Stormwater Biofiltration for Nutrient Control: A Summary of Three Years of Field-based Investigations

Douglas Daley, Associate Professor, P.E. (NY) and Jessica Buhrle, M.S. (2023)
Environmental Resources Engineering
SUNY College of Environmental Science & Forestry
Syracuse, NY

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ESF State University of New York College of Environmental Science and Forestry

Summary

- Study Design: Field-scale irrigated column-style mesocosms with replication
- Effects of organic matter (OM) and soil height (HT) on dissolved constituents of concern
  - Zinc: OM and HT were not significant factors
  - Copper: Low OM had significantly better removal. HT was not a significant treatment factor.
  - Phosphorous: Low OM had significantly better removal. HT was not a significant treatment factor.
  - Nitrogen: OM not significant for NO_3 or NH_4
    - HT significantly affects NO_3 removal
    - HT significantly affects NH_4 removal
- Vegetation effects: Not significantly different from bare soil

MOTIVATION

- Sponsored by NYSERDA commencing in 2017
- Interest in predicting treatment performance for dissolved constituents of concern
- Modification of the stormwater design manual (SWDM) by the NYS Department of Environmental Conservation (DEC)

NYSERDA

NEW YORK STATE OF OPPORTUNITY | Department of Environmental Conservation

Objectives

- Develop specification for biofiltration media based on particle size distribution
- Determine effect of organic matter (OM) content on **aqueous phase** constituents of effluent
  - Nitrogen Mix (greater organic matter)
  - Phosphorous Mix (lesser organic matter)
- Determine effect of soil column height (HT)
  - Residence period/contact time
- Determine effect of vegetation on effluent water quality

Biofiltration Soil Medium (BSM) Design (2017-2018)

Target: requires custom blending*

- Washed concrete sand
- Topsoil
- Clay
- Compost

Delivered vs design intent:

- More clay, less VF gravel is desirable
  - Clay controls infiltration
  - Provides adsorption sites
  - Blending clay was a challenge - clumping
- Soil texture: well-graded loamy sand (~5% silt/clay)

Particle Size	Design Target	As Delivered
Very Fine Gravel	-	23%
Very Coarse Sand	37%	11%
Coarse Sand	13%	11%
Medium Sand	26%	21%
Fine Sand	19%	21%
Very Fine Sand	5%	8%
Silt	5%	4%
Clay	4%	1%

NYSDEC SWDM (Draft May 2022)

- Ch 6: Table 6.14 Stormwater Filtering Design Specifications
- Filter Media for Infiltration Bioretention (F-4), Filtration Bioretention (F-5)
  - 60-75% of ASTM C-33 Sand
  - 25-40% Topsoil per NYSDOT 713-01 Roadside Mix

Topsoil	USCS Soil Type	Percent Passing
2″ (50 mm)	Gravel	100
1″ (25 mm)	Gravel	85-100
¼″ (6.3 mm)	Sand	65-100
0.075 mm (No. 200)	Silt	20 - 65
0.002 mm (2 um)	Clay	0-20

C-33 Sand	USCS Soil Type	Percent Passing
9.5 mm (3/8 in)	Gravel	100
4.75 mm (No. 4)	Coarse Sand	95-100
2.36 mm	Coarse Sand	80 to 100
1.18 mm	Medium Sand	50 to 85
0.6 mm	Medium Sand	25 to 60
0.3 mm	Fine Sand	5 to 30
0.15 mm	Find Sand	0 to 10

PDH check

- Target spec for BSM is 5% clay
- Topsoil (10% clay) is blended with ASTM C-33 sand at a rate of 40% topsoil (the max) to 60% sand (the minimum).
- Does the blend meet spec?

Topsoil	Sand	Mix
10% clay	0% clay	Target 5%
40 lb	60 lb	100 lb
4 lb clay	0 lb/clay	4 lb
		4/100 = 4%
		Miss

Study Design

Design Criteria	
Soil Column Design:	3 x 3 factorial with 3 replicates plus control 3 organic matter (OM) at 1.6%, 4.6%, 6.9% 3 soil depths at 18", 30", 48" 2-foot diameter HDPE culvert pipe
Target Analytes:	NO_3 NH_4 (Total N) P Cu Zn
Stormwater:	"Synthesized" to align with 4x national median stormwater concentrations. Focus on dissolved (aqueous) constituents.
# of Irrigation Trials:	6 – 14 per season
Experimental Period:	Summers 2019, 2020, 2021
Sampling:	Influent: 3x / trial Effluent: 3x / trial Samples @ 0.1 pore volume (PV); 1.1 PV and end of drainage
Irrigation Rate:	2"/hr (normal) with periodic stress tests at 6"/hr and 9"/hr
Irrigation Duration:	9 to 12 hours
Vegetation:	Yr 1: Bare Yr 2: Emerging Yr 3:Established

Lessons re. Construction Methods

- Layering effects on soil resistance in Year 1 (2019)
- Hydraulic vibration to consolidate soil in Year 2
  - Reduced infiltration rate from average ~ 18 in/hr (3.1 to 49) to average ~ 1.2 in/hr (0.2 to 3.5)
  - Breakthrough time increased from ~0.2 hours in all columns to ~3.4 hours.
- Individual columns still indicated preferential flow paths, while others exhibited ponding at various times
  - Biological sliming
  - Crust formation

