	(Henze et al. 2000)
DEN_2 Growth	$\mu_{max,N}X_N\frac{S_{NH_4^+}}{K_{NH_4^+,N}+S_{NH_4^+}}\frac{S_{NO_2^-}}{K_{NO_X^-,N}+S_{NO_2^-}}\frac{K_{O_2,N}}{K_{O_2,N}+S_{O_2}}\frac{S_S}{K_{S,N}+S_S}$	(Alpkvist et al. 2006)
Plant		
Uptake of NH_4^+	$\mu_{max,pl,NH_4^+}X_{N,pl}(1-\frac{X_{N,pl}}{X_{max,N,pl}/d})\frac{S_{NH_4^+}}{K_{NH_4^+,pl}+S_{NH_4^+}}$	(van Dam et al. 2007
Uptake of NO_3^-	$\mu_{max,pl,NO_3^-}X_{N,pl}(1-\frac{X_{N,pl}}{X_{max,N,pl}/d})\frac{S_{NO_3^-}}{K_{NO_3^-,pl}+S_{NO_3^-}}$	(van Dam et al. 2007
Decay of X_{pl}	$b_{pl}X_{pl}$	(Mburu et al. 2012)
Degradation of $X_{dead,pl}$	$b_{degrade}X_{dead,pl}$	(Mburu et al. 2012)
Root Oxygen Leaching	$k_{ol}X_{pl}(e^{S_{sat,O_2}-S_{O_2}}-1)$	(Mburu et al. 2012)
Biofilm		
Detachment	DeL_f	(Henze 2008)
Diffusion	$D_f\frac{d^2S_S}{dz^2}=-r_S \quad \frac{dS_S}{dz}=0\ at\ z=0;\ S_S=S_{bulk,S}\ at\ z=L_f$	(Henze et al. 2000)

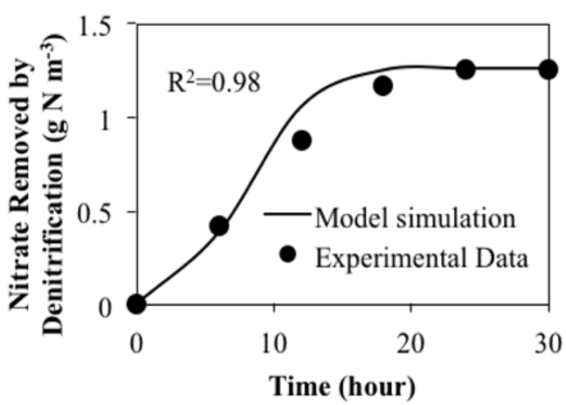
Material and Methods: Model calibration and validation

