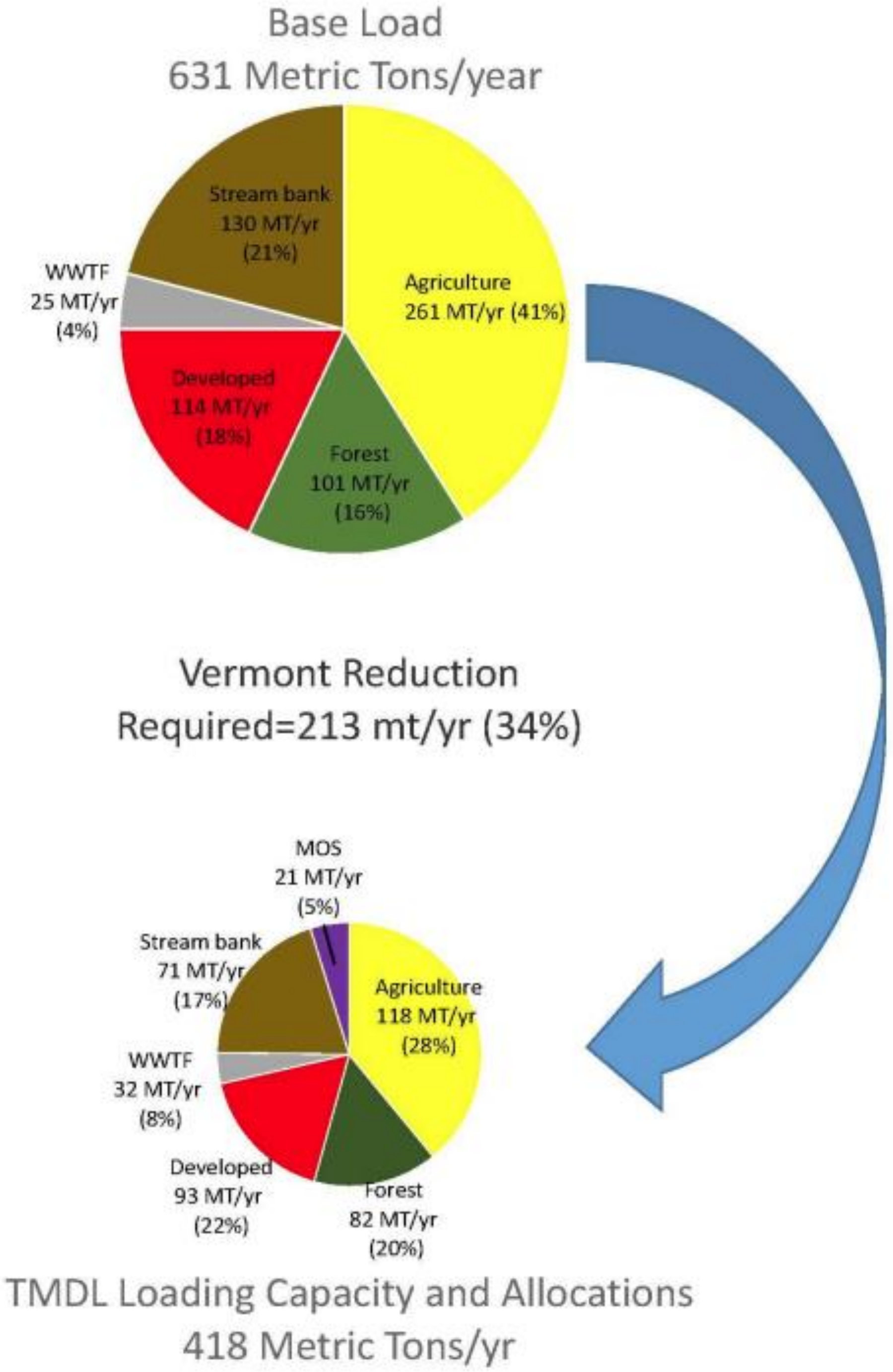
EPA Soak Up the Rain Seminar:
Dissolved Phosphorus & Green Infrastructure:
Fundamentals, Challenges, & Opportunities

Eric Roy, PhD
Associate Professor
Rubenstein School of Environment & Natural Resources
Dept. of Civil & Environmental Engineering
University of Vermont

Why phosphorus (P)?

- Of the 6 major elements required by life on Earth (CHNOPS), P is relatively scarce
- In many aquatic ecosystems, P availability strongly influences algal growth
- P load reductions are required to meet in-lake water quality targets for many lakes across the U.S. and beyond
  - **Example:** TMDL established for the Vermont Portion of the Lake Champlain Basin called for a **34% reduction in P loading** (EPA, 2016)



What is Green Infrastructure?

- **EPA:** "the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters."
- **Vermont DEC:** “a wide range of multi-functional, natural and semi-natural landscape elements located within, around, and between developed areas at all spatial scales. This includes everything from forests and meadows to wetlands, floodplains, and riparian areas.”

Recent UVM Research on P Dynamics in Green Infrastructure

Scale	Project	Sponsor(s)
Individual BMP level	Use of drinking water treatment residuals to enhance P removal in green stormwater infrastructure	EPA RARE Program (2 grants)
Individual BMP level	Evaluation of subsurface gravel wetlands for stormwater management	Lake Champlain Sea Grant
Ecosystem & Landscape	Quantifying the water quality benefits provided by restored riparian wetlands	Lake Champlain Basin Program, USDA NRCS, Gund Institute, Vermont DEC

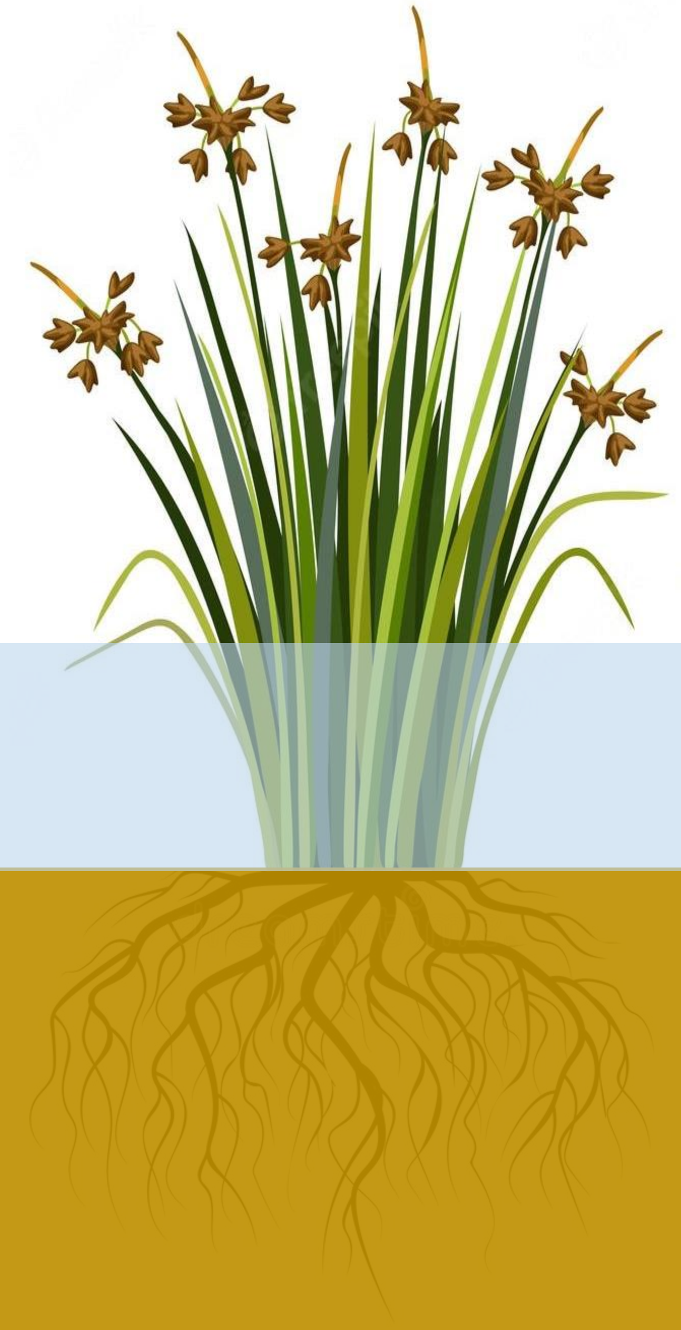
and more!

Outline for today's webinar

- Part 1: Fundamentals
  - What are the primary factors and mechanisms governing dissolved phosphorus dynamics in green infrastructure?
- Part 2: Challenges
  - Where and how do dissolved phosphorus dynamics jeopardize green infrastructure performance?
- Part 3: Opportunities
  - What design interventions can be used to improve control of dissolved phosphorus in green infrastructure?

Part 1: Fundamentals

- What are the primary factors and mechanisms governing dissolved phosphorus dynamics in green infrastructure?



forms

POP = Particulate organic P
DOP = Dissolved organic P
DIP = Dissolved inorganic P
PIP = Particulate inorganic P

Note: DIP is often used interchangeably with "soluble reactive phosphorus" (aka SRP) and PO_4^{3-}