Results

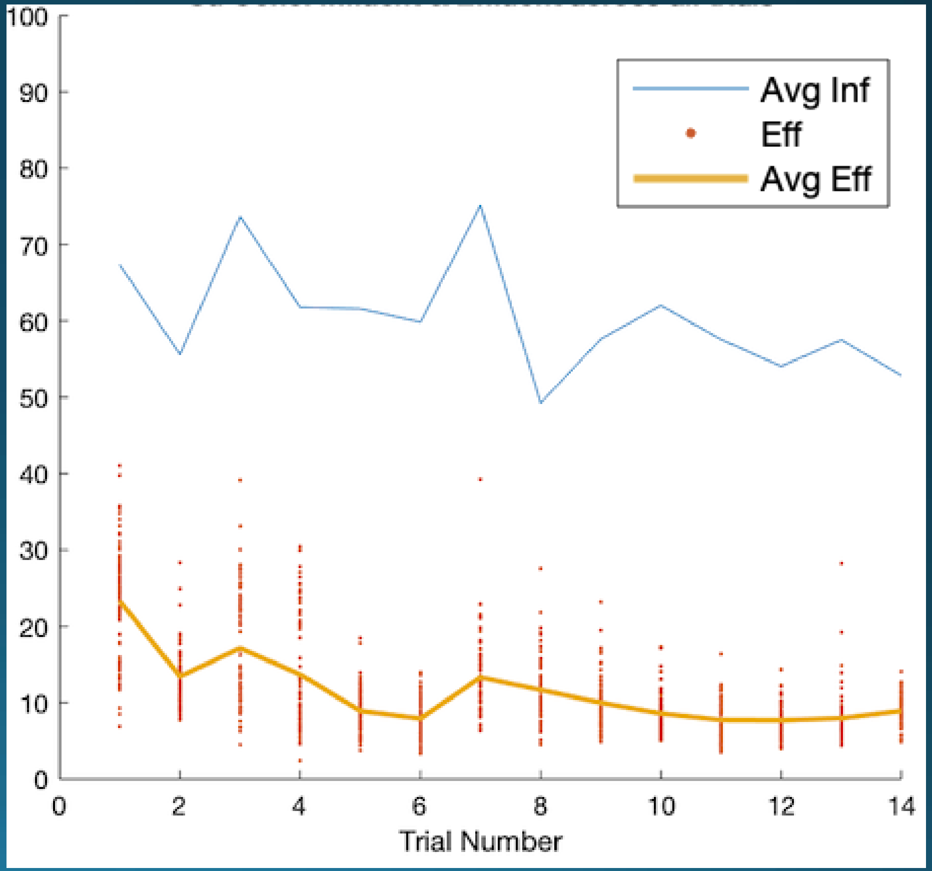
Jessica

Removal Rates

Treatment Effects

COPPER

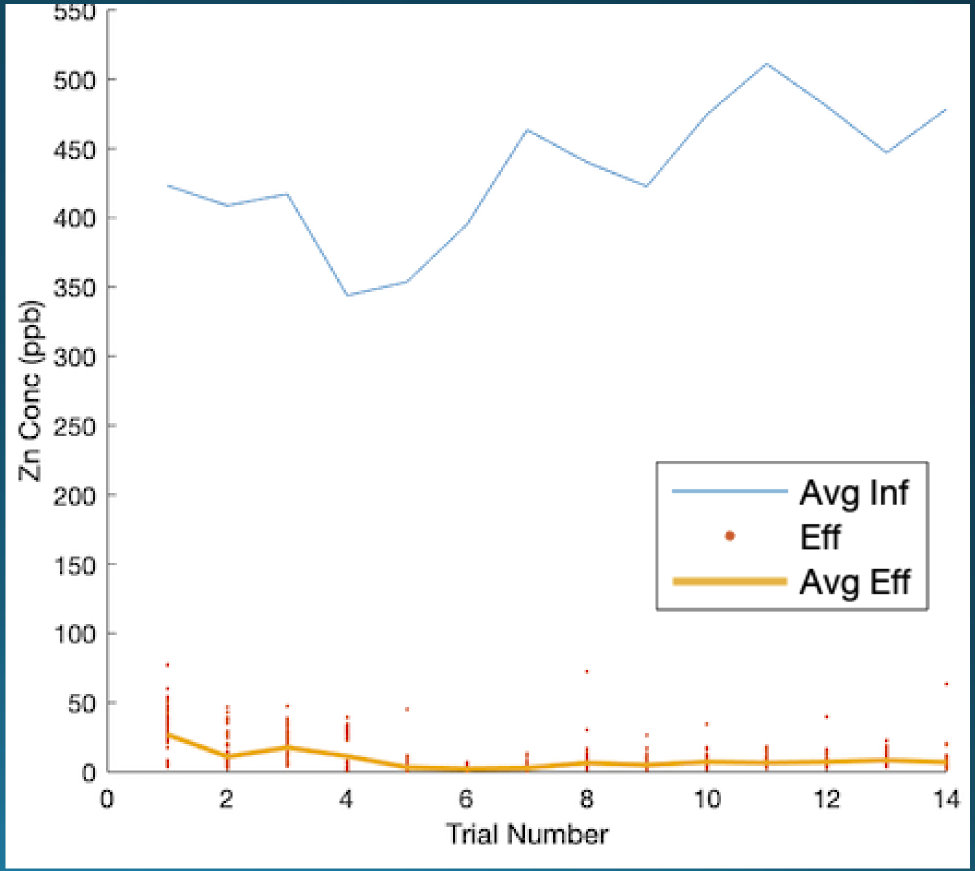
- Average 80% removal regardless of treatment or hydraulic loading (2019 - 2020).
- No significant difference amongst heights
  - Mean was slightly greater for 18” columns
- Significant difference amongst OMF
  - Greatest Cu removal ($\overline{x}$ =82%) with Low OMF (1.6% OMF)



Cu influent and effluent concentrations (ppm) 2020

ZINC

- Average 98% removal regardless of treatment or hydraulic loading during Years One and Two
- Neither OMF nor HT were significant factors in Zn removal
- High removal rates consistent with other studies

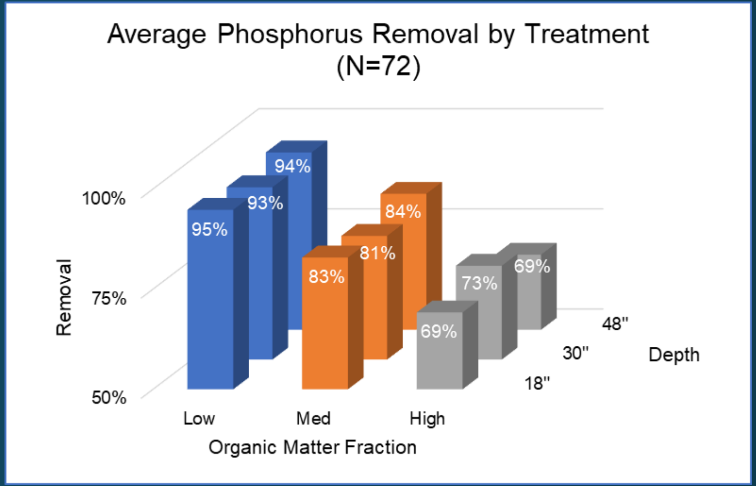


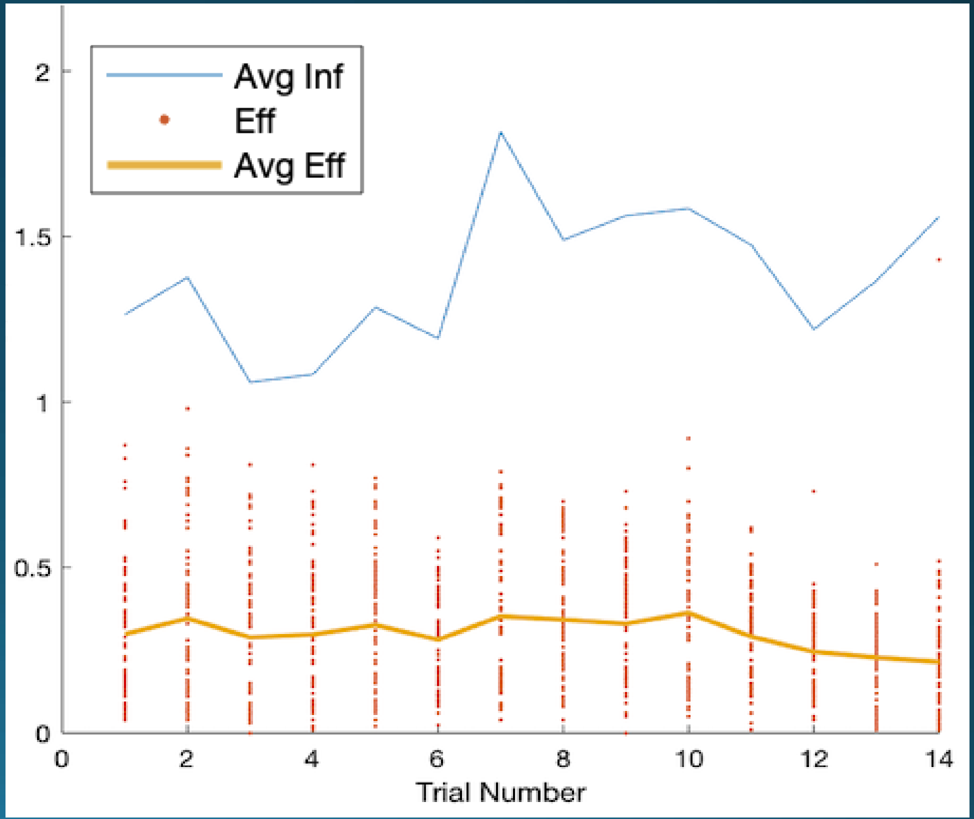
Zn influent and effluent concentrations (ppm) 2020