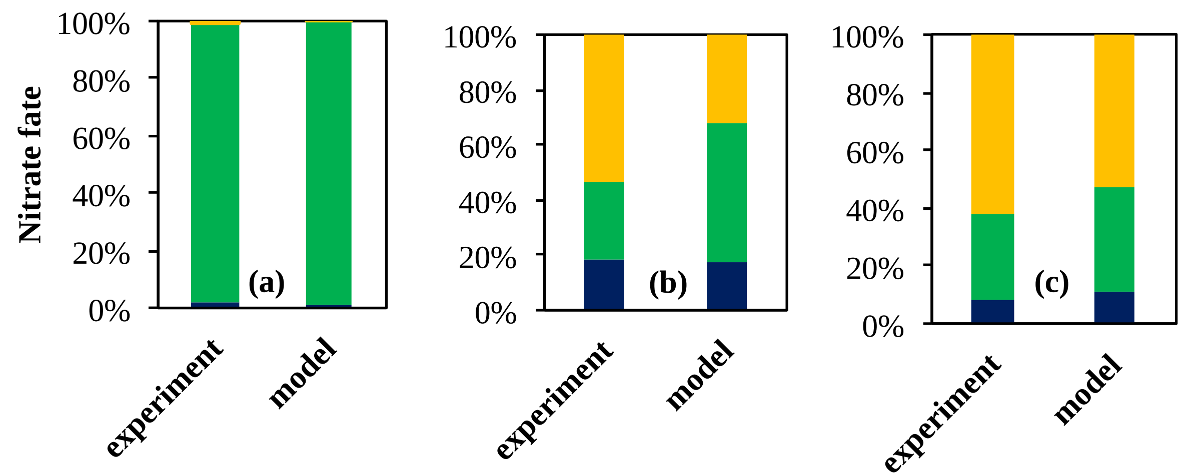
Model Calibration





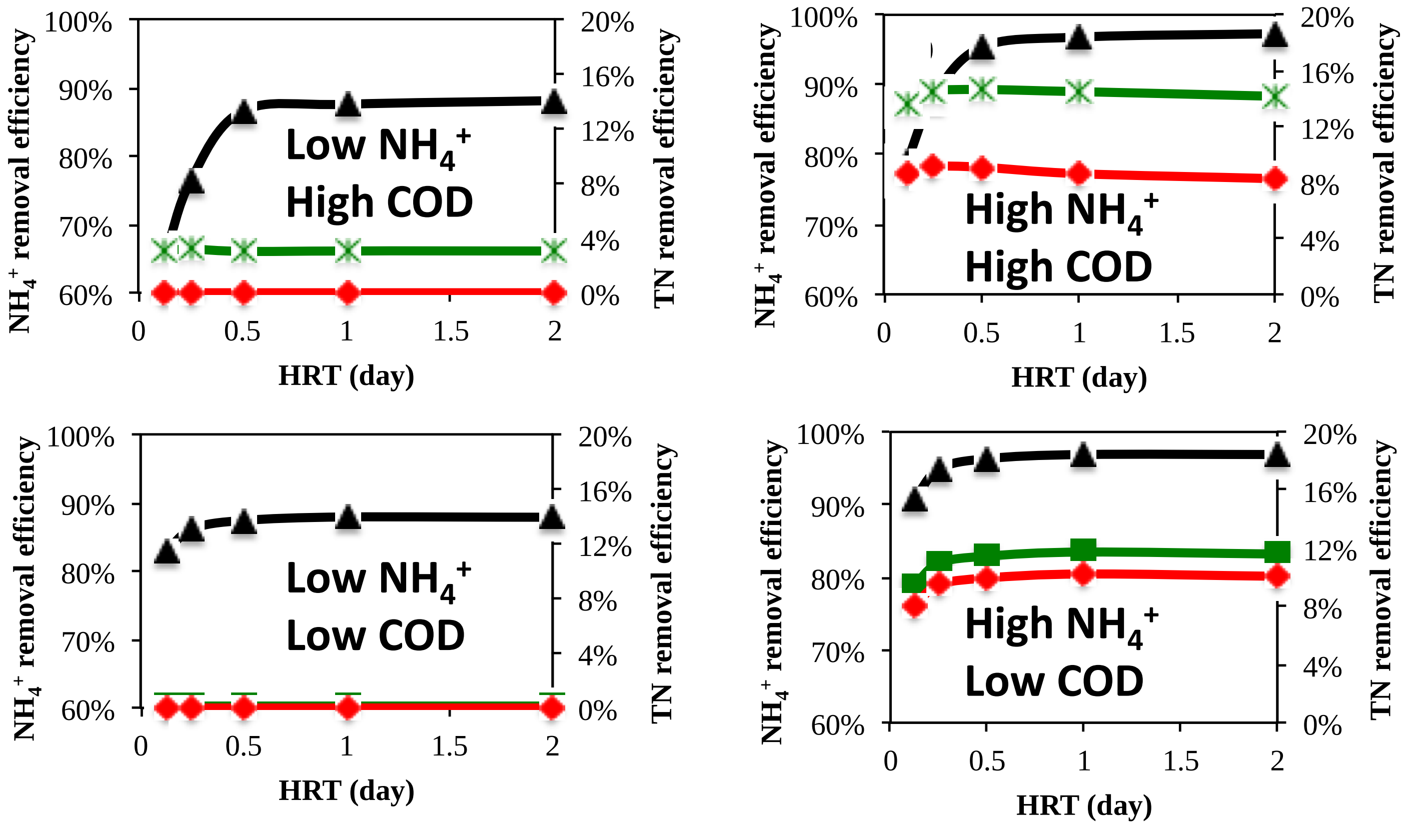
Model Validation





Literature data from Payne et al. (2014)