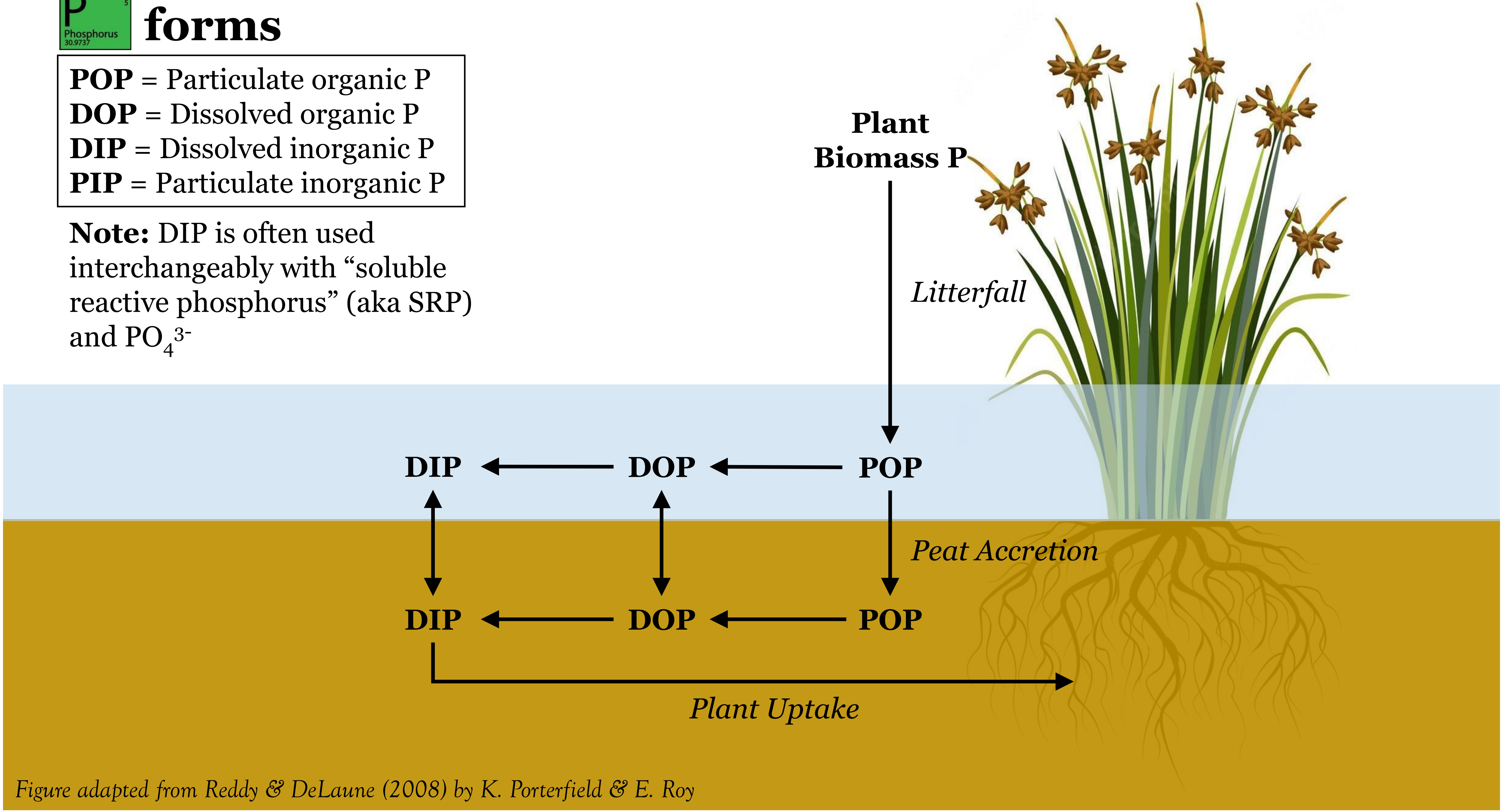


Figure adapted from Reddy & DeLaune (2008) by K. Porterfield & E. Roy

P forms

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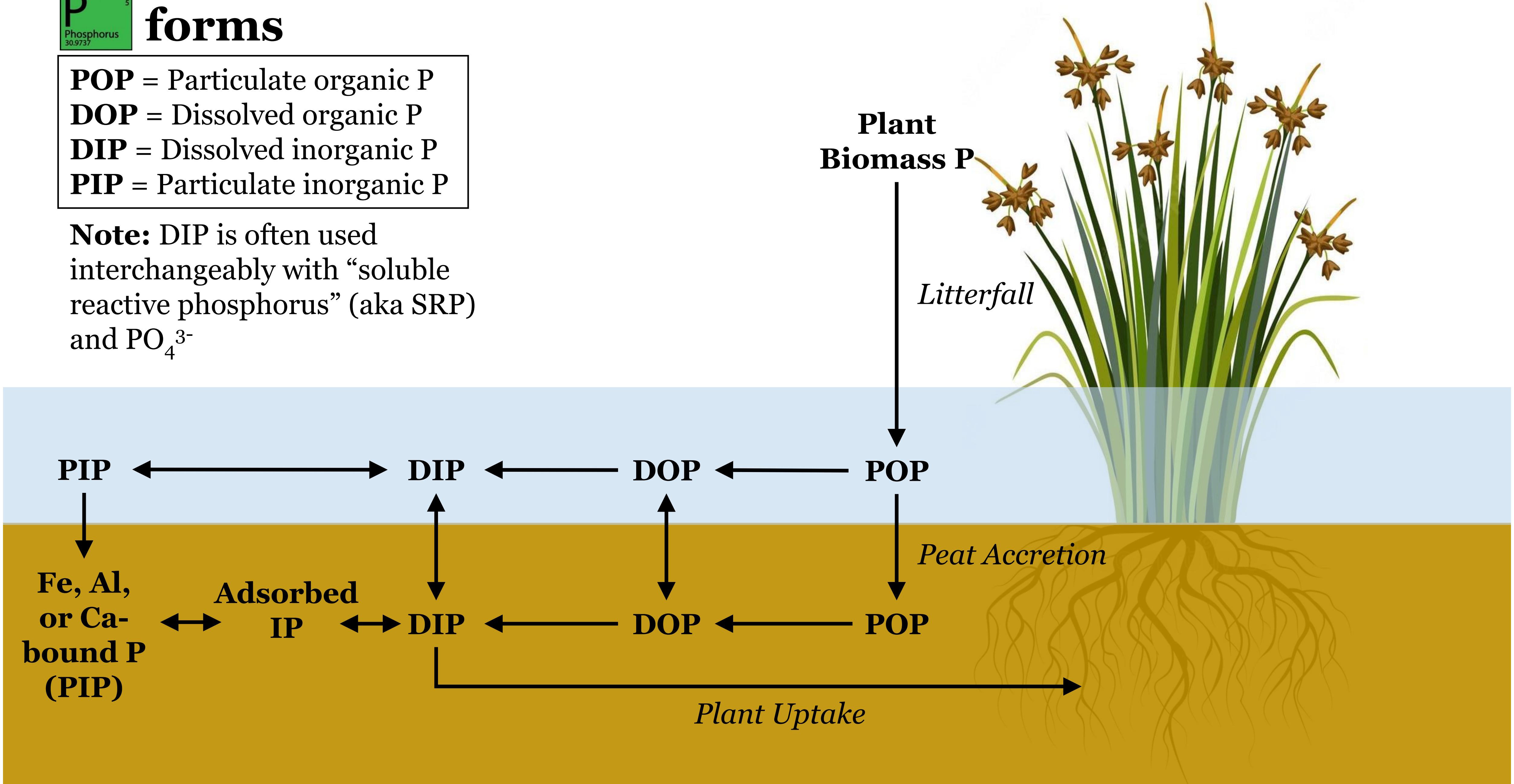
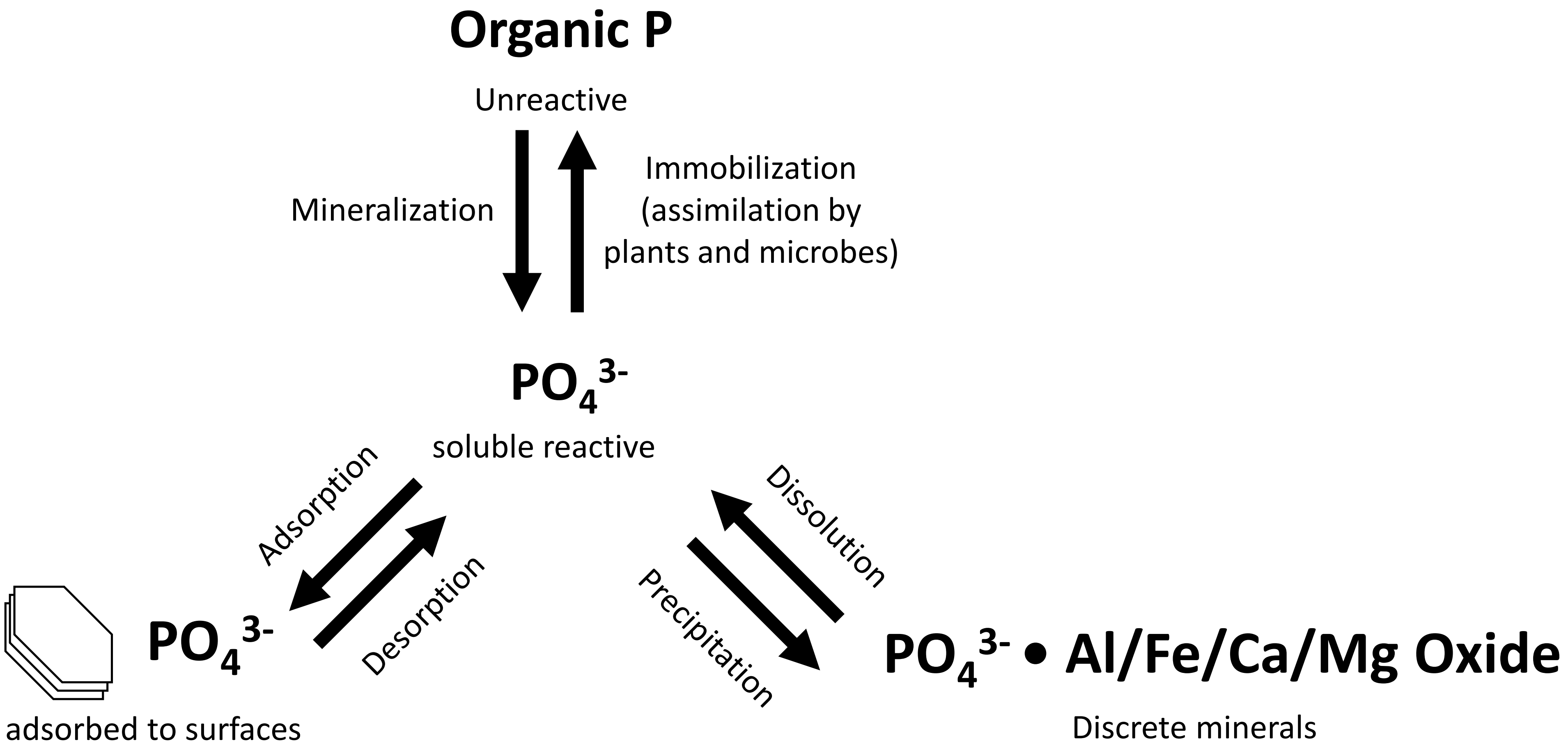


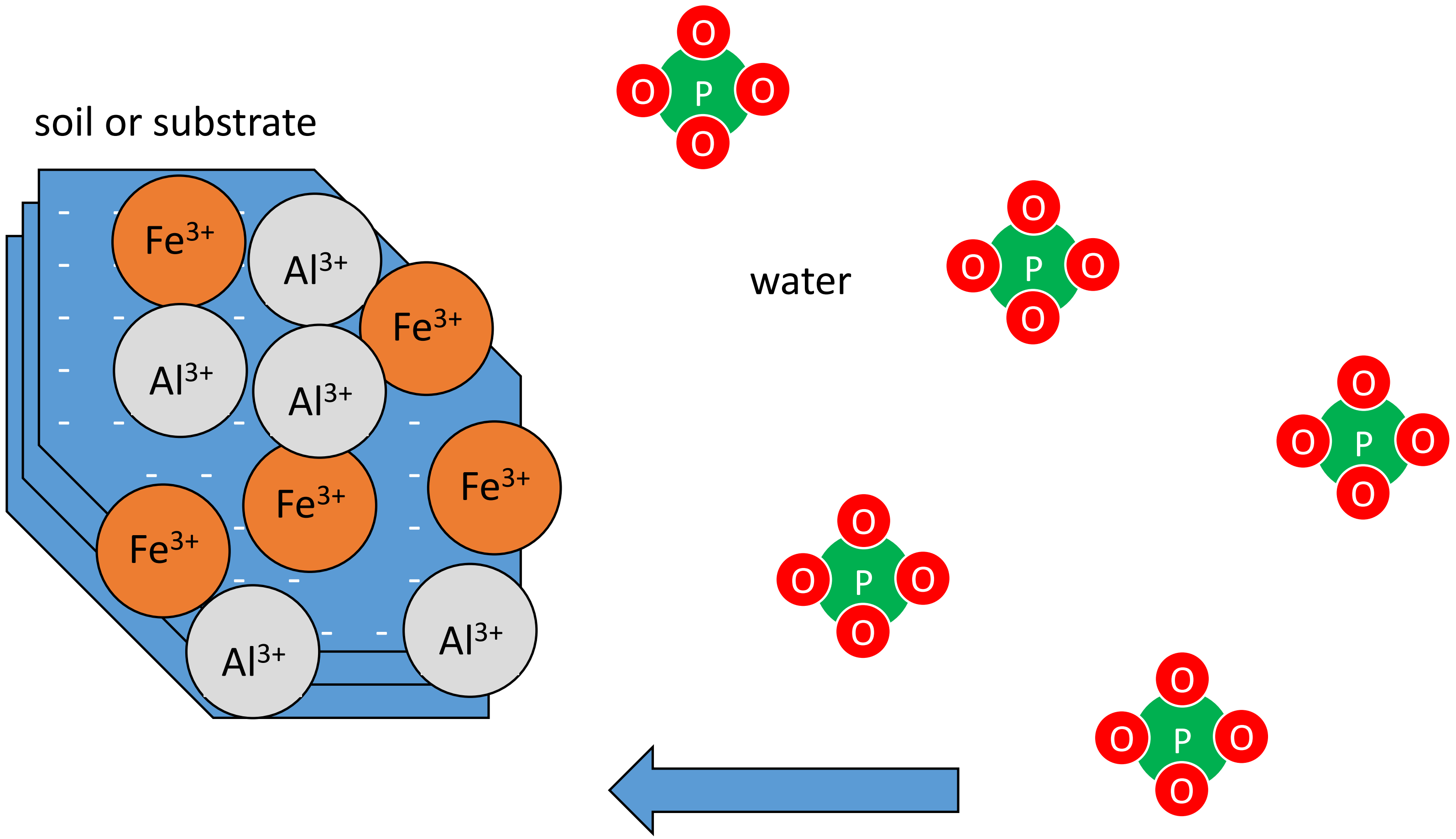
Figure adapted from Reddy & DeLaune (2008) by K. Porterfield & E. Roy

Phosphorus Forms & Fluxes

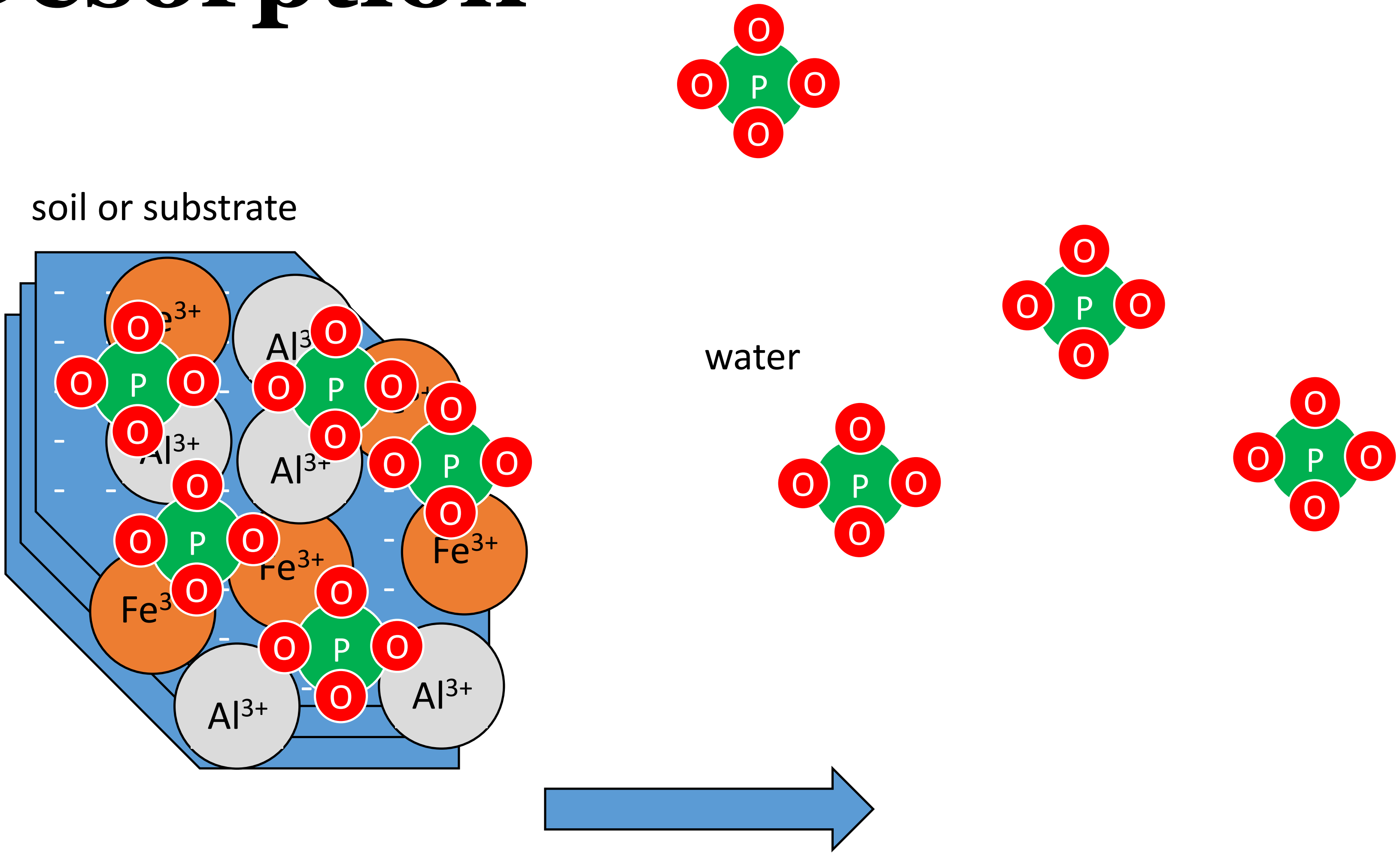


Reddy & DeLaune (2008)

Adsorption



Desorption



Fe and P Chemistry – Oxygen Matters

- **Aerobic soil**

  Fe typically present as **Fe-oxides**, **can readily sorb or precipitate SRP**

- **Anaerobic soil**

  ferric iron (**Fe^{3+}**) is **reduced to** ferrous iron (**Fe^{2+}**) **liberating P**

$$FePO_4 + H^+ + e^- \rightarrow Fe^{2+} + HPO_4^{2-}$$

Summary: Key Factors Controlling P Mobility in Dissolved Forms

- Rate of P release from organic material
- Rate of P uptake by vegetation and/or microorganisms
- Adsorption-desorption of P (depends on presence and form of Fe, Al, Ca, Mg)
- Chemical precipitation of P & dissolution (also depends on presence and form of Fe, Al, Ca, Mg)
- Oxygen presence/absence

Reddy & DeLaune (2008)

Change in Total P concentration?

Table 4-3. Influent/Effluent Summary Statistics for Total Phosphorus as P (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	43; 542 (1.5%)	44; 577 (1.7%)	0.138 - 0.428	0.107 - 0.320	0.250 (0.216; 0.262)	0.186 (0.170; 0.200)	▼▼▼
Retention Pond	71; 1161 (0.9%)	75; 1138 (2.0%)	0.0996 - 0.542	0.0500 - 0.263	0.246 (0.220; 0.268)	0.120 (0.104; 0.129)	▼▼▼
Wetland Basin	27; 690 (0.3%)	27; 647 (1.4%)	0.106 - 0.319	0.0660 - 0.222	0.170 (0.151; 0.177)	0.122 (0.108; 0.133)	▼▼▼
Wetland Channel	15; 256 (0.4%)	13; 214 (0.0%)	0.129 - 0.372	0.120 - 0.338	0.201 (0.179; 0.230)	0.184 (0.160; 0.207)	◇◇▼
Grass Swale	34; 574 (0.3%)	39; 671 (0.3%)	0.0700 - 0.270	0.104 - 0.300	0.129 (0.118; 0.140)	0.180 (0.165; 0.190)	△△△
Grass Strip	50; 893 (8.2%)	50; 666 (3.2%)	0.0800 - 0.300	0.120 - 0.460	0.185 (0.160; 0.190)	0.230 (0.206; 0.240)	△△△
Bioretention	47; 850 (4.8%)	44; 667 (3.1%)	0.0800 - 0.460	0.0900 - 0.553	0.190 (0.170; 0.210)	0.240 (0.190; 0.270)	◇△△
Media Filter	32; 494 (1.4%)	35; 525 (5.1%)	0.0900 - 0.285	0.0490 - 0.147	0.165 (0.150; 0.180)	0.0900 (0.0800; 0.0973)	▼▼▼
HRBF	6; 100 (0.0%)	6; 100 (8.0%)	0.0640 - 0.157	0.0377 - 0.0848	0.0990 (0.0854; 0.112)	0.0500 (0.0409; 0.0600)	▼▼▼
HRMF	19; 349 (1.7%)	19; 351 (3.1%)	0.0680 - 0.500	0.0496 - 0.277	0.120 (0.100; 0.130)	0.0800 (0.0703; 0.0900)	▼▼▼
HDS	23; 338 (0.3%)	23; 303 (1.7%)	0.117 - 0.474	0.102 - 0.370	0.230 (0.198; 0.268)	0.176 (0.150; 0.197)	◇▼▼
OGS	10; 170 (4.7%)	10; 138 (10.9%)	0.0815 - 0.691	0.0367 - 0.530	0.316 (0.206; 0.428)	0.115 (0.0700; 0.213)	◇▼▼
PFC	NA	6; 124 (0.0%)	NA	0.0380 - 0.100	NA	0.0625 (0.0500; 0.0745)	NA
Porous Pavement	13; 447 (0.9%)	21; 365 (1.4%)	0.110 - 0.360	0.0700 - 0.194	0.170 (0.150; 0.180)	0.100 (0.0980; 0.112)	▼▼▼

*Confidence interval about the median computed using the BCa bootstrap method described by Efron and Tibishirani (1993).
** Each symbol represents an influent/effluent comparison test. Left position compares overlap of 95% confidence intervals around influent/effluent medians. Middle position compares Mann-Whitney rank-sum hypothesis test P-value to a significance value of 0.05. Right position compares Wilcoxon signed-rank hypothesis test P-value to a significance value of 0.05.