TOTAL PHOSPHOROUS

- Mean 78% removal across all treatments
- OMF had a significant effect on TP removal
  - Removal effectiveness decreases as OMF increases
- No significant difference amongst heights
- Consistent with prior studies, lower OMF should be used in P-restricted environments

	TP % Removal		
	2019	2020	2021
Mean (SD)	82% (19%)	78% (4%)	65% (27%)
Median	90%	77%	74%
Maximum	98%	86%	89%
Minimum	-1%	71%	18%

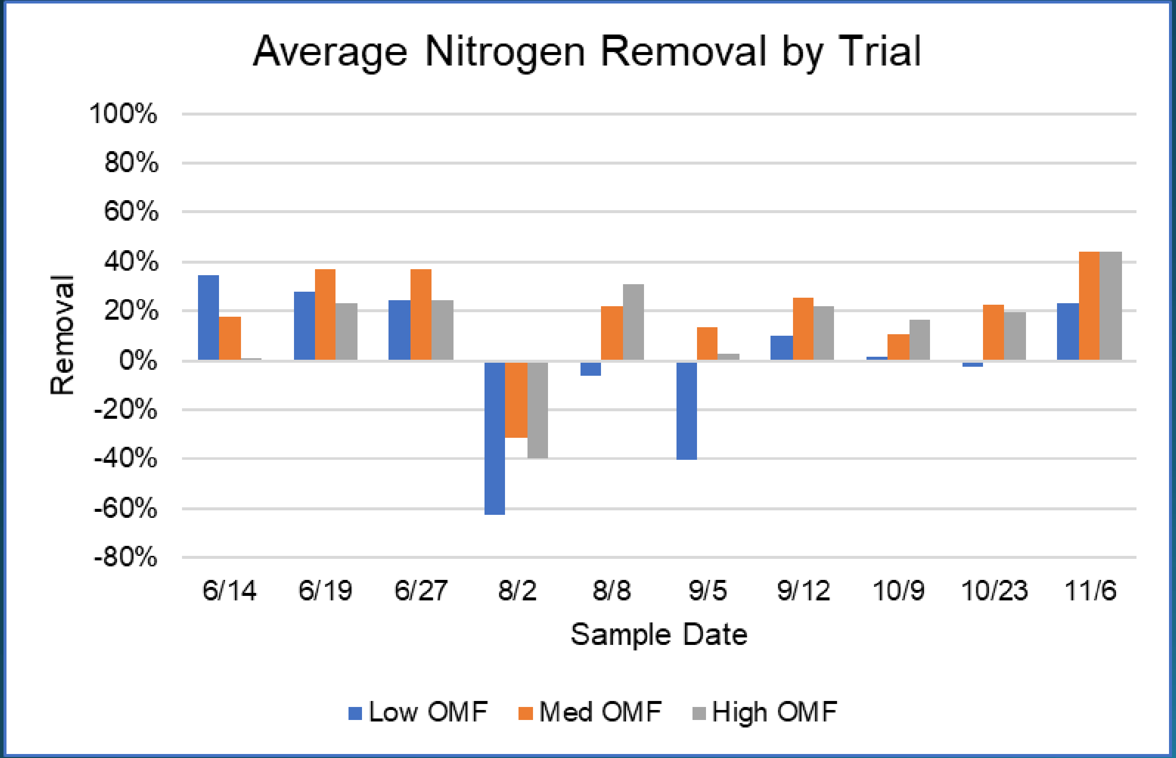


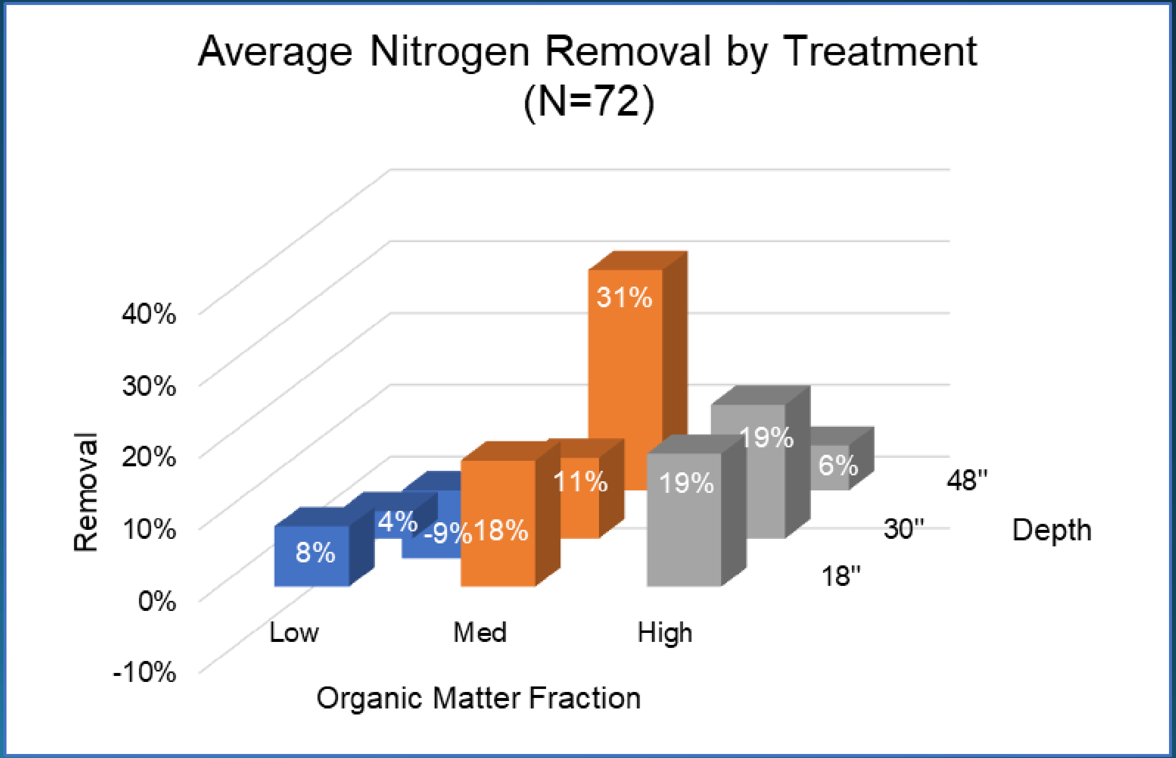


TP influent and effluent concentrations (ppm) undifferentiated by treatment (2020)

Total Nitrogen (2019)

- Mean for all treatments = 12% (s=30%)
  - Greatest removal (30%) with Medium OMF and 48" Depth