Results: Effect of HRT on steady-state NH_4^+ and TN removal efficiencies



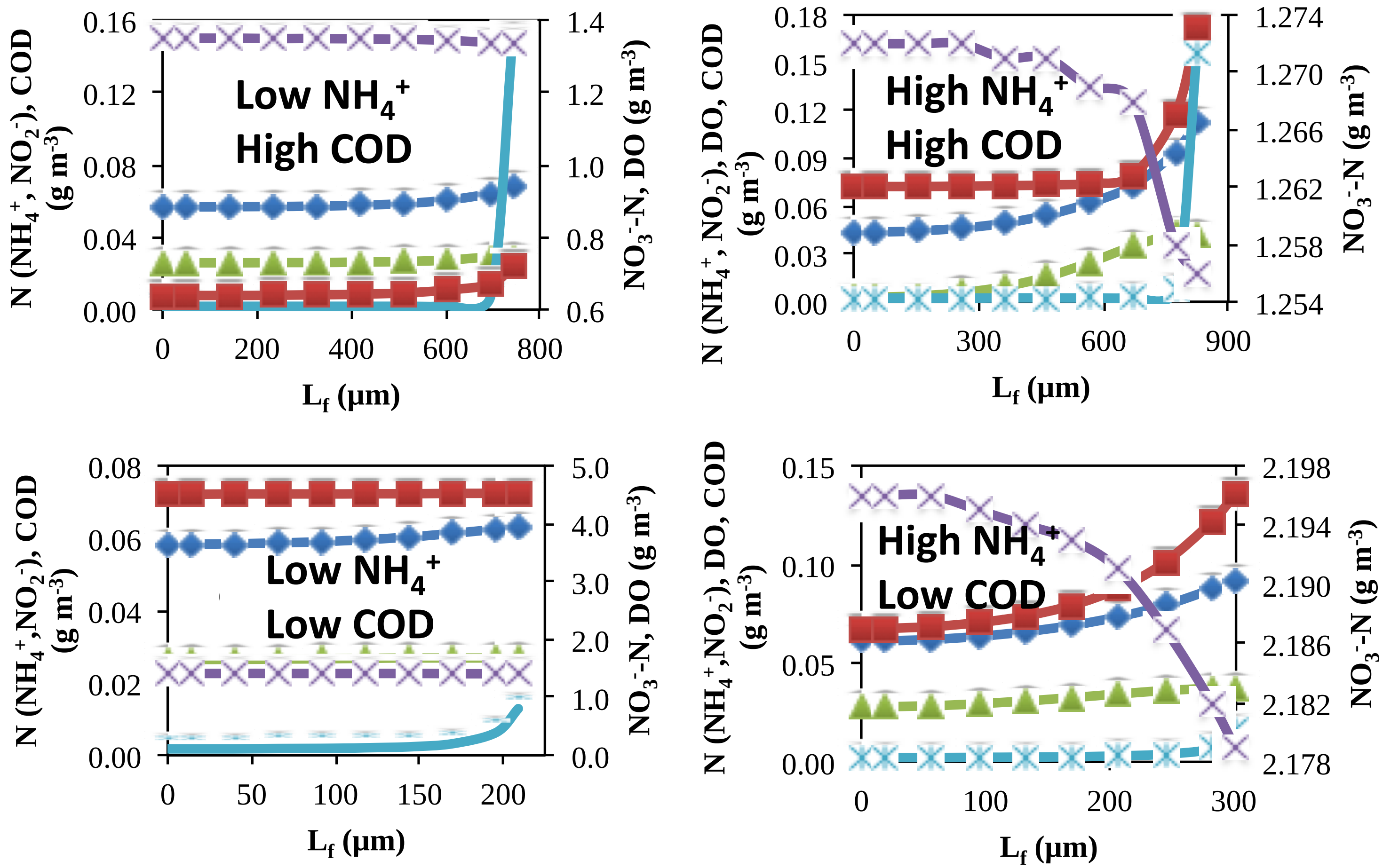
Black: NH_4^+ removal

Green: TN removal with AMX

Red: TN removal without AMX

- 0.5 days HRT should be sufficient for stormwater NH_4^+ removal.
- TN removal efficiency improves along with the increase of stormwater reducing power (NH_4^+ and COD).
- The contribution of AMX to TN removal increases along with the increase of stormwater reducing power (NH_4^+ and COD).