% ND   percentage of non-detects
NA   not available or less than three studies for BMP/constituent
◇   influent/effluent comparison test indicates no significant difference in concentrations
▼   influent/effluent comparison test indicates significant reduction in concentrations
△   influent/effluent comparison test indicates significant *increase* in concentrations

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Source:
International Stormwater BMP Database: 2020 Summary Statistics

Change in Dissolved P concentration?

Table 4-5. Influent/Effluent Summary Statistics for Dissolved Phosphorus as P (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	14; 195 (5.1%)	14; 182 (6.0%)	0.0417 - 0.150	0.0149 - 0.140	0.0800 (0.0690; 0.0924)	0.0700 (0.0470; 0.0800)	◇◇◇
Retention Pond	20; 396 (2.5%)	23; 435 (7.8%)	0.0700 - 0.212	0.0300 - 0.144	0.129 (0.114; 0.145)	0.0642 (0.0550; 0.0700)	▼▼▼
Wetland Basin	9; 338 (0.3%)	8; 311 (0.6%)	0.0320 - 0.101	0.0250 - 0.0815	0.0550 (0.0468; 0.0595)	0.0460 (0.0400; 0.0490)	◇▼◇
Wetland Channel	6; 121 (3.3%)	5; 89 (2.2%)	0.0600 - 0.192	0.0600 - 0.140	0.116 (0.0796; 0.134)	0.0900 (0.0700; 0.100)	◇◇◇
Grass Swale	12; 170 (4.1%)	11; 146 (2.1%)	0.0300 - 0.0800	0.0500 - 0.120	0.0480 (0.0400; 0.0500)	0.0700 (0.0600; 0.0700)	△△△
Grass Strip	5; 40 (0.0%)	6; 45 (0.0%)	0.0600 - 0.143	0.150 - 0.920	0.0800 (0.0600; 0.0800)	0.260 (0.140; 0.300)	△△△
Bioretention	6; 132 (9.1%)	5; 105 (2.9%)	0.0900 - 0.230	0.230 - 0.507	0.134 (0.113; 0.149)	0.350 (0.310; 0.370)	△△△
Media Filter	13; 128 (2.3%)	15; 155 (1.3%)	0.0200 - 0.100	0.0160 - 0.0907	0.0521 (0.0310; 0.0633)	0.0468 (0.0300; 0.0520)	◇◇▼
HRMF	9; 194 (14.4%)	9; 194 (14.9%)	0.0200 - 0.228	0.0200 - 0.190	0.0500 (0.0390; 0.0535)	0.0400 (0.0300; 0.0500)	◇◇▼
HDS	7; 125 (0.8%)	7; 119 (0.8%)	0.0370 - 0.160	0.0300 - 0.135	0.0740 (0.0558; 0.0990)	0.0570 (0.0393; 0.0710)	◇◇▼
Porous Pavement	4; 264 (6.8%)	4; 126 (3.2%)	0.0300 - 0.0800	0.0400 - 0.110	0.0500 (0.0425; 0.0575)	0.0600 (0.0486; 0.0600)	◇△△

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*Confidence interval about the media computed using the BCa bootstrap method described by Efron and Tibishirani (1993).

** Each symbol represents an influent/effluent comparison test. Left position compares overlap of 95% confidence intervals around influent/effluent medians. Middle position compares Mann-Whitney rank-sum hypothesis test P-value to a significance value of 0.05. Right position compares Wilcoxon signed-rank hypothesis test P-value to a significance value of 0.05.

% ND percentage of non-detects

NA not available or less than three studies for BMP/constituent

◇ influent/effluent comparison test indicates no significant difference in concentrations

▼ influent/effluent comparison test indicates significant reduction in concentrations

△ influent/effluent comparison test indicates significant *increase* in concentrations

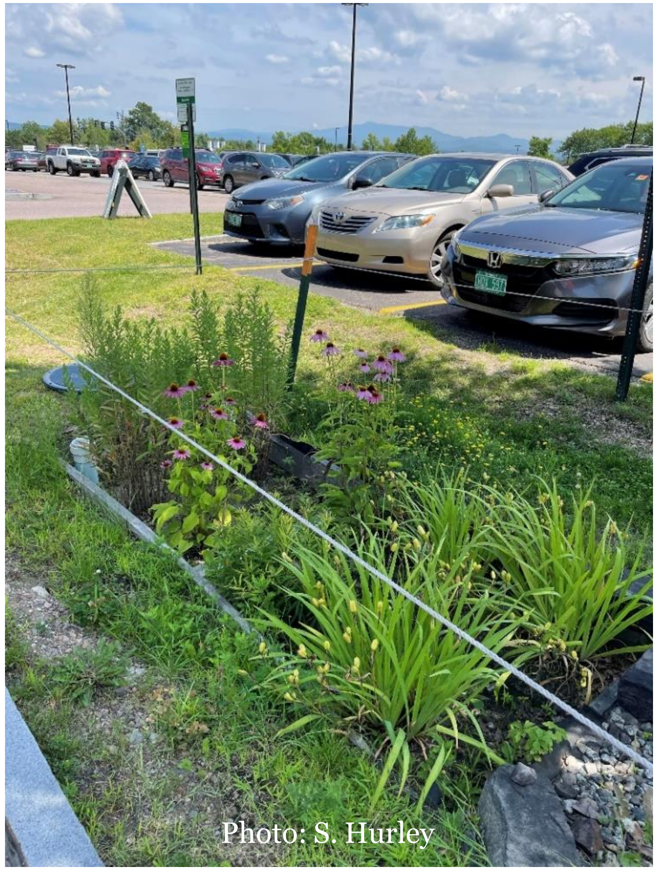
Source:
International Stormwater BMP Database: 2020 Summary Statistics

Part 2: Challenges

- Where and how do dissolved phosphorus dynamics jeopardize green infrastructure performance?
  - **Scenario 1:** Substrates included in green infrastructure design have insufficient P sorption capacity
  - **Scenario 2:** Substrates included in green infrastructure design leach P over time
  - **Scenario 3:** Existing legacy phosphorus on the landscape results in release of dissolved P

Scenario 1: Substrates included in green infrastructure design have insufficient P sorption capacity

Study: Sand media in bioretention cells



Collaborators: Dr. Michael Ament (Minn. Pollution Control Agency), Dr. Stephanie Hurley (UVM), Dr. Yongping Yuan (EPA), Mark Voorhees (EPA), Eric Perkins (EPA)

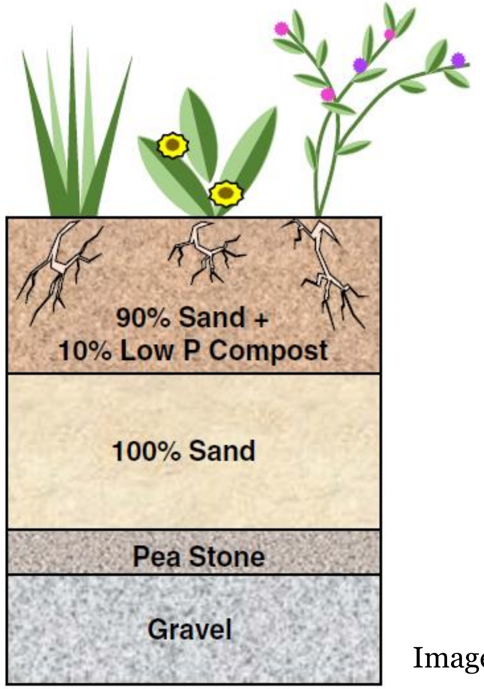


Image: Ament et al. (2022) JSWBE

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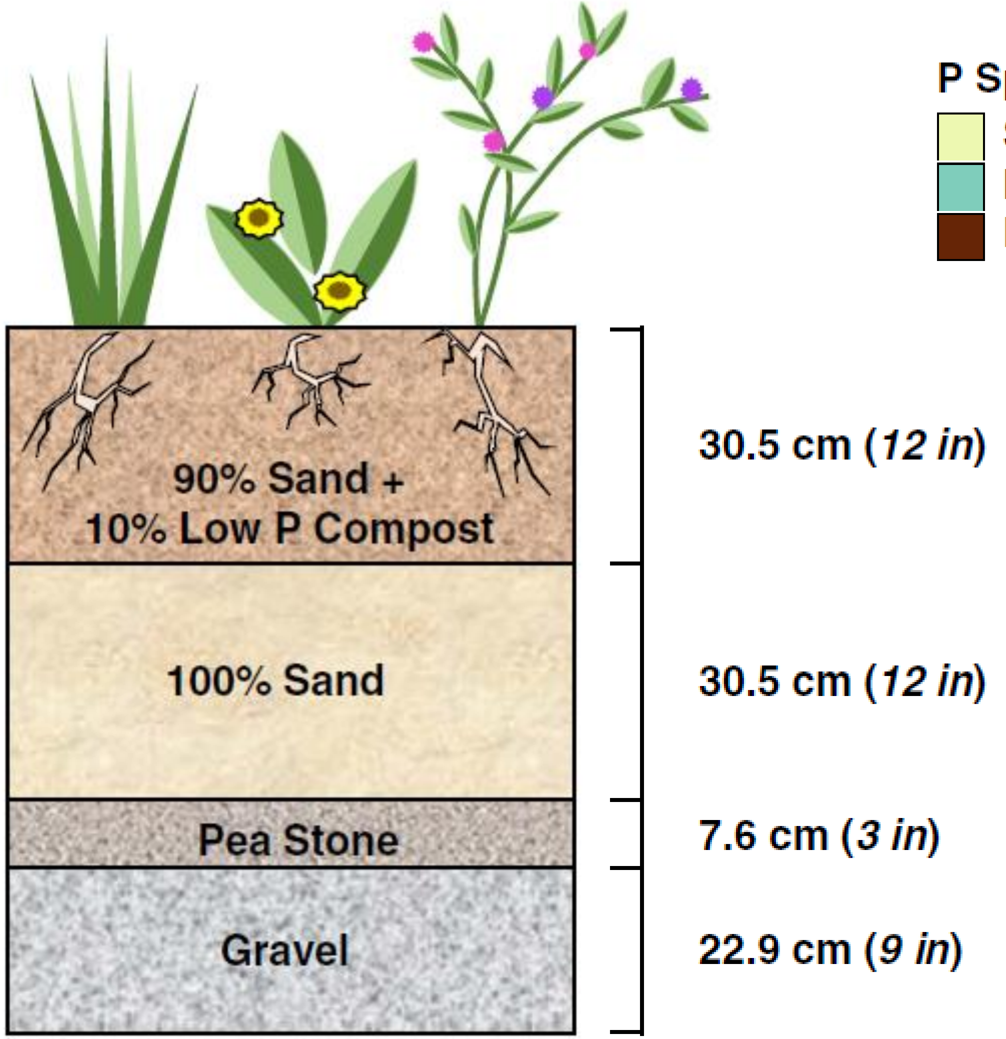
UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

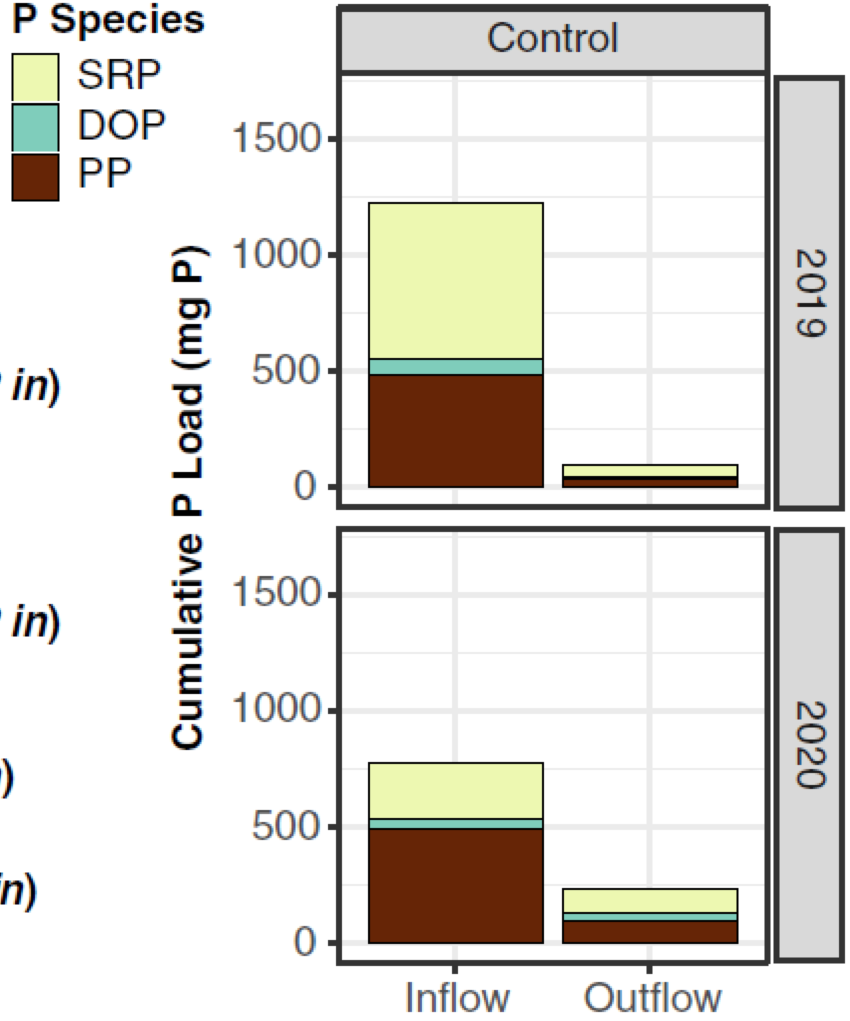
Funding:
US EPA RARE Program

Evidence from the field (Ament et al. 2022 JSWBE)

Two roadside bioretention systems monitored on UVM campus ove

SRP removal efficiency dropped by 16% and 59% for two cells in Year 2

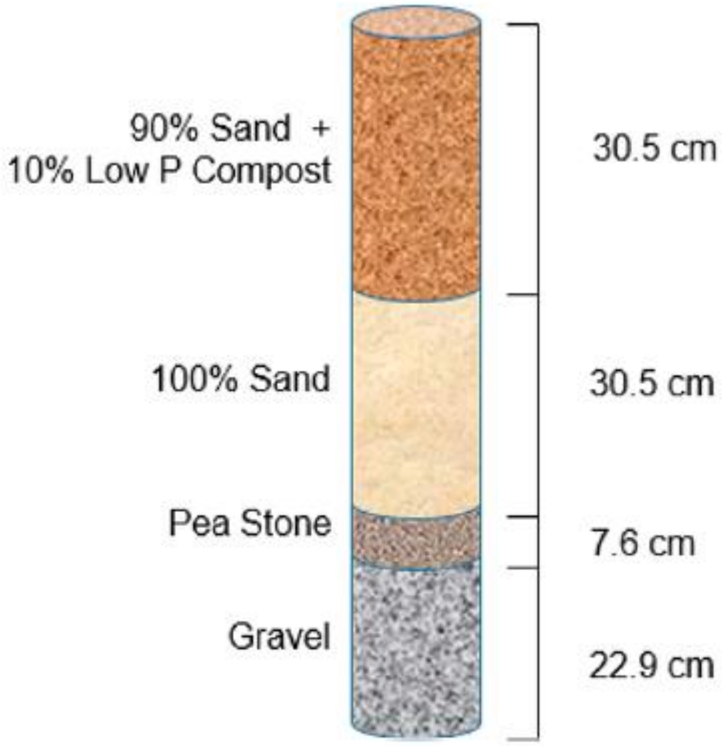




Evidence from the lab (Ament et al. 2021 ACS ES&T Water)