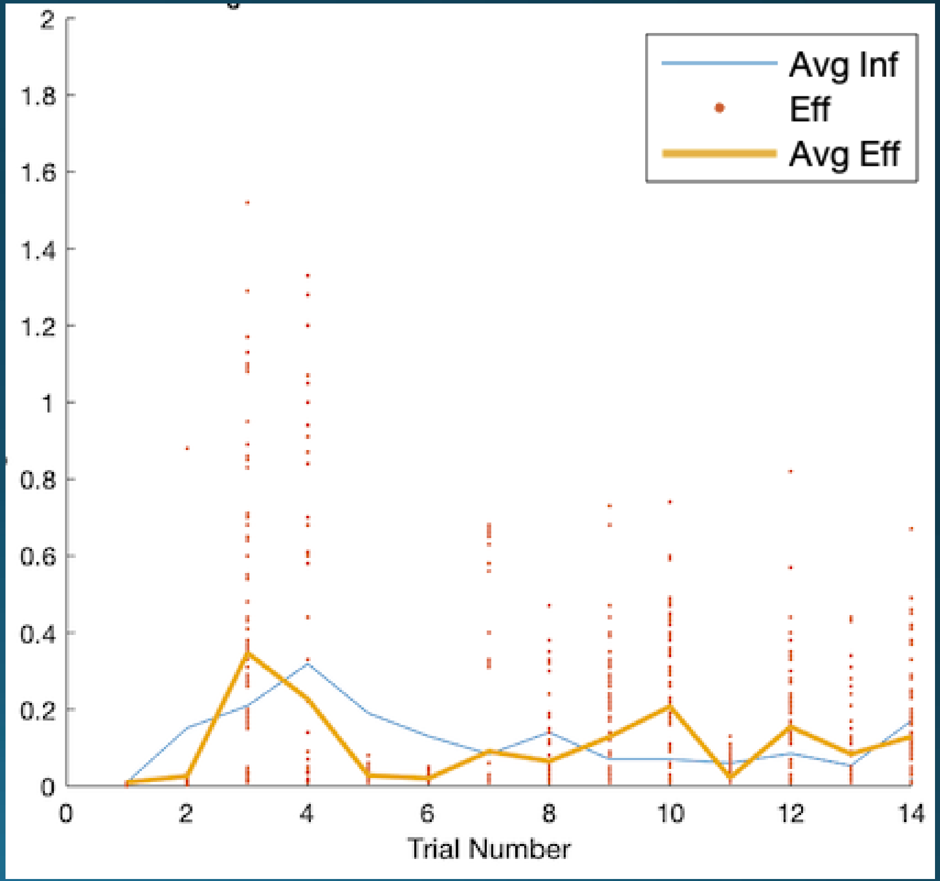




AMMONIUM

- Highly variable effluent concentrations across columns
- Median effluent ~ 0.01 mg/L (below detection limit)
- Confounding variables:
  - Soil temperature: denitrification increases with warming temperature
  - Soil moisture: extended antecedent dry periods increase NO3 export

	NH_4 Removal	
	2020	2021
Mean (SD)	-8% (98%)	13% (60%)
Median	8%	23%
Maximum	96%	88%
Minimum	-211%	-81%

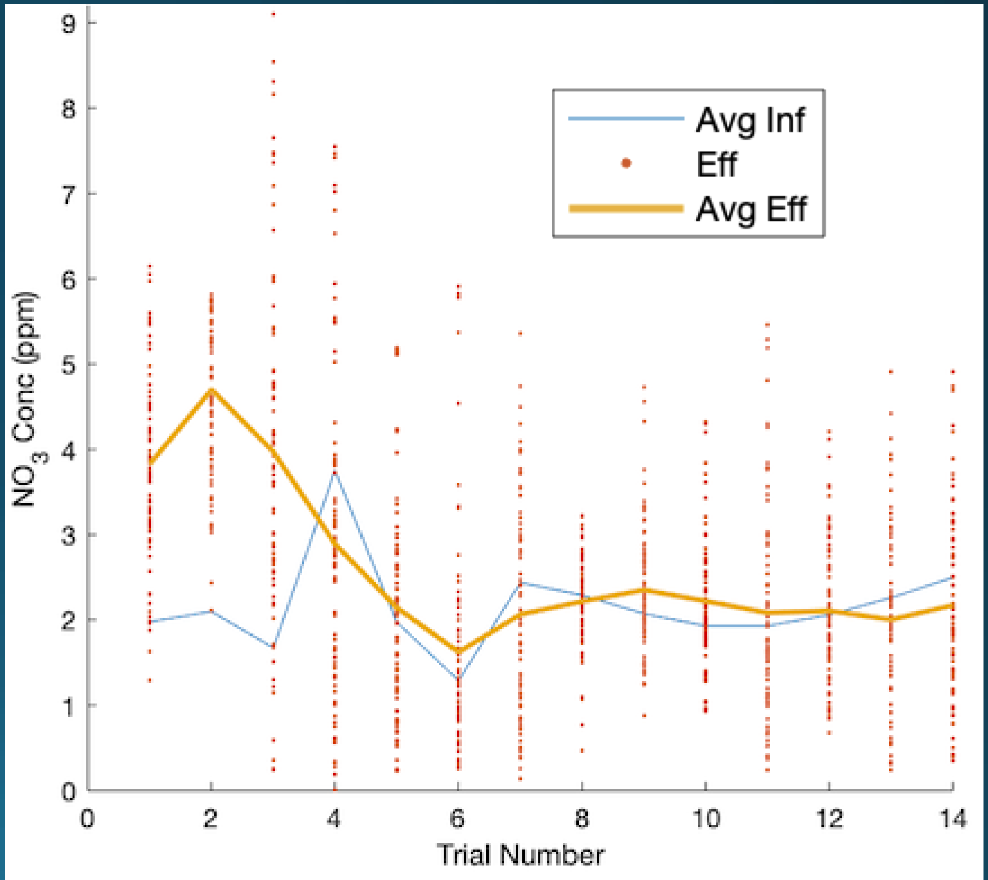


T-NH_4 influent and effluent concentrations (ppm) undifferentiated by treatment (2020)

NITRATE

- 2020: Grass sowed after Trial 2
- Nitrate export likely a result of nitrification, flushing of old pore water during irrigation
  - HYDRUS 1D modeling yielded similar results

	NO_3 Removal	
	2020	2021
Mean (SD)	-35% (59%)	-40% (41%)
Median	-12%	-42%
MAX	15%	19%
Min	-193%	-100%