Results: Substrate distribution in biofilm



Dark blue: NH_4^+

Green: NO_2^-

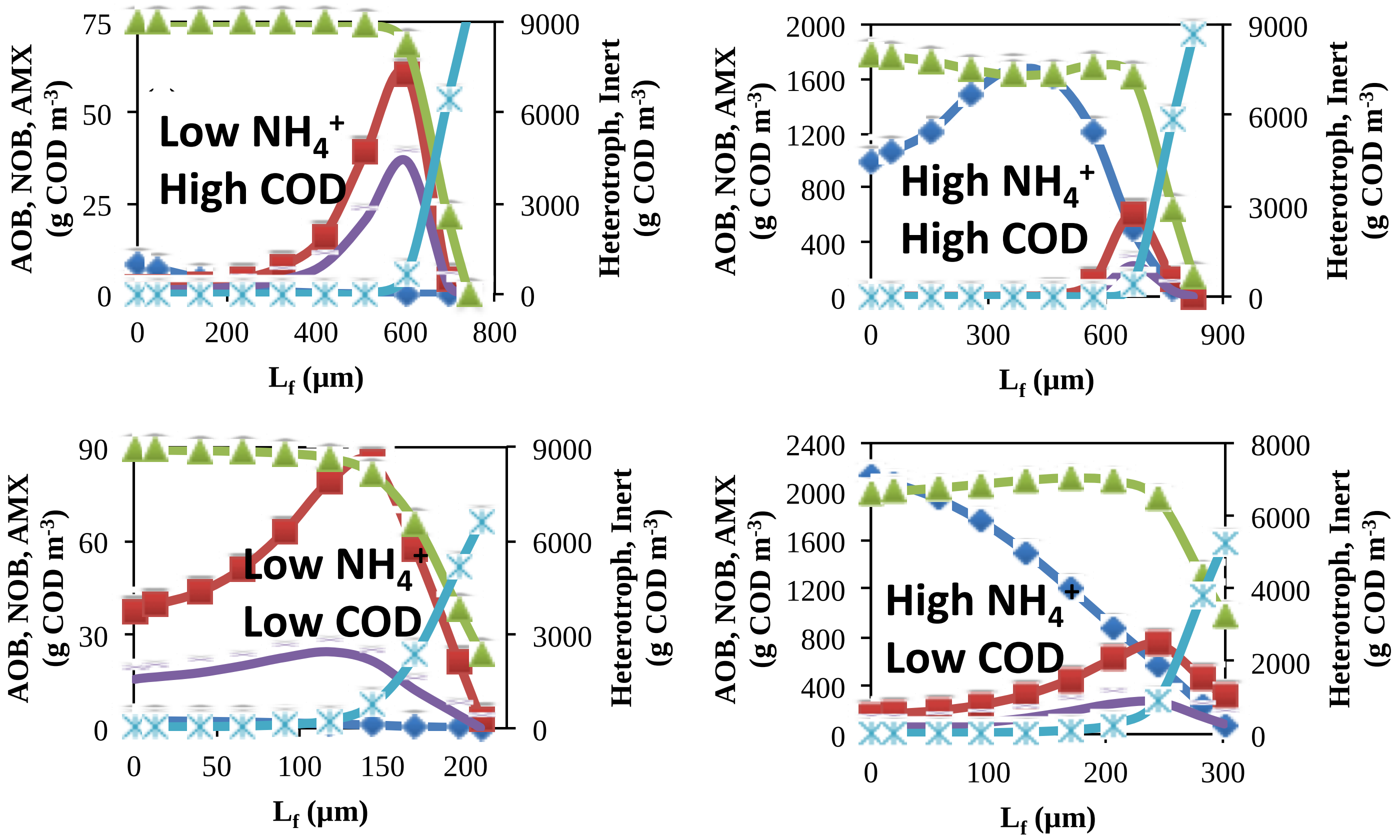
Purple: NO_3^-

Blue: COD

Maroon: DO

- COD can be oxidized within the top 50 μm layer in the biofilms.
- NH_4^+ oxidation occurs further inside biofilm beneath the layer where COD oxidation occurs.
- The extent of NH_4^+ oxidation depends on the penetration of remaining DO.