Large column studies of bioretention media designs

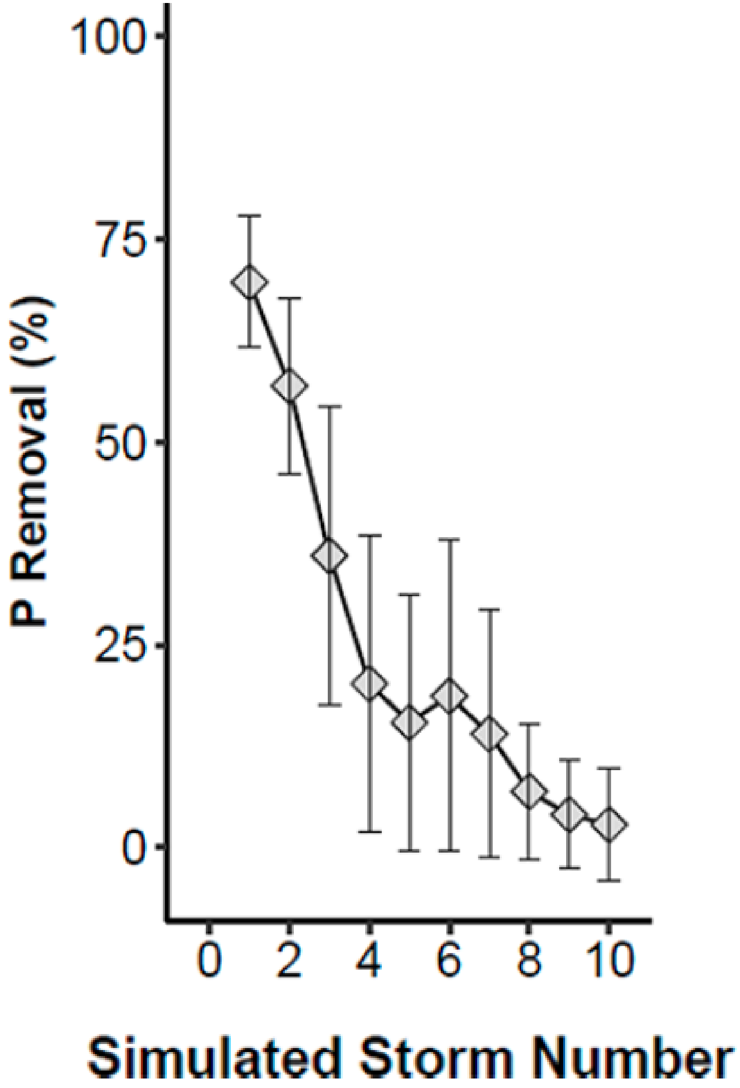
column diameter = 15 cm



For each of 10 days, columns received a 15 L dose of synthetic stormwater:

0.5 mg L^{-1} NH_4-N
0.5 mg L^{-1} NO_3-N
0.2 mg L^{-1} PO_4-P
in 0.01 M KCl, pH 7

Each storm was equivalent to a 2.5 cm rain event



Scenario 2: Substrates included in green infrastructure design leach P over time

- **Study:** Stormwater subsurface gravel wetlands in Vermont

Collaborators: Marcos Kubow (UVM), Dr. Donna Rizzo (UVM), Andres Torizzo (Watershed Consulting LLC), Nisha Nadkarni (Watershed Consulting LLC)

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WATERSHED CONSULTING

Funding:
Lake Champlain Sea Grant

Sea Grant Lake Champlain

Stormwater Subsurface Gravel Wetlands:

Desired P load reductions: 60-80%

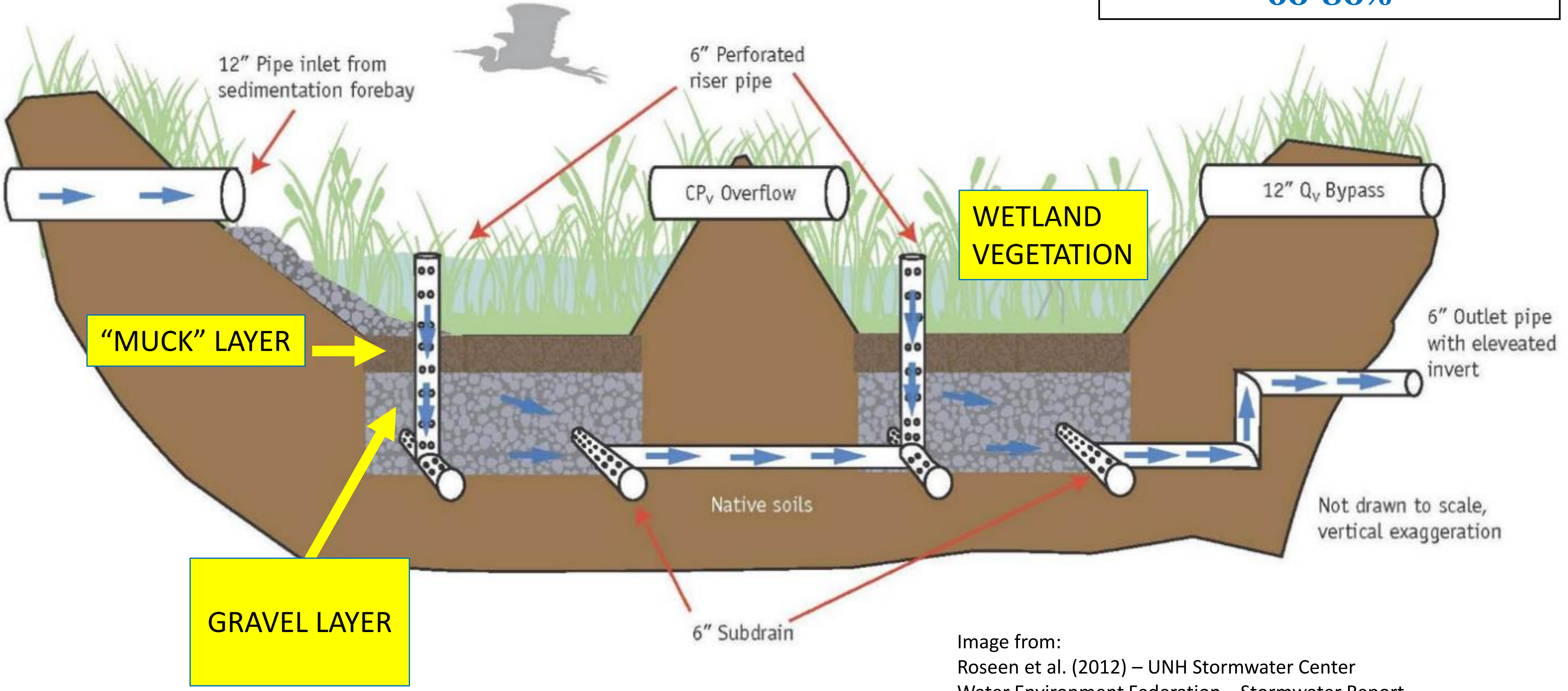
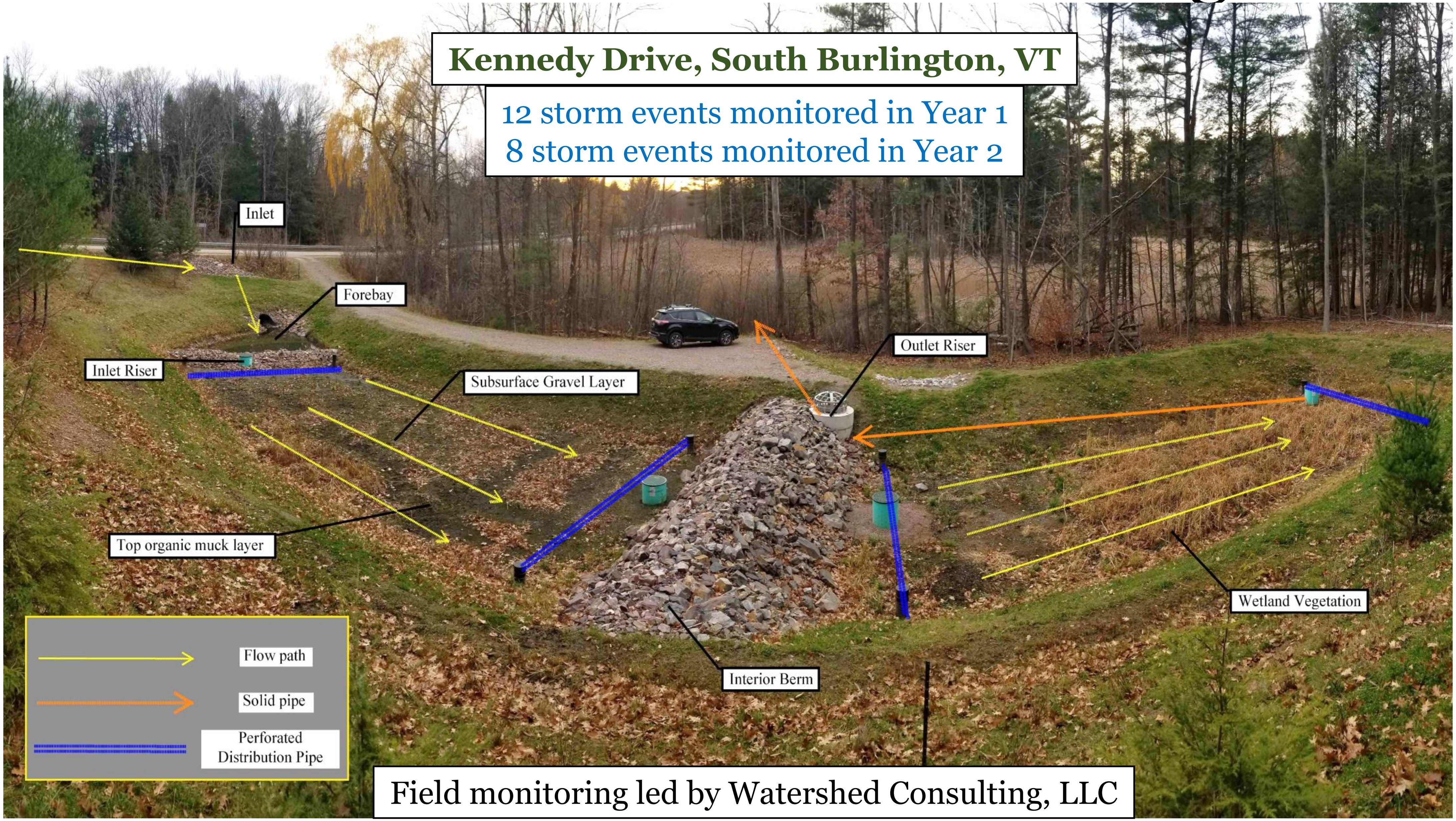
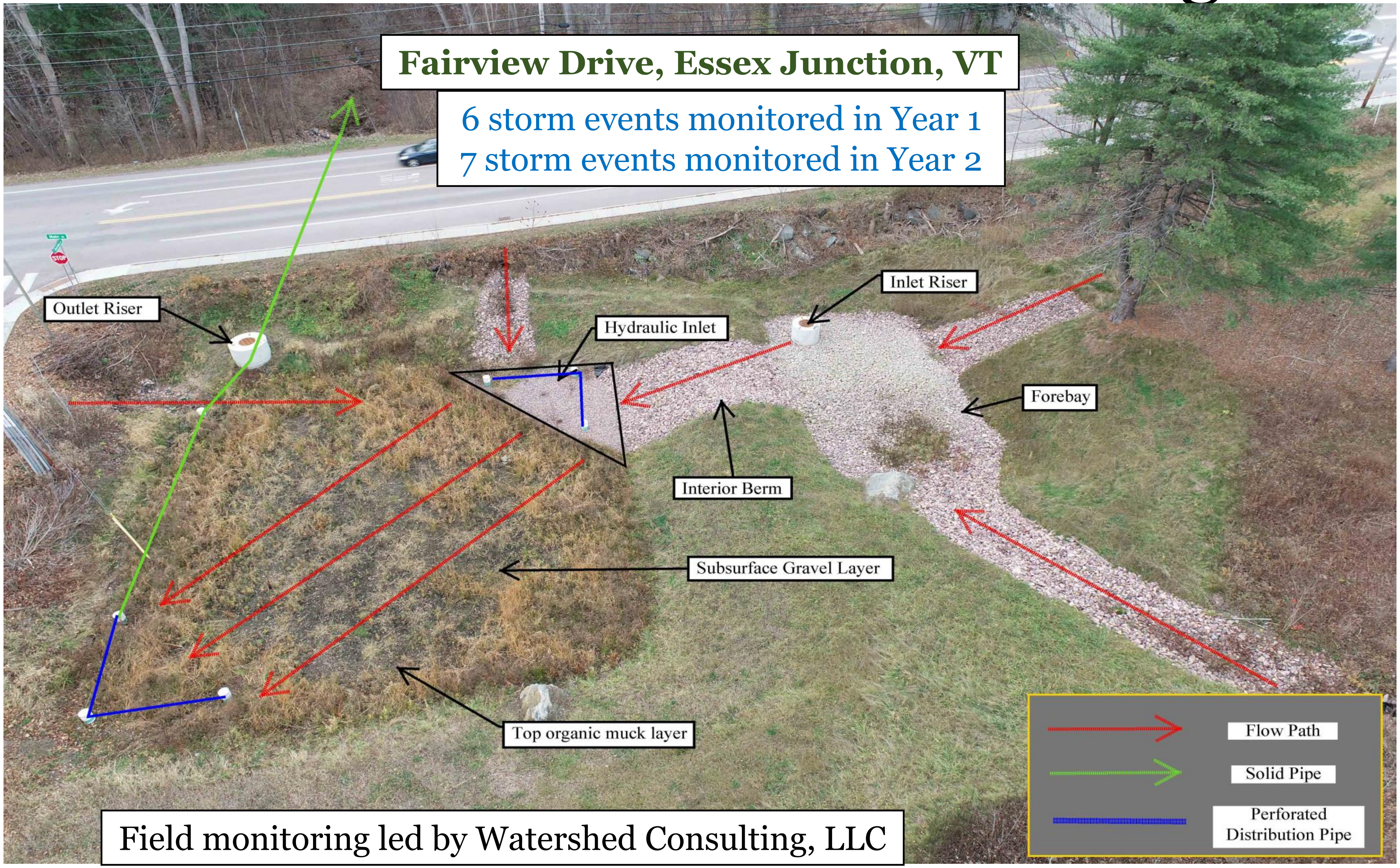


Image from:
Roseen et al. (2012) – UNH Stormwater Center
Water Environment Federation – Stormwater Report