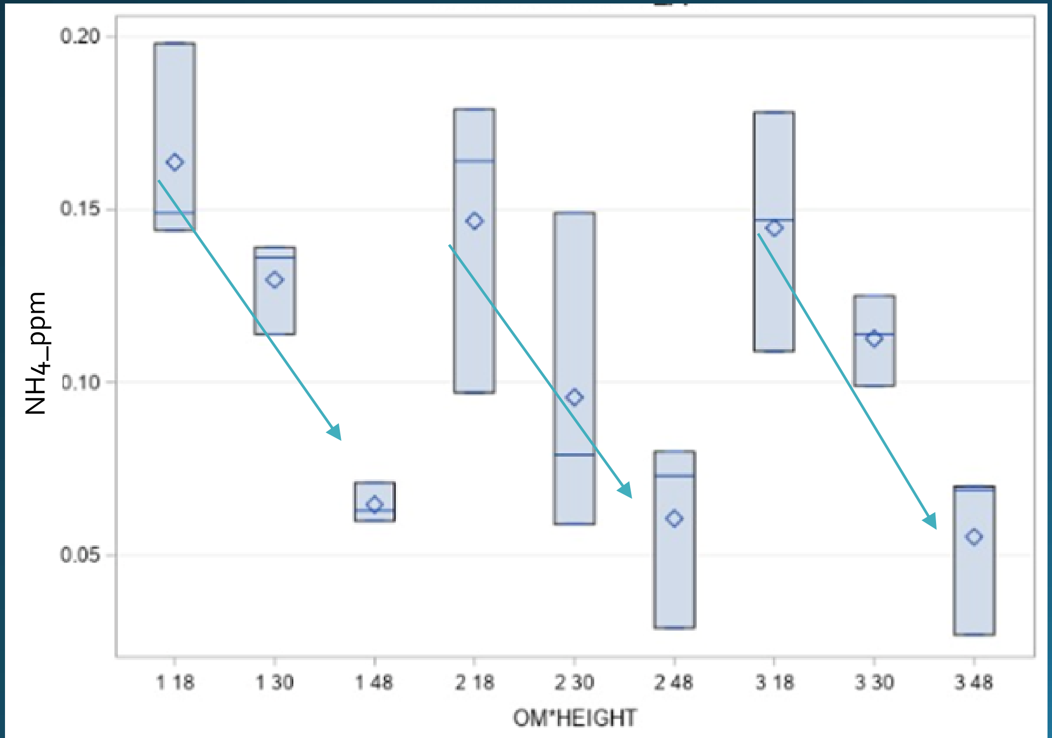


NO_3 influent and effluent concentrations (ppm) undifferentiated by treatment (2020)

AMMONIUM & NITRATE

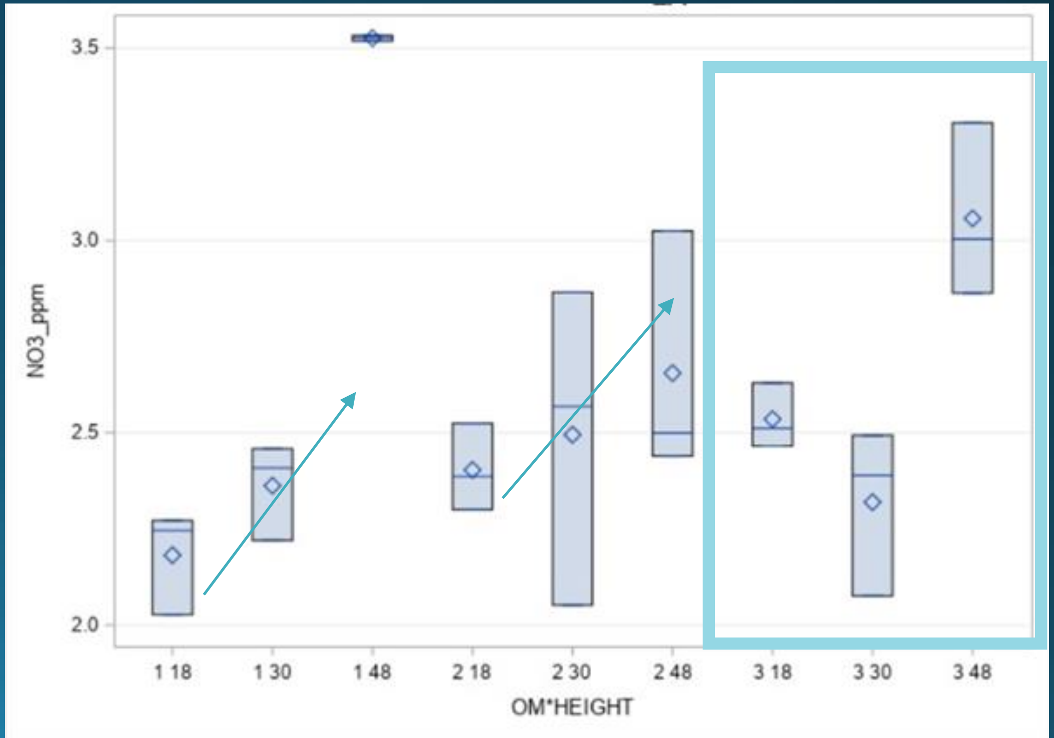
AMMONIUM:

- No significant difference amongst OM levels
- Effluent concentration decreases significantly with increasing height (HT)



NITRATE:

- No significant difference amongst OM levels
- 48" height: significantly greater nitrate export
- Significant interaction OMF*HT



PDH Check

I'm in a P-limited watershed. My biofiltration mix should contain:

[redacted]

b) Less than 7% organic matter by weight

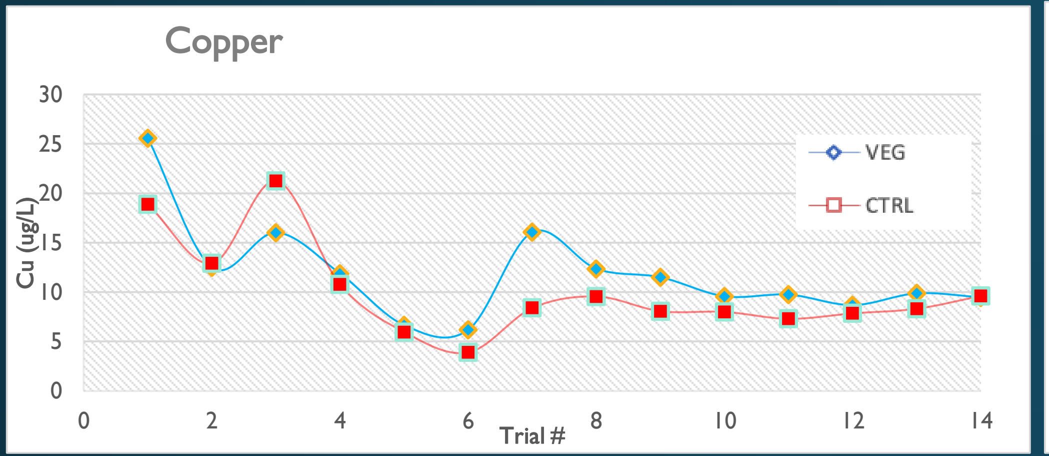
[redacted]

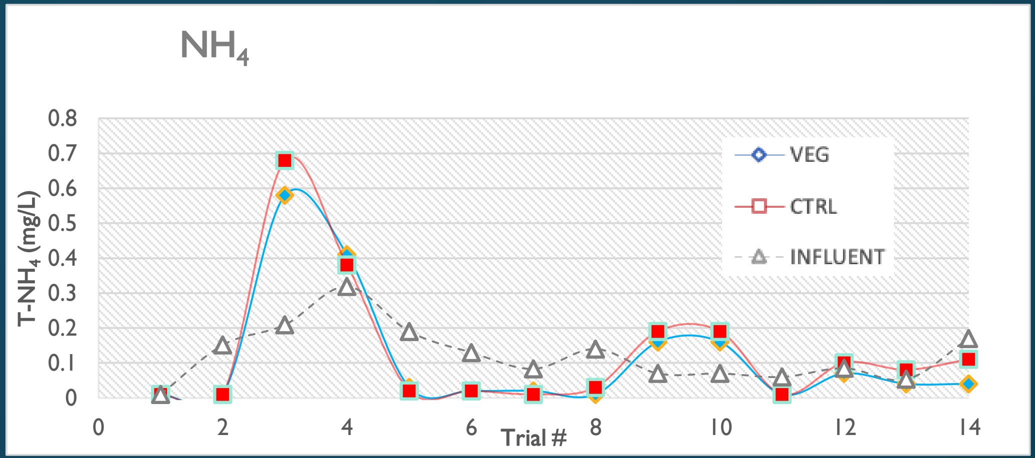
Vegetation (Tall Fescue) Effect on Effluent Concentration (2020)