Results: Bacteria distribution in biofilm



Dark blue: AMX

Purple: NOB

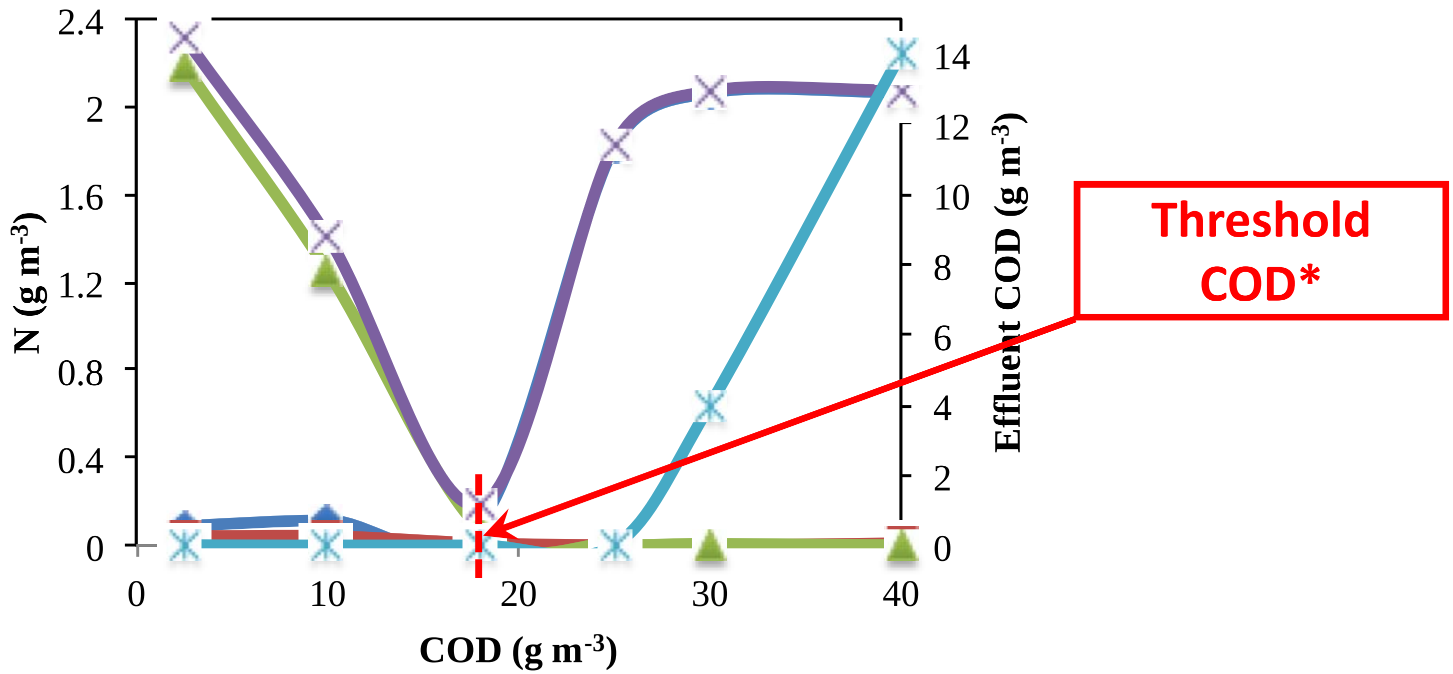
Maroon: AOB

Green: Inert

Blue: Heterotroph

- Heterotroph, AOB and NOB predominate the top layers of biofilms where COD and DO are depleted.
- AMX only grow deep inside the biofilms where COD and DO are lean but NO_2^- and NH_4^+ are affluent.
- Only stormwater with a relatively high reducing power (NH_4^+ and COD) offers the possibility to cultivate biofilms with an anoxic local environment for AMX prosperity.

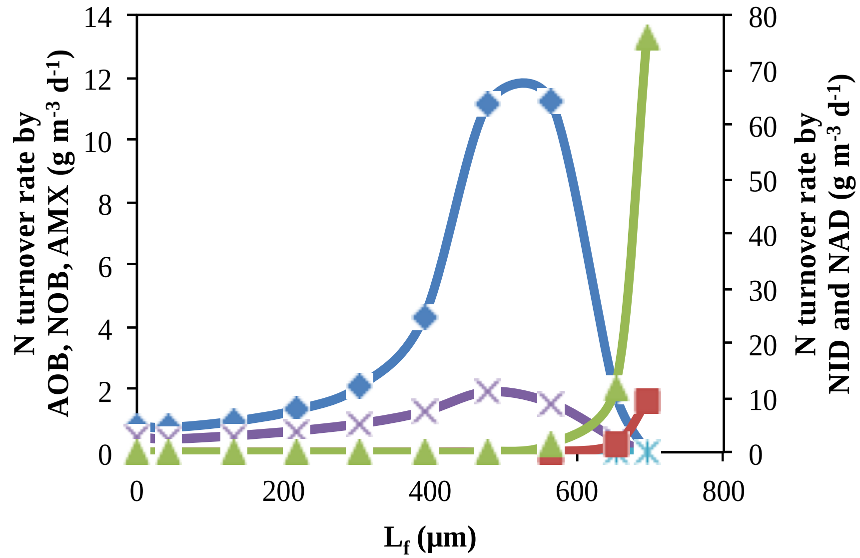
Results: Effect of COD on BNR



Dark blue: NH_4^+, Green: NO_3^-, Maroon: NO_2^-, Purple: TN, Blue: COD

- TN keeps decreasing to almost zero as the influent COD increases to a threshold COD value (COD*).
- Continuous increase of influent COD will result in increase of TN and effluent COD concentration.