Results from field monitoring

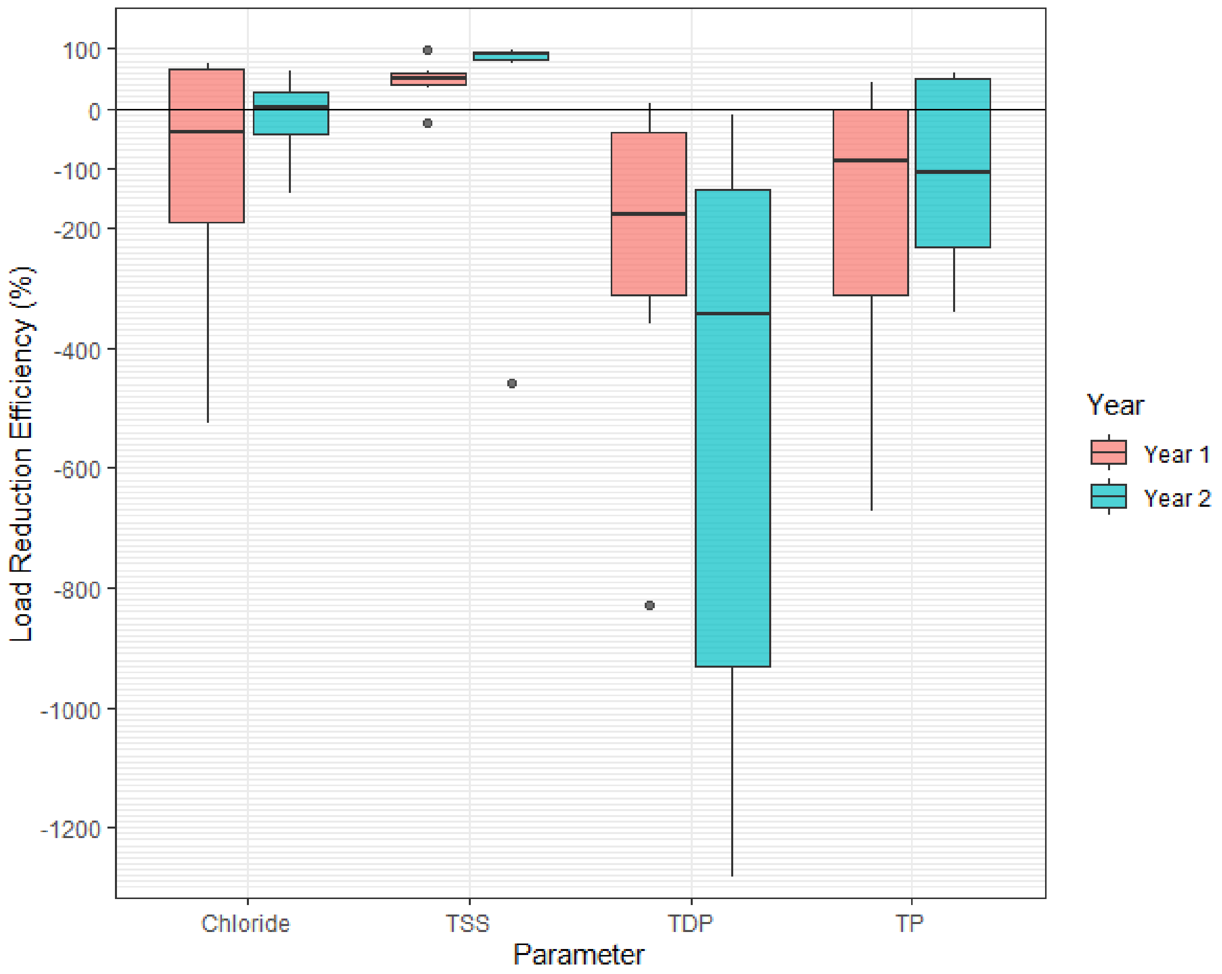


Results from field monitoring

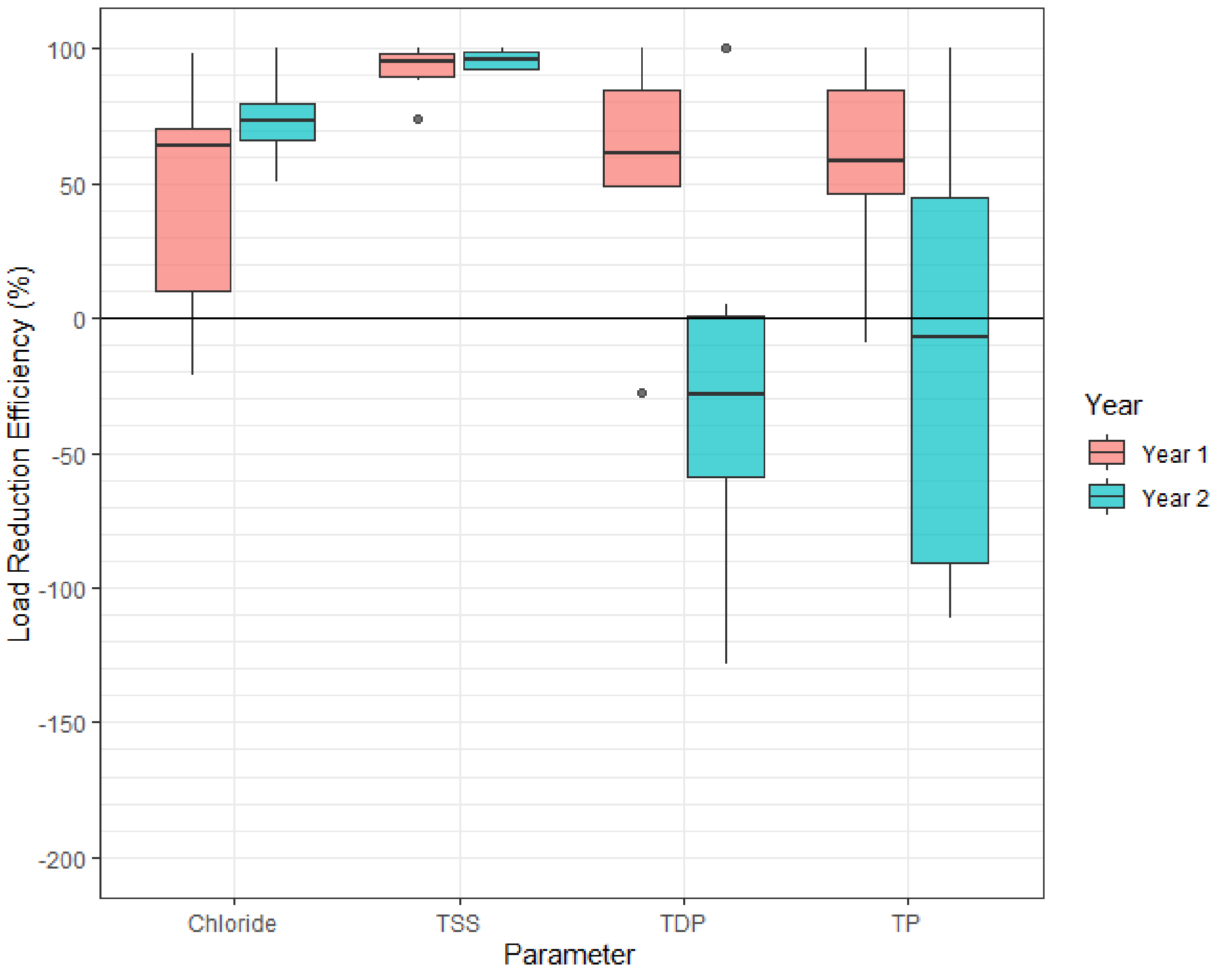


Results from field monitoring

Kennedy Drive, South Burlington, VT



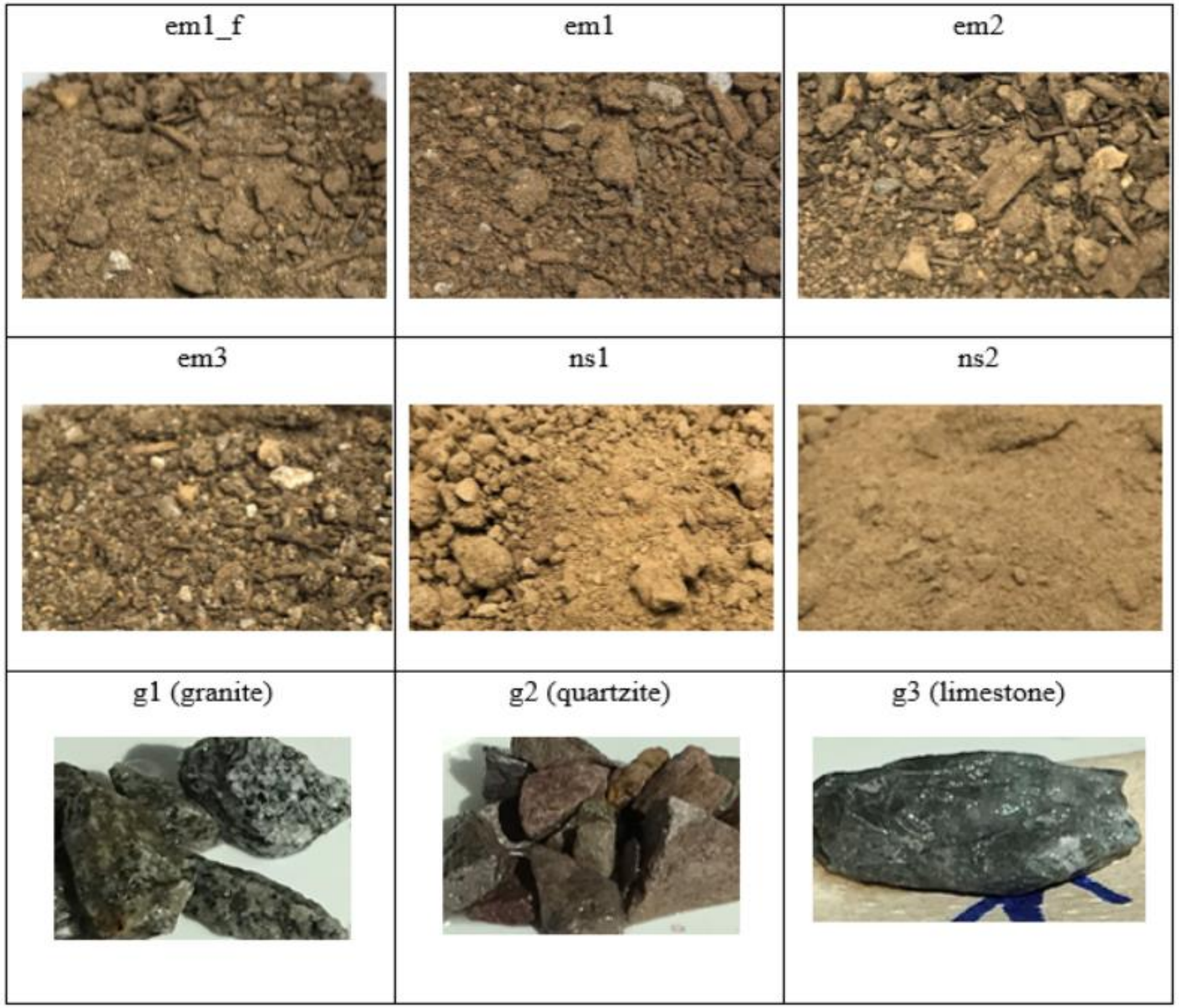
Fairview Drive, Essex Junction, VT



Data from Watershed Consulting, LLC

Muck and Gravel Materials Tested in the Lab

em = engineered muck
ns = native soil



Gravels: 1/2” – 3/4”

em = engineered muck
ns = native soil

Muck Characteristics

Two of the three engineered mucks showed high potential for dissolved P loss

Sample	WEP (mg P kg $^{-1}$)	Modified Morgan (mg P kg^{-1})	Mehlich-3 (mg P kg^{-1})	Mehlich-3 PSR	K_{sat} (ft day^{-1})
em1	41 ± 3	307	339	1.34	0.49 ± 0.29
em1_f	22 ± 0	192	316	0.75	0.56 ± 0.32
em2	27 ± 5	572	676	1.00	65.12 ± 26.19
em3	3 ± 2	30	161	0.10	6.75 ± 5.78
ns1	2 ± 0	3	56	0.04	2.49 ± 2.58
ns2	1 ± 1	2	10	0.01	5.59 ± 4.95

Roy et al. (in prep)

Muck Characteristics

em = engineered muck
ns = native soil

All engineered mucks & native soils tested had K_{sat} well above the target of 0.01 to 0.10 ft/day

Sample	WEP ($mg\ P\ kg^{-1}$)	Modified Morgan ($mg\ P\ kg^{-1}$)	Mehlich-3 ($mg\ P\ kg^{-1}$)	Mehlich-3 PSR	K_{sat} ($ft\ day^{-1}$)
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ns2	1 ± 1	2	10	0.01	5.59 ± 4.95

Roy et al. (in prep)

Overall Lab Column Testing Approach for Mucks & Gravels

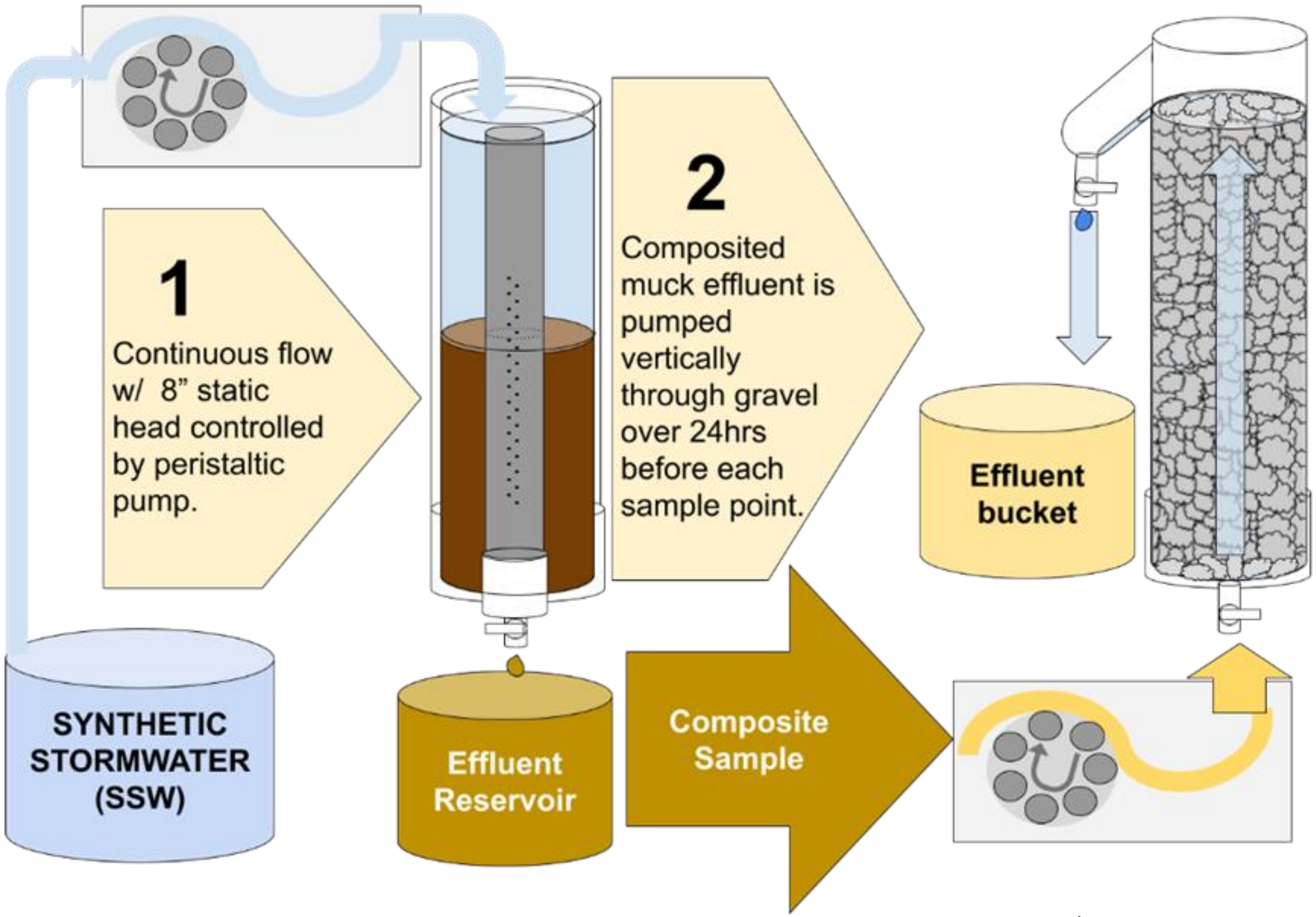


Figure: Marcos Kubow

Muck Column Testing Set-up

Synthetic Stormwater Characteristics:

0.2 mg PO_4-P L^{-1}
0.5 mg NO_3-N L^{-1}
0.5 mg NH_4-N L^{-1}
650 mg Cl^-/L

Triplicate columns for each treatment, with triplicate controls for each of 2 experimental rounds