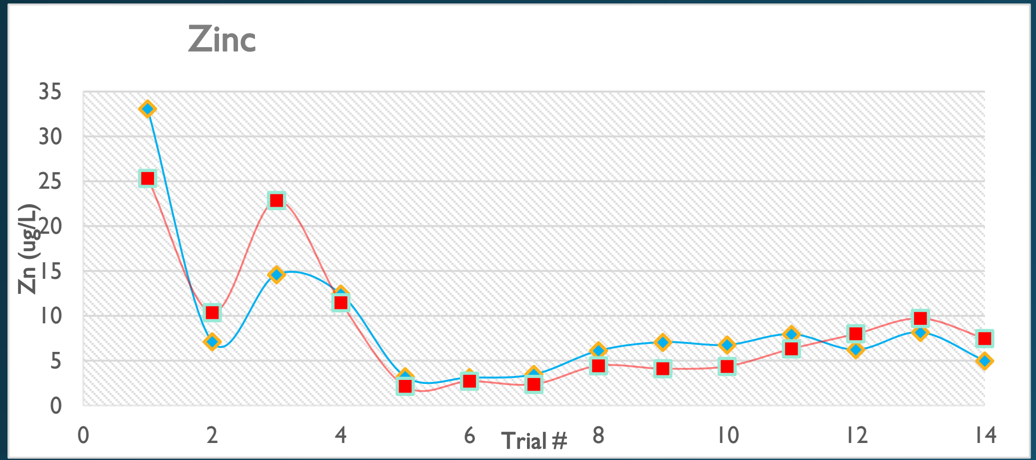
High OM

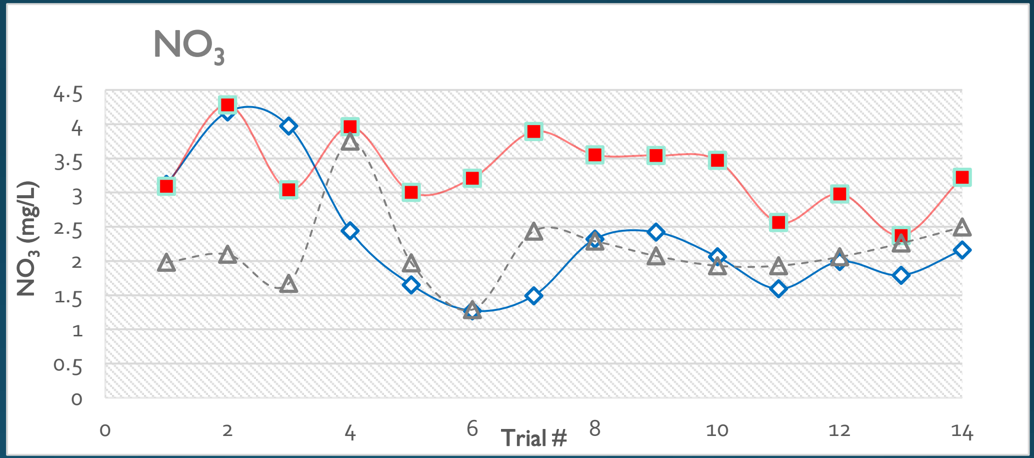
30”

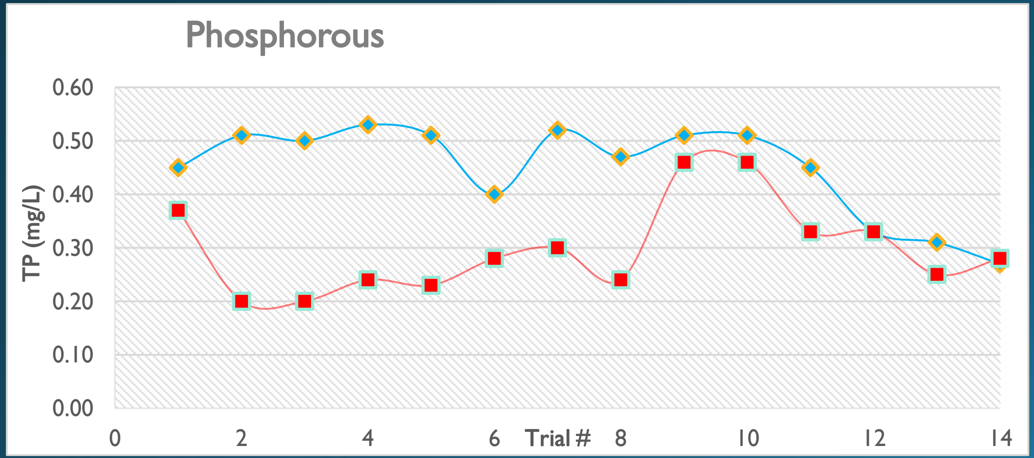
Vegetated vs Bare











Vegetation did not have significant effect on effluent quality (2020)

Trends:

- TP: Vegetated > Bare
- NO_3: Vegetated < Bare
- NH_4: Vegetated = Bare

Conclusions

- Mix design requires custom blending
- Construction techniques affect hydraulic performance
- Adsorption (clay, OM) main process for P, Cu, Zn
- NO_3 and NH_4 have inverse treatment relationship
  - Nitrification f(residence time, elapsed period, temperature, moisture)
  - Denitrification needed

Performance Design Targets					
	P	Cu	Zn	NO_3	T-NH_4
Height	---	---	---	18″ or 30″	48″
OM	LOW	LOW	---	---	---

Zinc
- OM and HT were not significant factors
  - Average removal ~98% (430 ppm to 8 ppm)

Copper
- Low OM had significantly better removal (82%)
- HT was not a significant treatment factor.
  - Average removal ~79% (60 ppm to 11 ppm).