Results: BNR at COD*



Dark blue: AMX

Purple: AOB

Blue: NOB

Maroon: NID

Green: NAD

Two major characteristics of BNR at COD*:

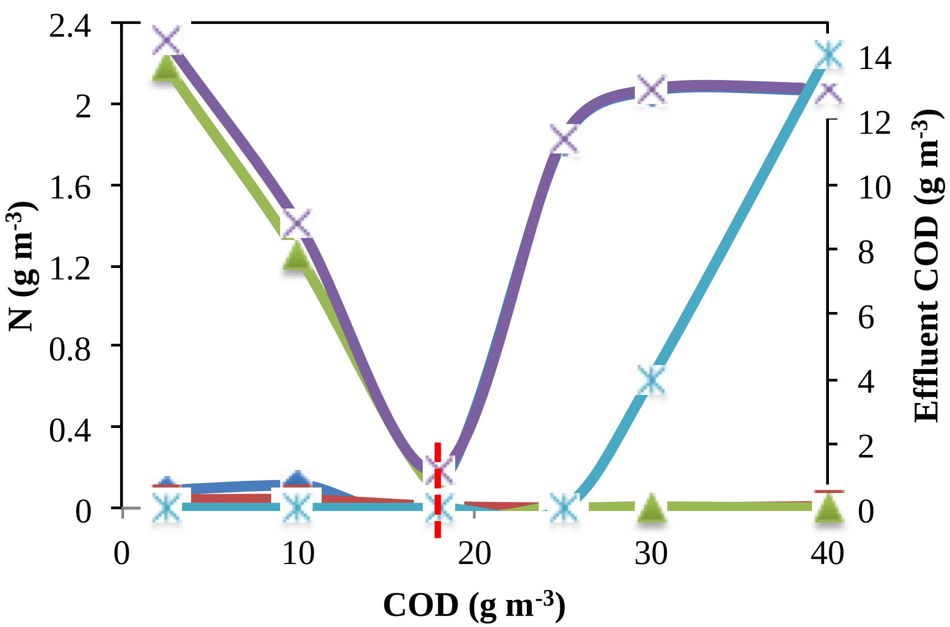
i) Majority (90%) of nitrogen (NH_4^+ or NO_3^-) is removed through AMX while only 10% through NID.

ii) Only partial nitritation occurred with no need of NOB. Therefore, the primary BNR pathway at COD* is through partial nitritation and AMX for the least COD consumption.

Results: BNR at COD*

COD* must be provided to enable the co-existence of aerobic and anoxic conditions required by BNR.

- COD < COD* leads to BNR failure because of the inadequate reducing power (NH_4^+ and COD) for anoxic condition establishment.
- COD > COD* causes insufficient NH_4^+ nitrification due to inadequate DO remains for AOB after COD oxidation.



Dark blue: NH_4^+

Green: NO_3^-

Maroon: NO_2^-

Purple: TN

Blue: COD

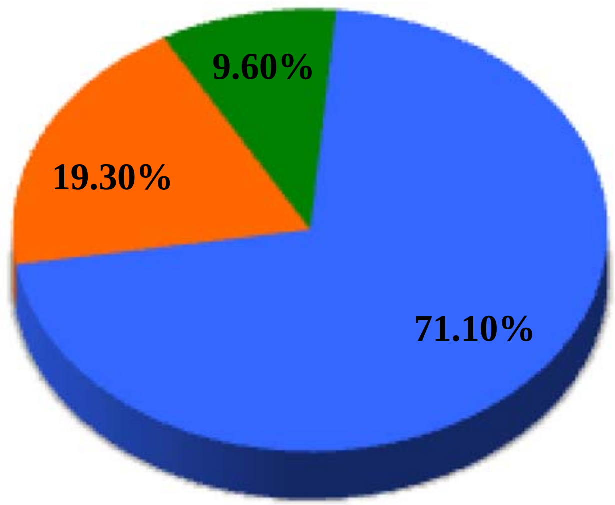
Discussion: Stoichiometric estimation of COD*

- Three scenarios can be generalized for stormwater BNR with regard to COD* demand.