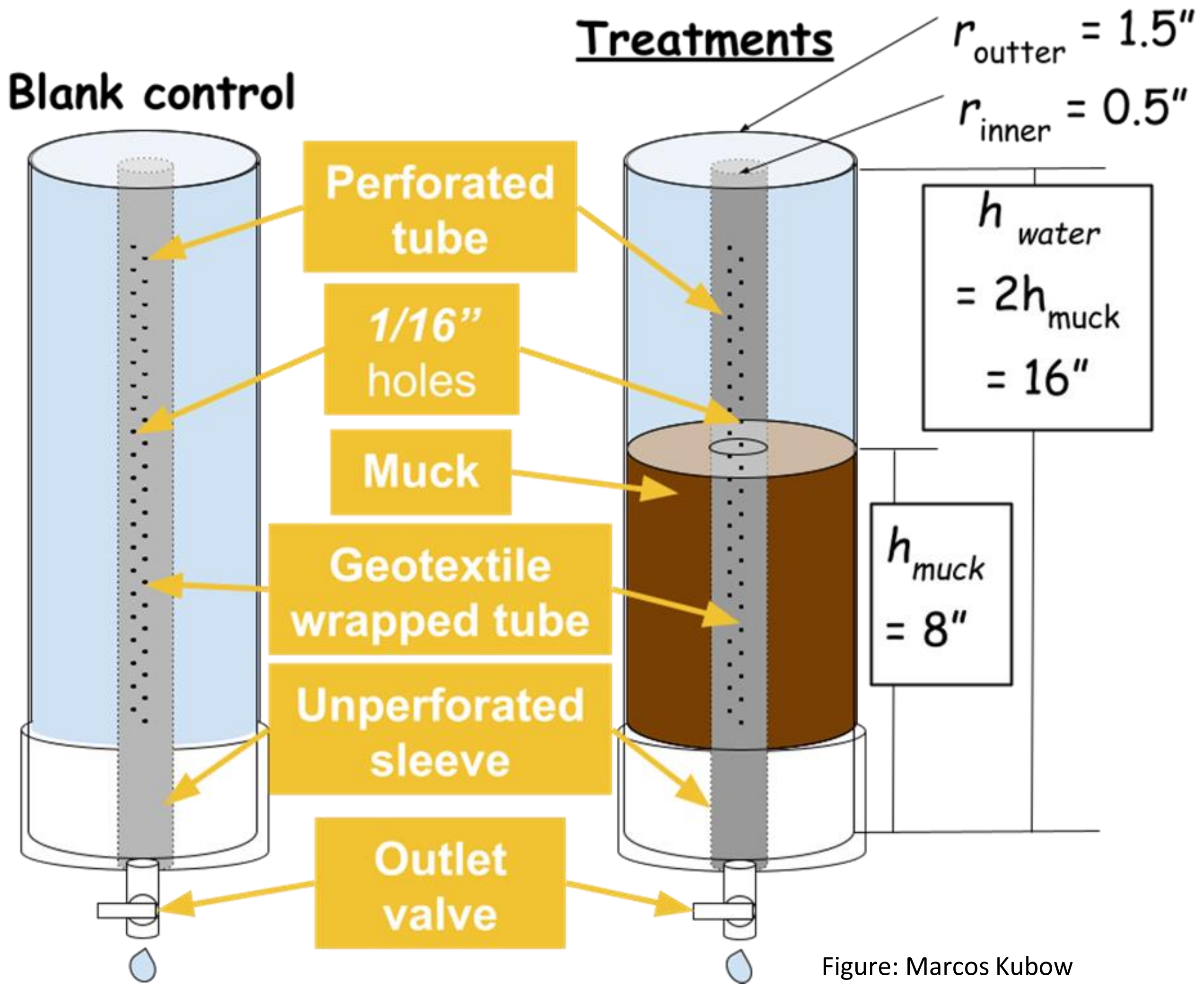


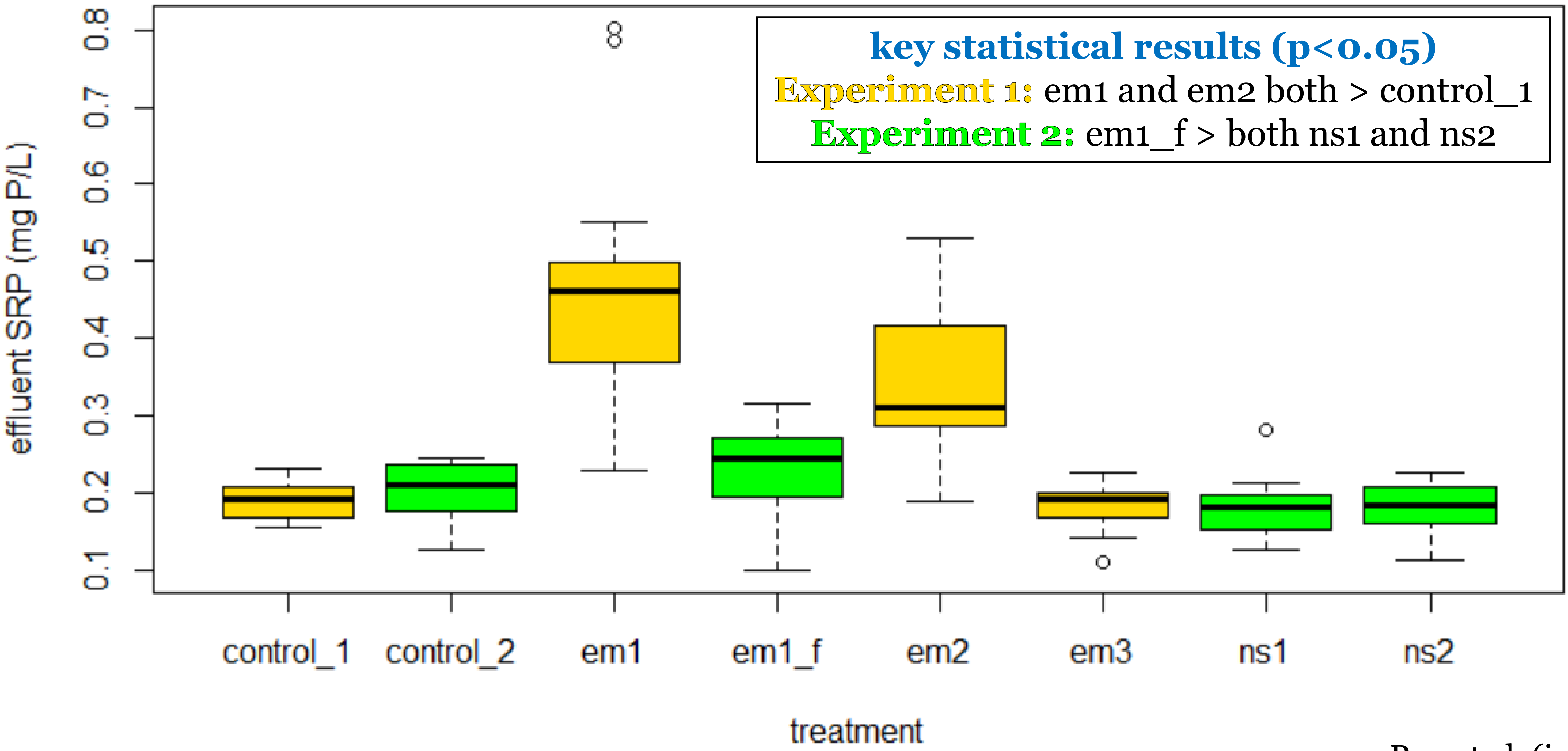
Figure: Marcos Kubow

6 simulated "storms" per column:

- Synthetic stormwater added to achieve an 8" ponding depth
- Hold for 1 hr to allow chemical equilibrium
- Initiate draining @ 3-6 cm^3 s^{-1} with constant 8" ponding depth
- Total storm volume = 3 L

Muck Column Results

boxplots (6 simulated storms x 3 replicate columns per treatment)



Roy et al. (in prep)

Scenario 3: Existing legacy phosphorus on the landscape results in release of dissolved P

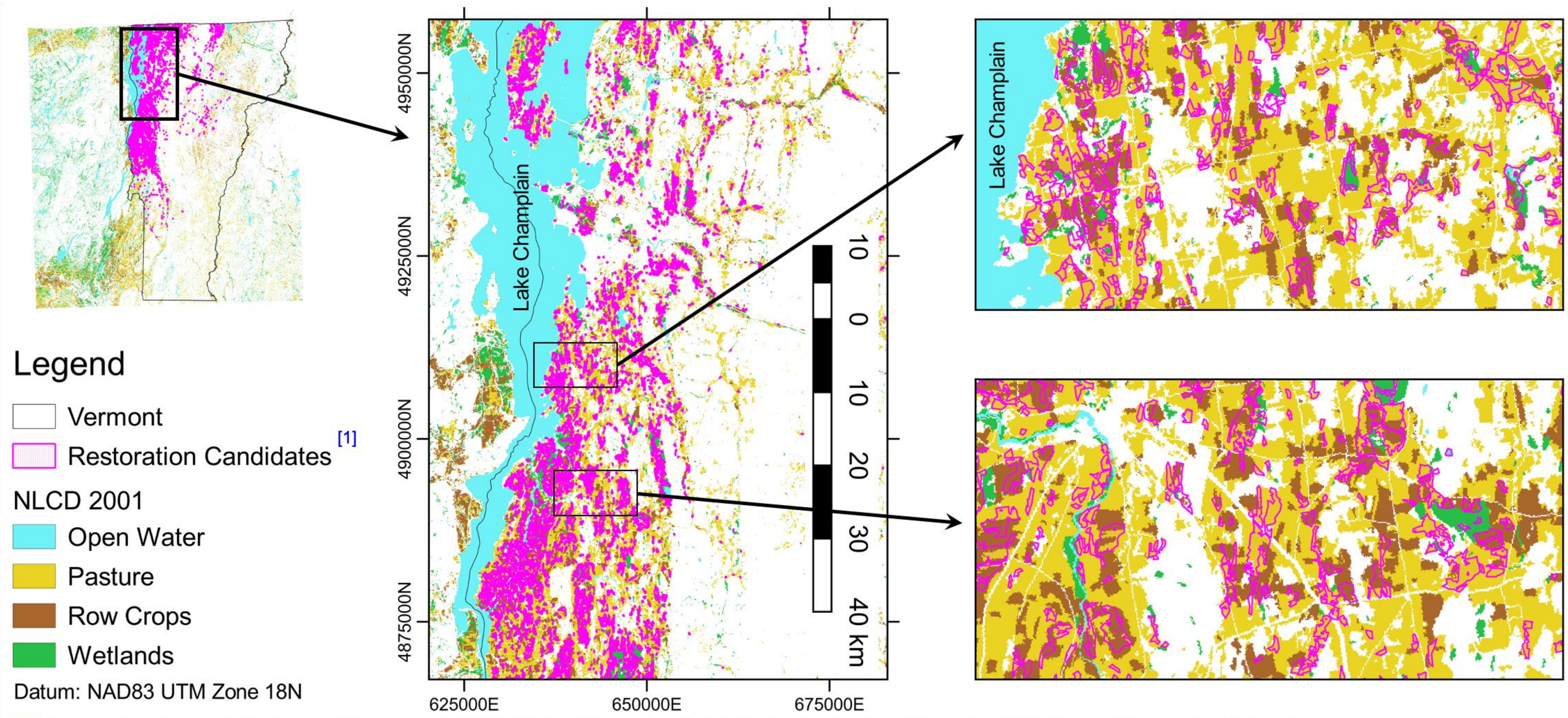
- **Study:** Restoring riparian wetlands on former agricultural land in Vermont

Collaborators: Dr. Adrian Wiegman (USDA ARS), Dr. Rebecca Diehl (UVM), Dr. Kristen Underwood (UVM), Dr. Breck Bowden (UVM), Harrison Myers (UVM), Maya Fein-Cole (UVM), Marcos Kubow (UVM), Tiffany Chin (UVM), Dr. Don Ross (UVM), Isabelle Augustin (UVM), Venesa Perillo (Instituto Argentino de Oceanografía)

The UNIVERSITY of VERMONT

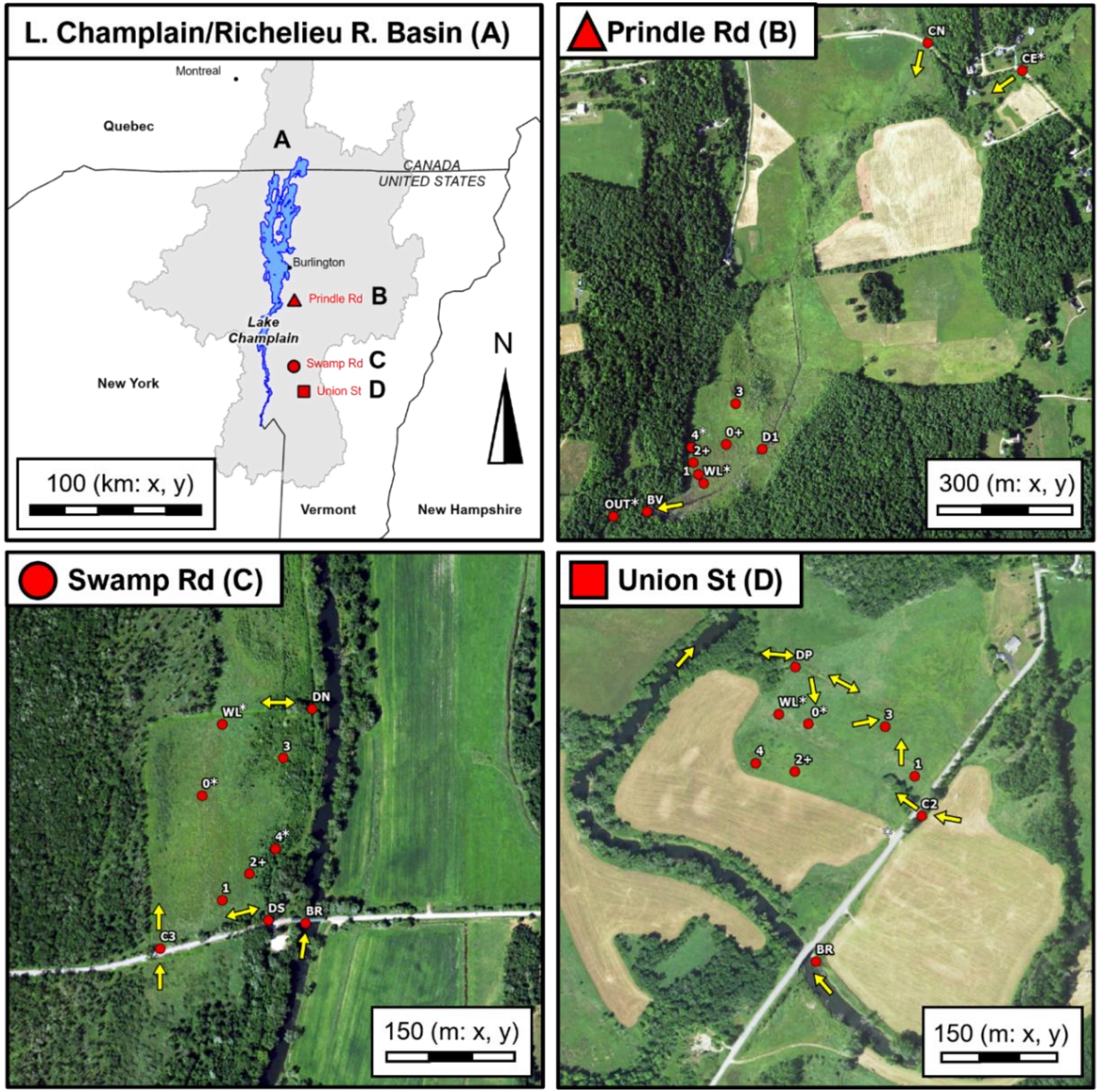
Funding:
Lake Champlain Basin Program
Vermont DEC
Gund Institute for Environment
USDA NRCS

Most wetland restoration candidate sites in Lake Champlain Basin overlay drained agricultural soils



[1] Arrowwood Environmental & Fitzgerald Environmental (2017) Wetland Restoration Model Site Prioritization (Lake Champlain 2017) Regional Conservation Partnership