Phosphorous:
- Low OM had significantly better removal (94%)
- HT was not a significant treatment factor.
  - Average 78% - 82% removal (1.38 ppm to 0.3 ppm)

Nitrogen:
- OM not significant for NO3 or NH4
- HT significantly affects NO3 removal - 48″ worst
- HT significantly affects NH4 removal - 48″ best

Vegetation effects: Not significantly different from bare soil

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Dr. Tim Morin
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Dr. Lianjun Zhang
Mr. Timothy Toland

ESF Lab Staff:
Deb Driscoll
Marlene Braun
Chuck Schirmer

ESF Graduate Students:
Mr. Geoff Golick
Ms. Shaen Guang
Ms. Corinne Healey
Mr. Michael Fox
Mr. Joel Requena

ESF State University of New York College of Environmental Science and Forestry

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Discussion

Supplemental information

- First Flush (old water vs new water)
  - Residence time between irrigations – NH_4 transformation, nitrification
- Climate effects
  - Intermittent precipitation
  - Temperature
- Construction methods
- 2020 Vibratory consolidation under saturated conditions
  - Decreased infiltration rate (mean = 1.2 in/hr, range 0.2 – 3.5 in/hr)
  - Mean soil resistance: 18" (28 psi); 30" (59 psi); 48" (91 psi)
- Ponding
  - Bioslime growth
  - Rooting
  - Unexplained (1B3)

Biofiltration Column Treatments

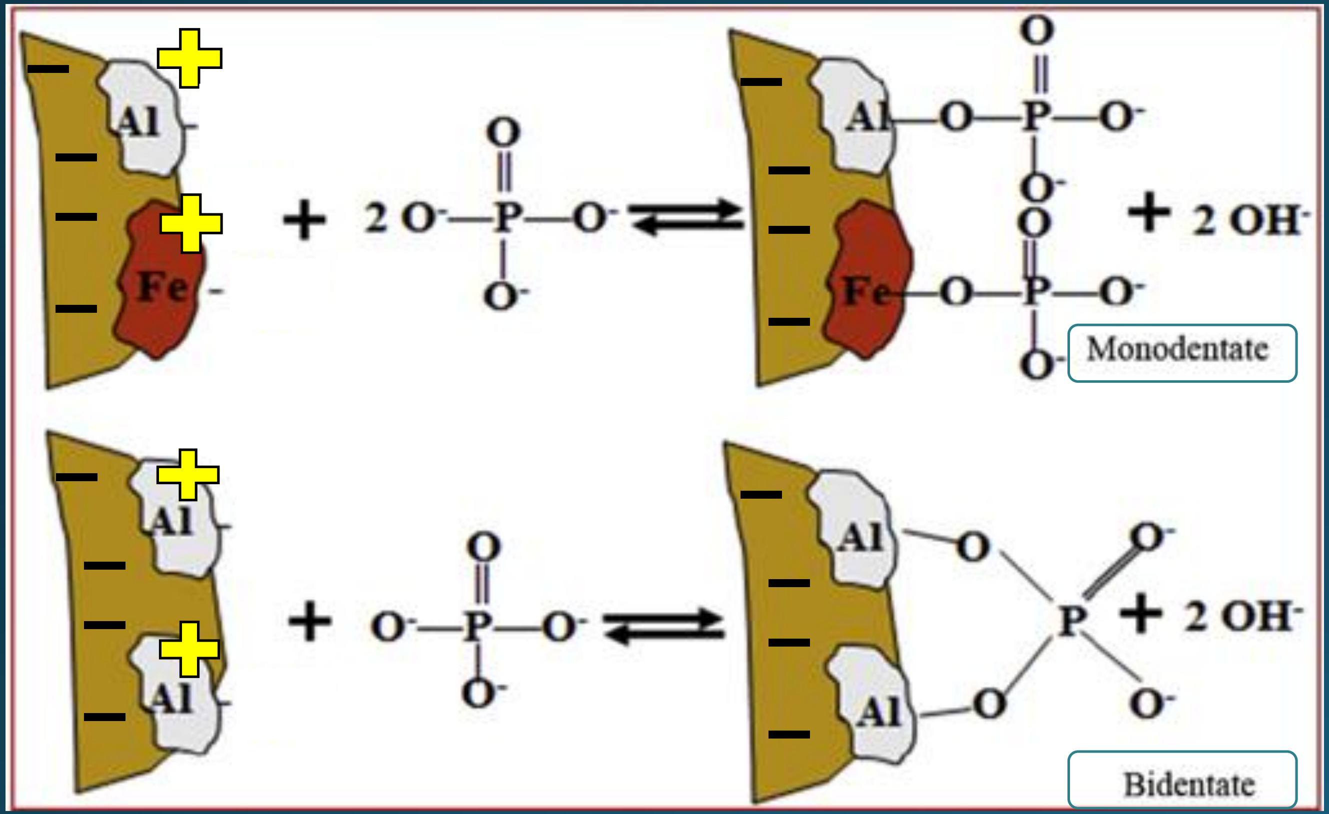
	Low -1.6% - OM	Med - 4.6% - OM	High - 6.9% - OM	
C (48”)	7 8 9	16 17 18	25 26 27	
	Trtmt 3	Trtmt 6	Trtmt 9	
B (30”)	4 5 6	13 14 15	22 23 24	28 29 30
	Trtmt 2	Trtmt 5	Trtmt 8	Control: No vegetation; Trtmt 5
A (18”)	1 2 3	10 11 12	19 20 21	
	Trtmt 1	Trtmt 4	Trtmt 7	

Synthetic Stormwater

Pollutant of Concern	Source Chemical Compound	Target Concentration (mg/L)
Nitrogen-NO_3	KNO_3	2
Nitrogen-NH_4	$CO(NH_2)_2$	4
Phosphorus	KH_2PO_4	1
Copper	$CuSO_4$	0.046
Zinc	$ZnCl_2$	0.516

Ksat – Soil Columns

		5/05/20	5/11/20	11/13/20	5/05/20	5/11/20	11/13/20
Treatment (OM + HT)	Soil Depth (cm)	Avg K_{sat} (cm/hr)	Avg K_{sat} (cm/hr)	Avg K_{sat} (cm/hr)	BT(hr)	BT(hr)	BT(hr)
Low + 18	40.64	96.4	16.4	20.1	0.4	2.5	2.0
Med + 18		38.4	14.6	28.8	1.1	2.9	1.5
Hi + 18		204.3	8.8	36.6	0.2	4.6	1.1
Lo +30	69.54	137.2	21.8	NA	0.5	3.1	NA
Med + 30		328.7	15.1	16.1	0.2	4.6	4.3
Hi + 30		433.5	28.0	17.1	0.1	2.5	4.2
CONTROL	71.52		25.4	7.1	NA	2.8	10.2
Lo + 48	113.87	352.9	20.1	45.4	0.3	5.7	2.5
Med + 48		288.7	30.3	119.1	0.4	3.7	0.9
Hi + 48		1470.4	82.0	117.9	0.1	1.4	1.0