	Exemplary $S_{NH_4^+-in}$: $S_{NO_3^--in}$ ratio	Percentage of nitrogen being removed by different pathways			
		Denitrification	AMX	Bacterial uptake	Residual
Scenario 1 $S_{NH_4^+-in} : S_{NO_3^--in} > 1.15$	2.50	6.6%	84.3%	9.1%	0.0%
Scenario 2 $S_{NH_4^+-in} : S_{NO_3^--in} \leqslant 1.15$	0.50	61.3	10.0%	28.7	0.0%
Scenario 3 $S_{NH_4^+-in} : S_{NO_3^--in} < \frac{2Y_{NH}}{Y_{NO}} = 0.44$	0.30	35.3%	0.0%	23.1%	41.6%

Discussion: Stoichiometric estimation of COD*

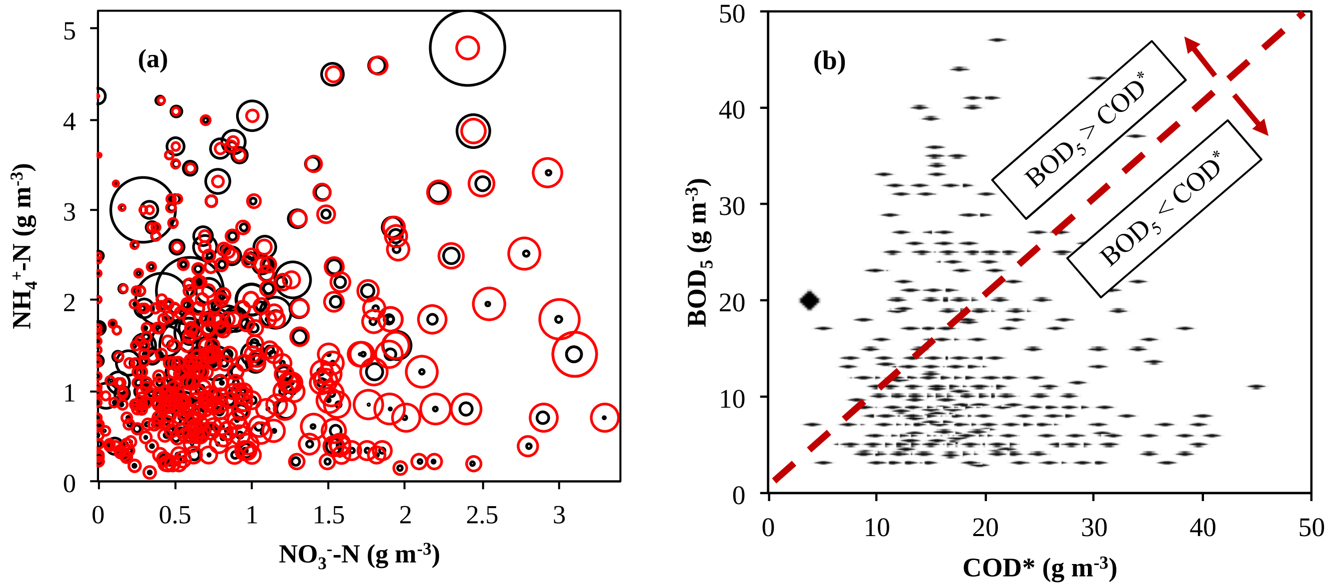
- About **9.6%** stormwater events in National Stormwater Quality Database (NSQD) are subjected to NH_4^+ limitation (scenario 3).



Fraction of U.S. stormwater runoff in NSQD with NH_4^+-N to NO_3^--N ratio under scenario 1 (blue), scenario 2 (orange), and scenario 3 (green)

Discussion: Stormwater COD availability for BNR

- 82.6% U.S. stormwater in NSQD contains BOD_5 lower than COD* required for complete BNR.
- Vegetation planted in the topsoil of bioretention system may release some COD.
- The slow COD-releasing biofilm carriers developed in recent years may be applied as an alternative for COD supplementation.