Study Sites

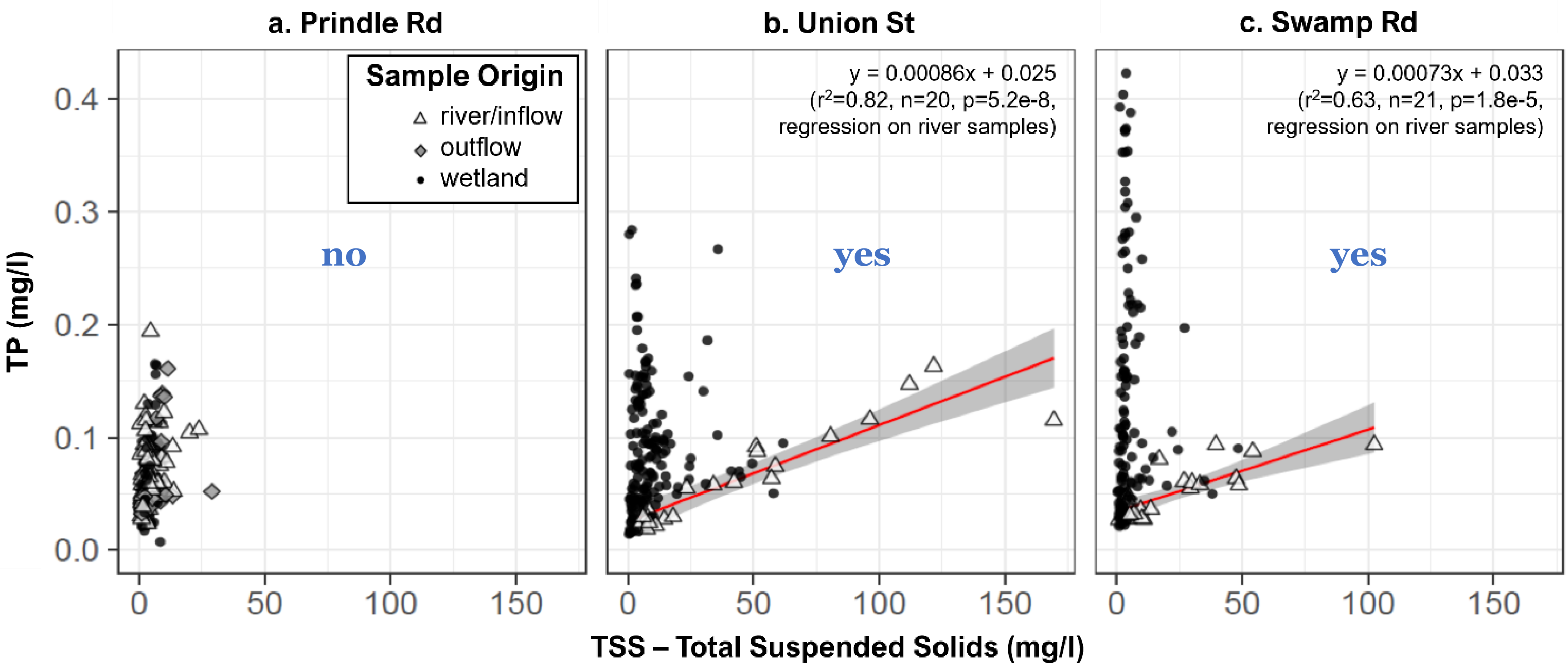


Agricultural activity ceased in 2006

Agricultural activity ceased >10 yrs ago

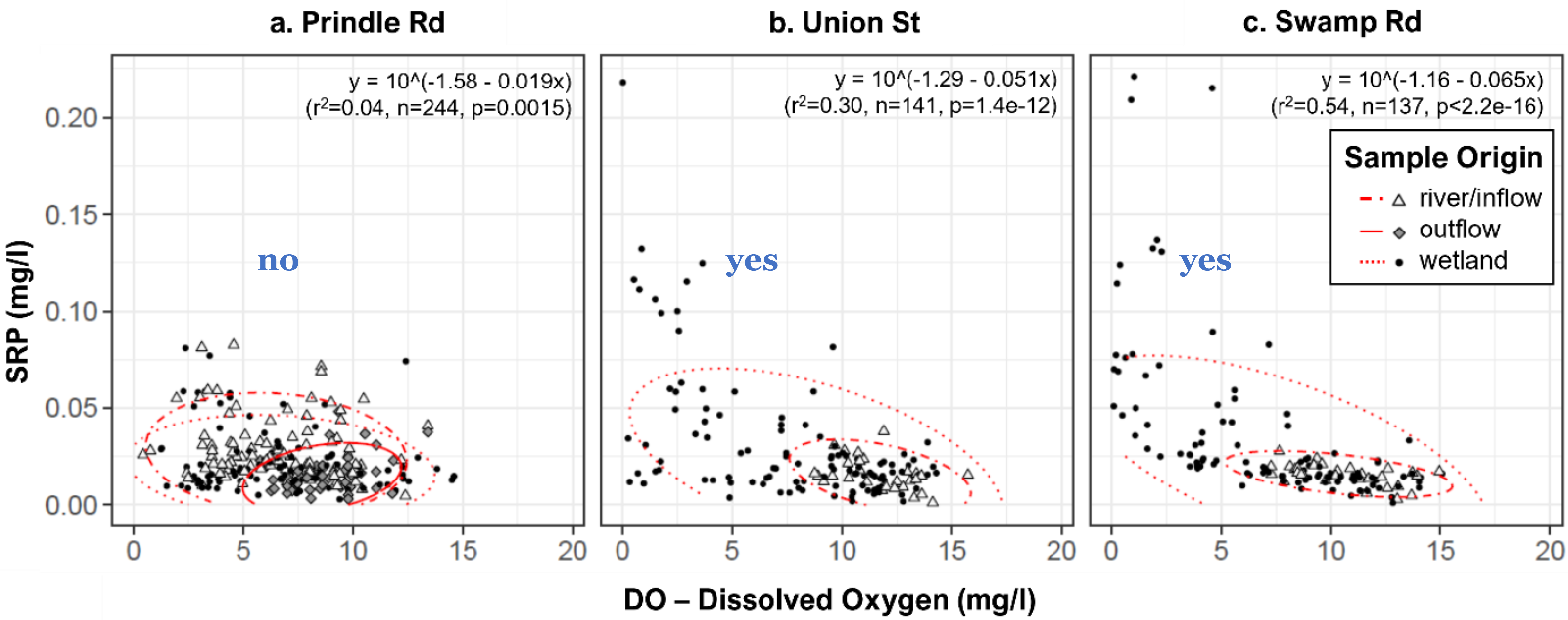
Agricultural activity ceased in 2004

Is there evidence of internal SRP release in the study wetlands?



Wiegman (2022)

Do sites show patterns of decreased DO & increased SRP in wetland relative to river?

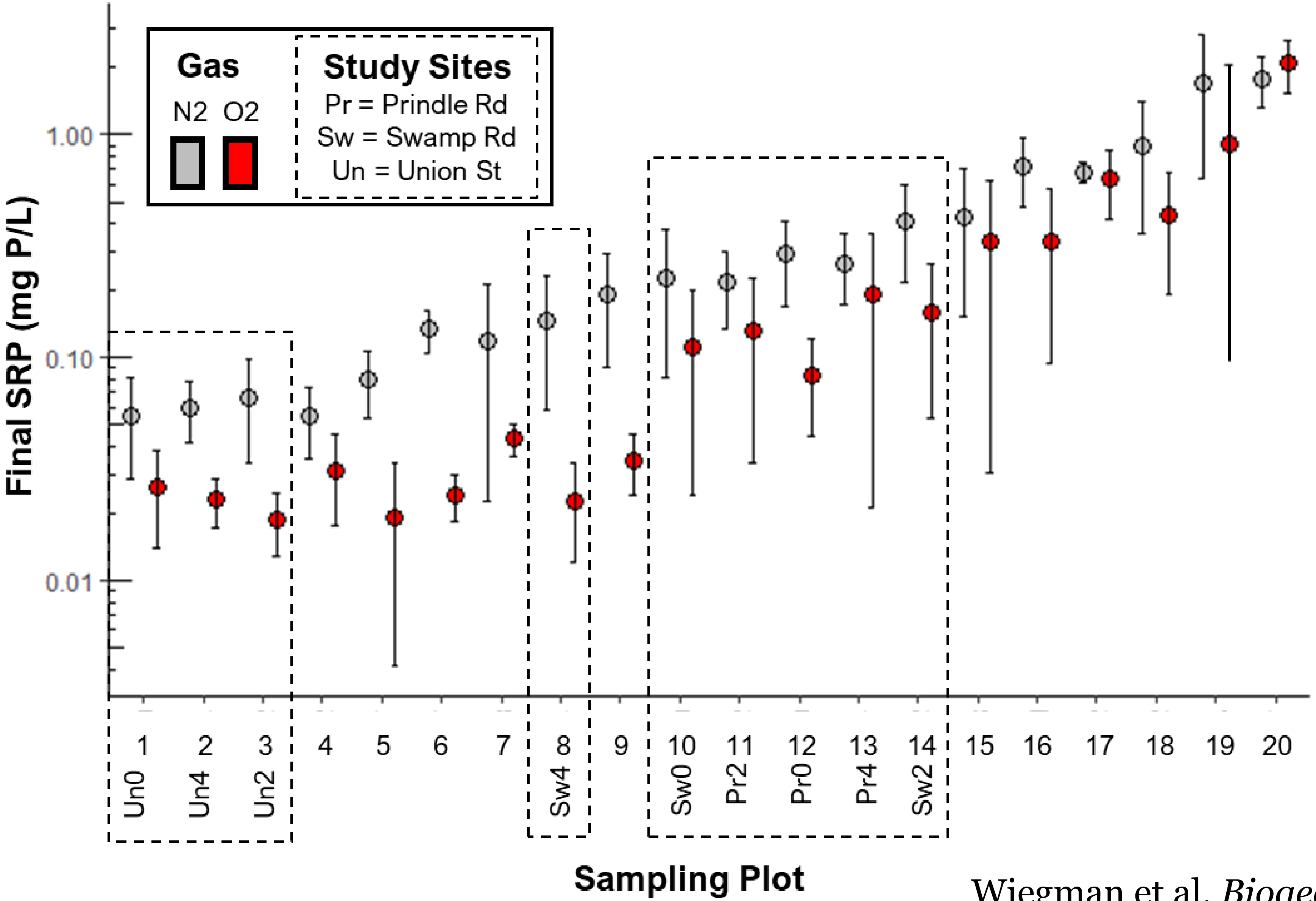


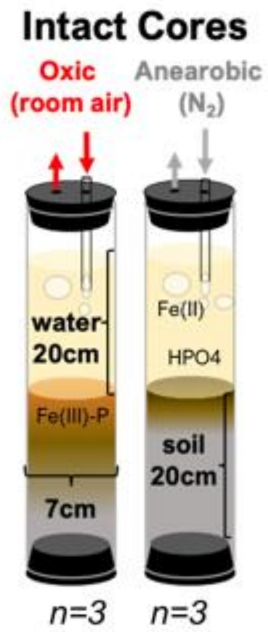
Wiegman (2022)

Is there evidence of internal SRP release in the study wetlands?

Intact core incubations in lab completed for 3 LCBP sites plus several others (20 plots across 14 sites in total)

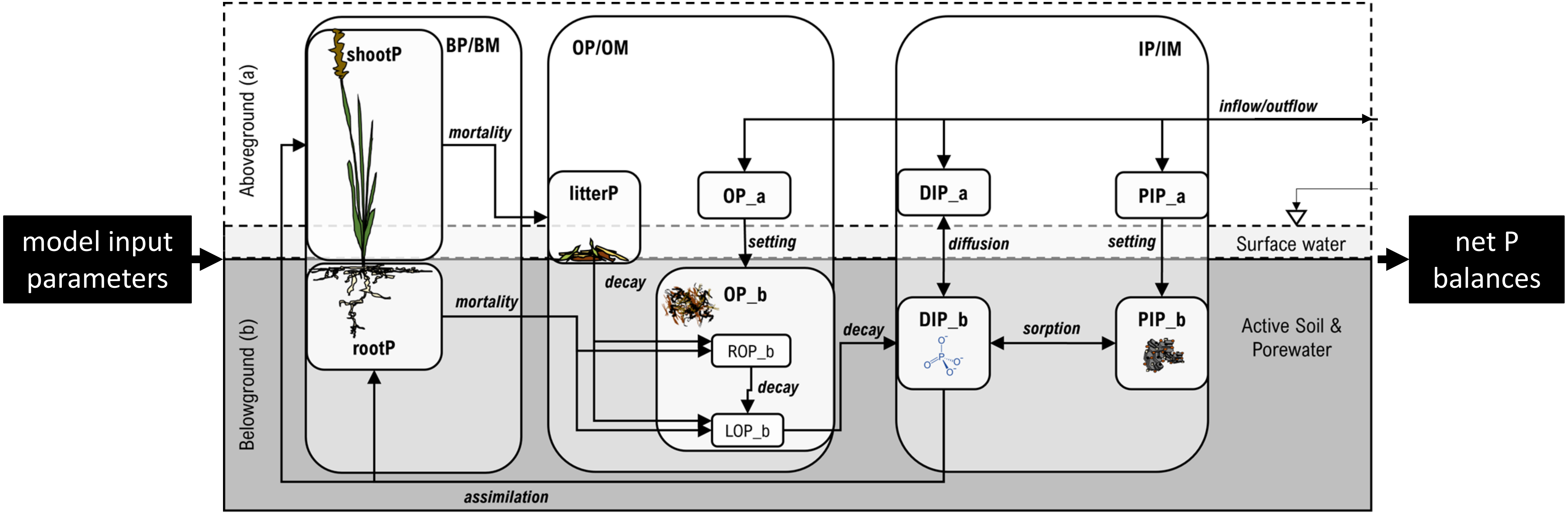
Is there evidence of internal SRP release?





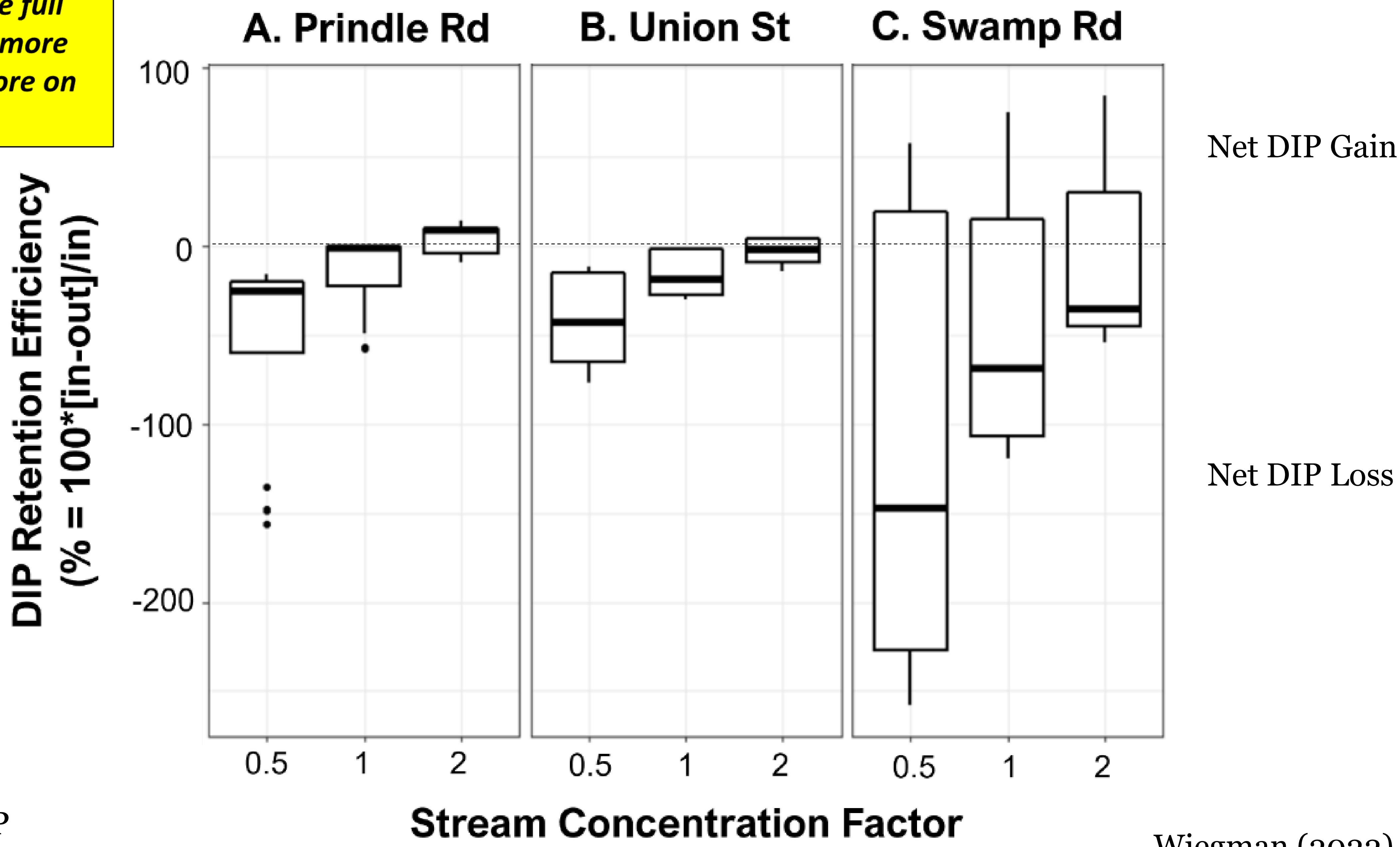
Wiegman et al. *Biogeochemistry* (2022)

Modeling P dynamics in riparian wetlands



Wiegman (2022)

This is only the DIP part of the story! The full picture is much more encouraging. More on that soon.