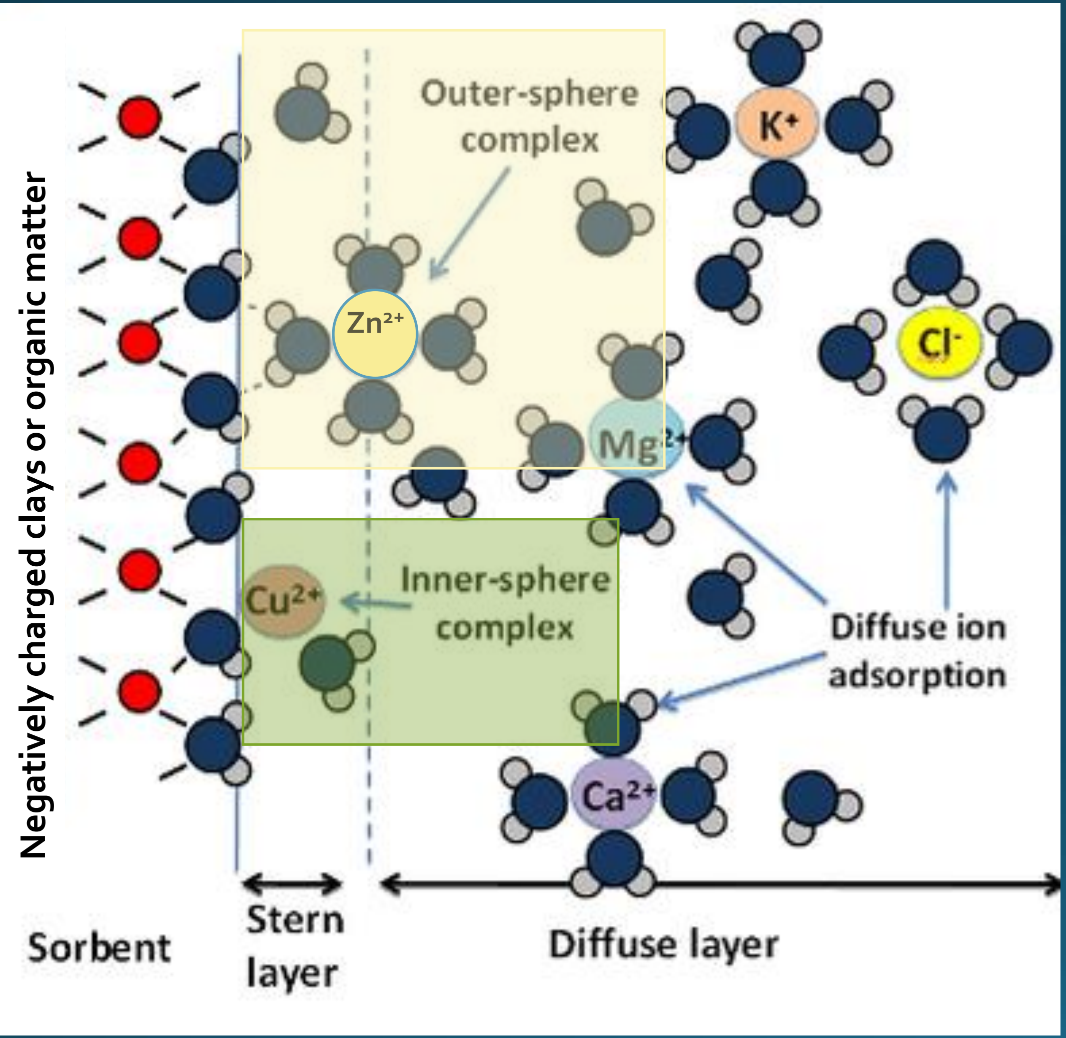


TOTAL PHOSPHORUS

- PO_4^{3-}, high negative charge
- Attracted to Al and Fe hydroxides
- Mono- or bi-dentate adsorption to soil particles

Source: Li, J., & Davis, A. P. (2016). A unified look at phosphorus treatment using bioretention. *Water Research*, *90*, 141–155. https://doi.org/10.1016/j.watres.2015.12.015

Aqueous METALS



Source: Thompson, A. & Goyne, K. W. (2012) Introduction to the Sorption of Chemical Constituents in Soils. *Nature Education Knowledge* 4(4):7

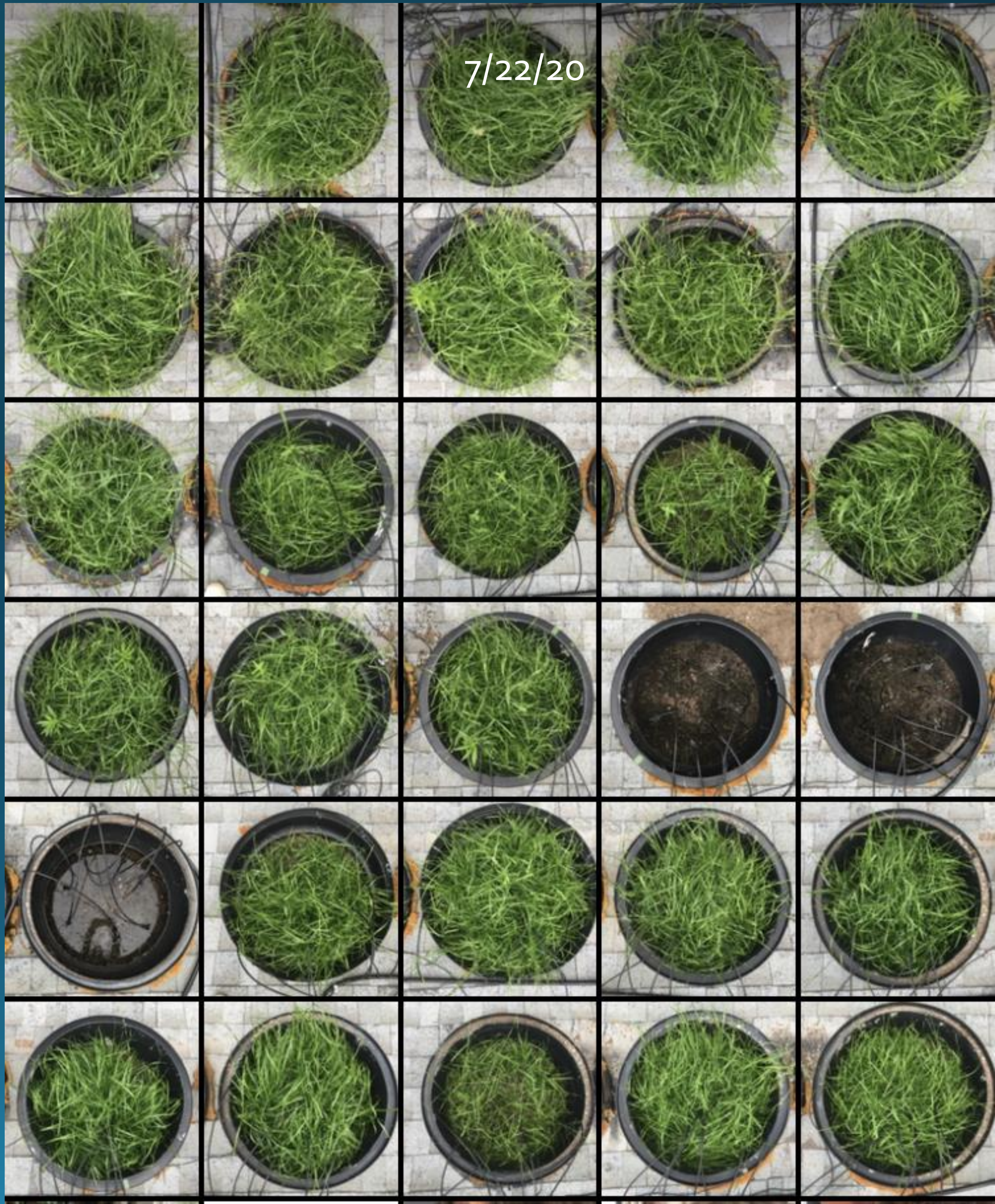
- Cu^{2+}
- Zn^{2+}
- Adsorb to soil surface by forming inner and/or outer complexes

Grass cover

Sowed: 6/12/20

% Mixture	Seed Description	Purpose
38.34	BarElite Tall Fescue	Forage, perennial
35.28	BarRobusto Tall Fescue	Landscape with endophyte
14.36	Panterra V Italian Ryegrass	Turf annual
0.933	Baron Kentucky Bluegrass	Lawn annual

6/25/20

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