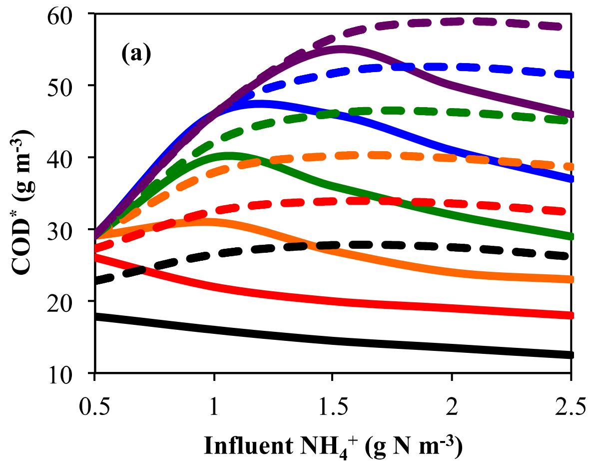


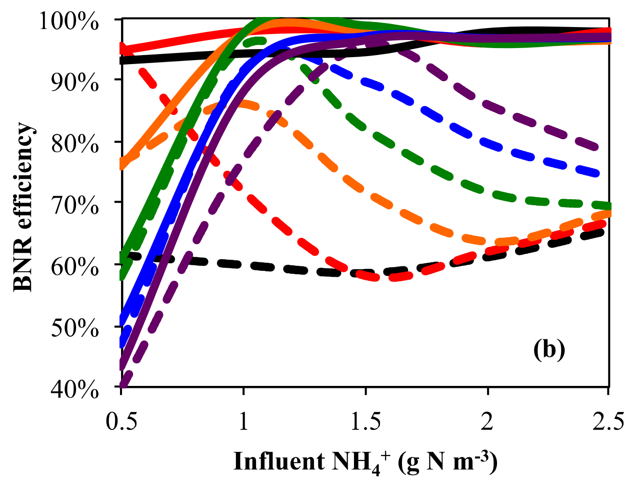
(a) BOD_5 : (black circle size) COD* (red circle size)

(b) BOD_5 vs COD* plot

Discussion: Importance of AMX for stormwater BNR

- COD* without AMX can be two-fold higher than the COD* with AMX.
- BNR efficiency can be significantly compromised without AMX, which is true especially at higher $S_{NH_4^+\_in}:S_{NO_3^-\_in}$ ratio.



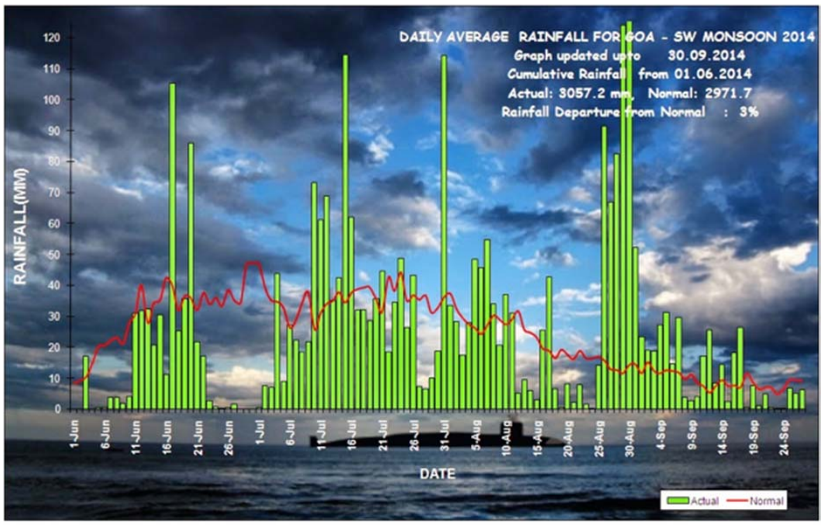


Solid line: with AMX
Dashed line: without AMX

NO_3^- (g N m^{-3}) = 0.5 (black)
1 (red)
1.5 (orange)
2 (green)
2.5 (blue)
3 (purple)

Discussion: Model limitations and future work

- Homogeneous condition was assumed in bioretention systems in which heterogeneous environment may exist.
- The effect of inter-event duration was not considered in current model development.
- Experimental validation of the mathematical model is needed in future work.



Daily average rainfall graph in Goa, India (Jun to Sept. 2014)
http://weatheringoa.blogspot.com/2014/10/goa-monsoon-2014-analysis-happy-ending.html

Validation study is being carried out in our collaborator's (Dr. Changwoo Ahn) mesocosm complex in George Mason University

Concluding remarks:

- A mathematical model was for the first time developed to simulate the spatial distribution of BNR activity in biofilms growing on bioretention media for stormwater treatment.
- A threshold influent carbon source concentration (COD*) was found for maximizing BNR efficiency. Application of AMX can significantly lower COD* and enhance BNR efficiency.
- 71.1% urban stormwater runoff contains adequate NH_4^+ for both AMX and denitrification, 19.3% contains adequate NH_4^+ for denitrification but inadequate for AMX, while the NH_4^+ content in 9.6% urban stormwater is inadequate for neither AMX nor denitrification.

We would like to extend our sincerest thanks to **4-VA Competitive Research Grants** and **Sussman Internship funding** for supporting this project.

Thank your for listening!

Yewei Sun

PhD Student
Occoquan Laboratory
Department of Civil and Environmental Engineering, Virginia Tech
9408 Prince William Street, Manassas, VA 20110-5670

Office: 703-361-5606 x 136
Fax: 703-361-7793
Email: yeweis12@vt.edu