Note: DIP = SRP

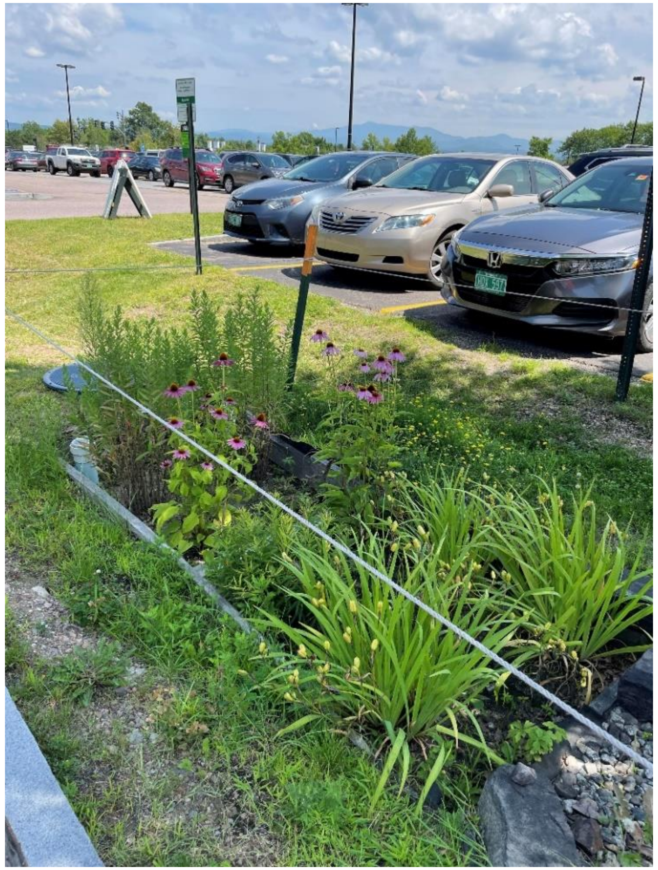
Wiegman (2022)

Part 3: Opportunities

- What design interventions can be used to improve control of dissolved phosphorus in green infrastructure?
  - **Strategy 1:** Increase the P sorption capacity of green infrastructure substrates via geochemical augmentation
  - **Strategy 2:** Use P metrics to guide site evaluation and BMP design
  - **Strategy 3:** Facilitate soil development that eventually results in lesser potential for dissolved P loss (and be patient)

Strategy 1: Increase the P sorption capacity of green infrastructure substrates via geochemical augmentation

Study: Drinking water treatment residuals in bioretention cells



Collaborators: Dr. Michael Ament (Minn. Pollution Control Agency), Dr. Stephanie Hurley (UVM), Dr. Yongping Yuan (EPA), Mark Voorhees (EPA), Eric Perkins (EPA), Andrea Traviglia (EPA)

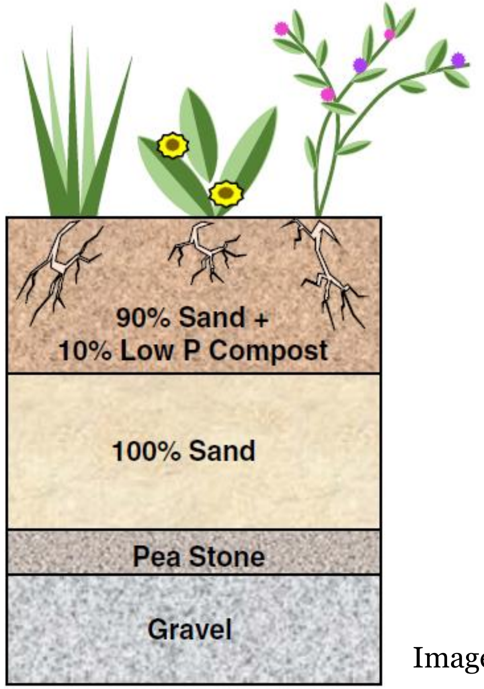


Image: Ament et al. (2022) JSWBE

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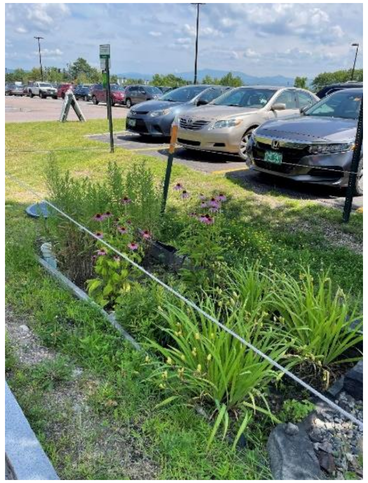
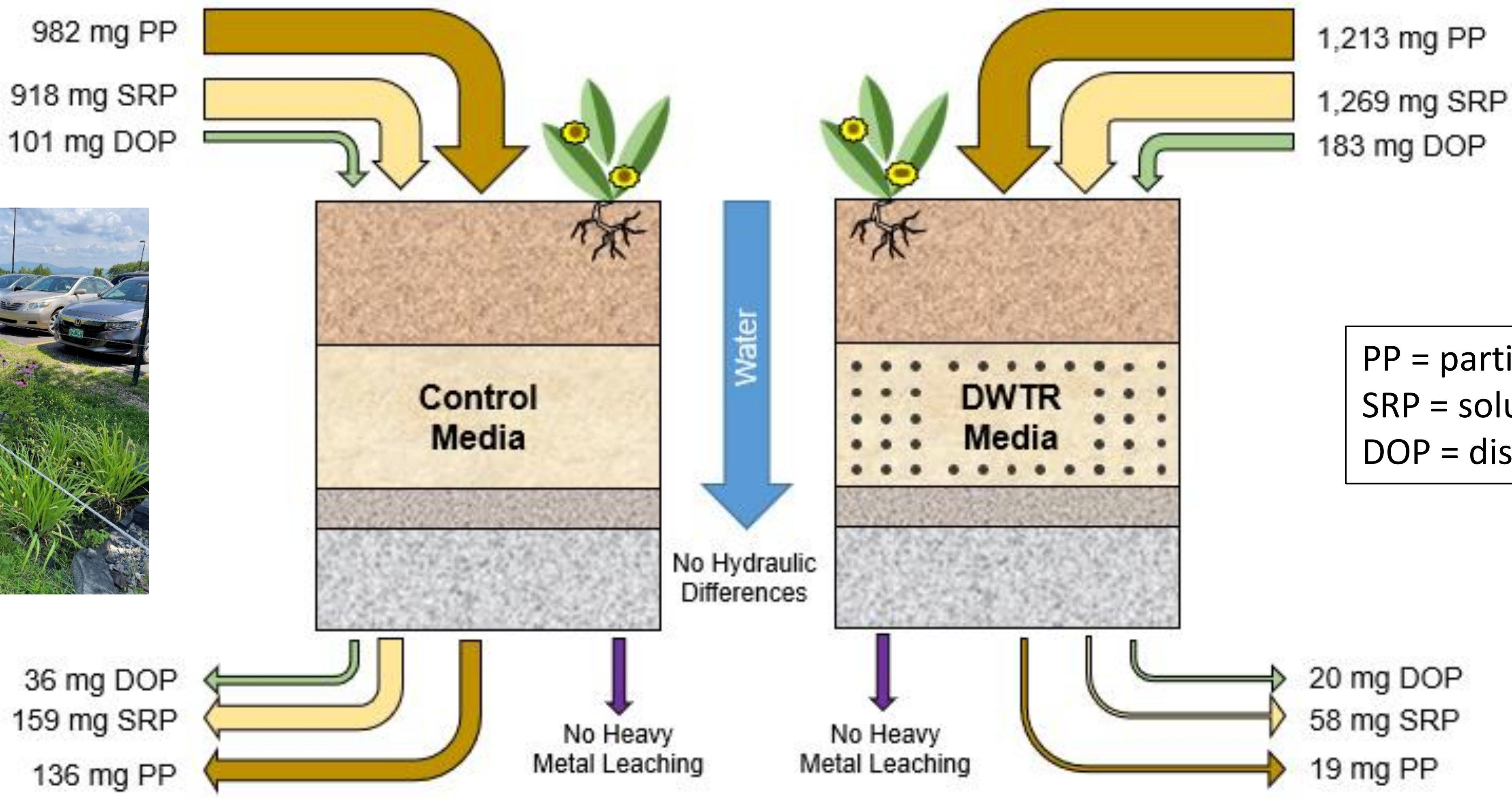
UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Funding:
US EPA RARE Program

Evidence from the field – UVM Bioretention Lab

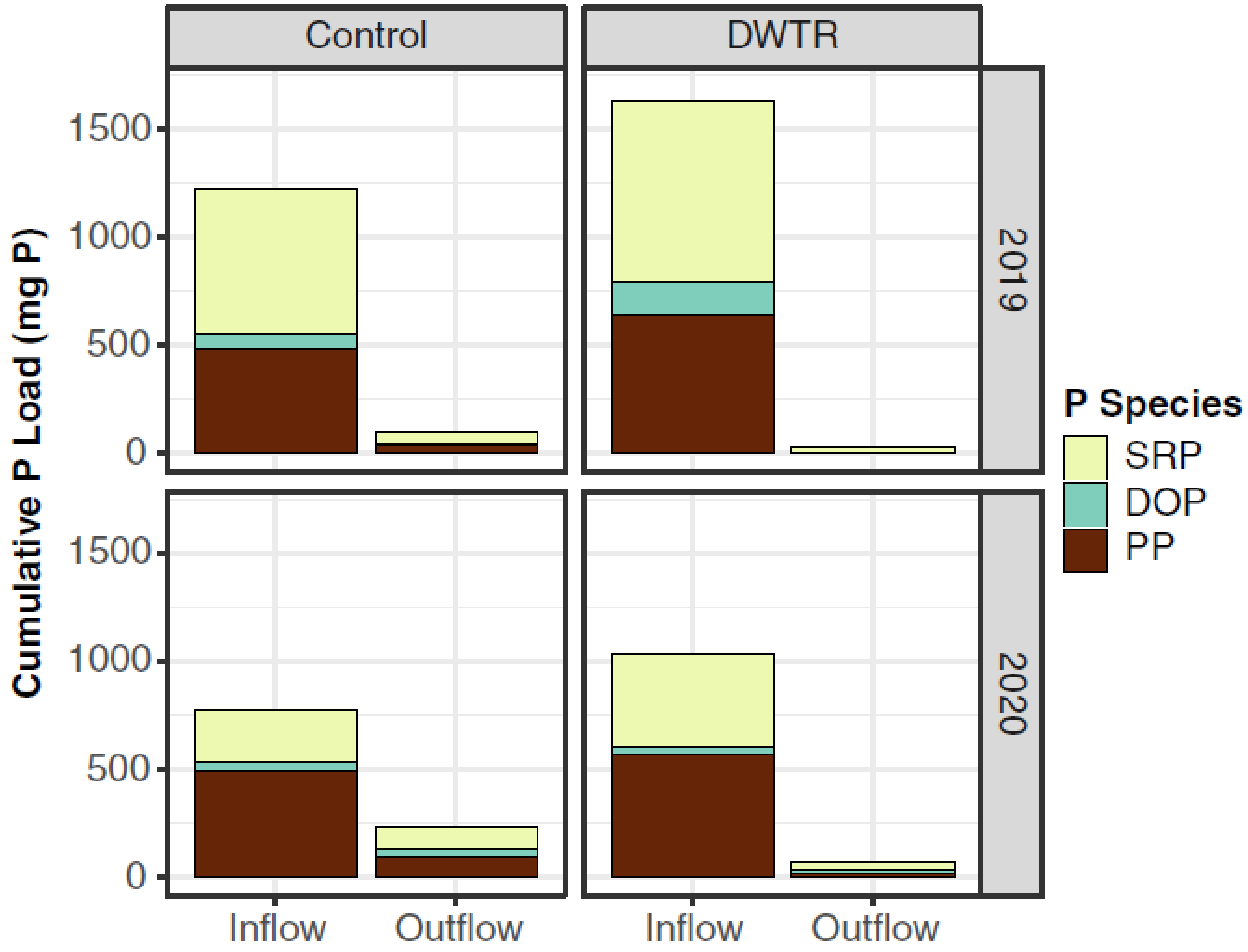




PP = particulate P
SRP = soluble reactive P
DOP = dissolved organic P

(Ament et al. 2022 JSWBE)

Evidence from the field – UVM Bioretention Lab



Decrease in SRP removal efficiency between 2019 and 2020:

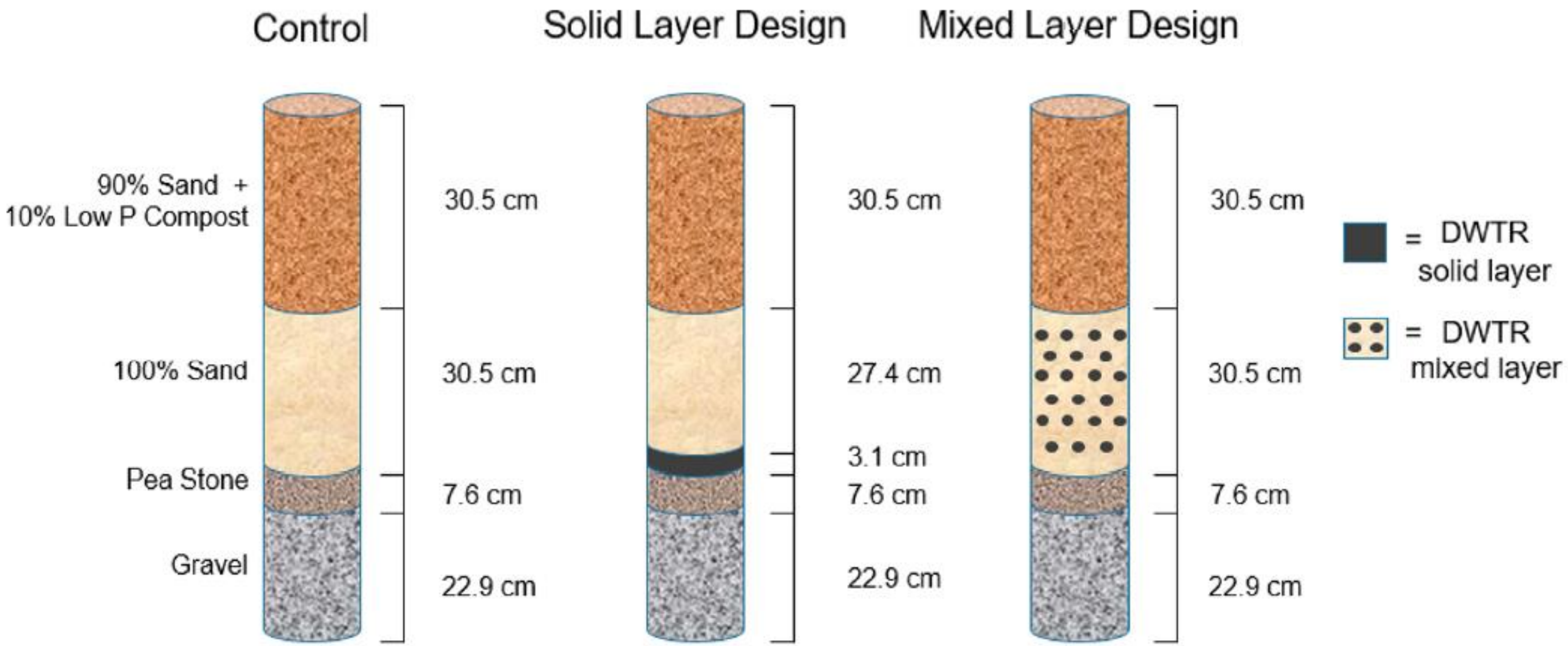
16% and 59% decrease for the two **control** cells

5% and 3% decrease for the **DWTR** cells, despite receiving greater SRP inputs

(Ament et al. 2022 JSWBE)

Evidence from the lab (Ament et al. 2021 ACS ES&T Water)

Large column studies of bioretention media designs



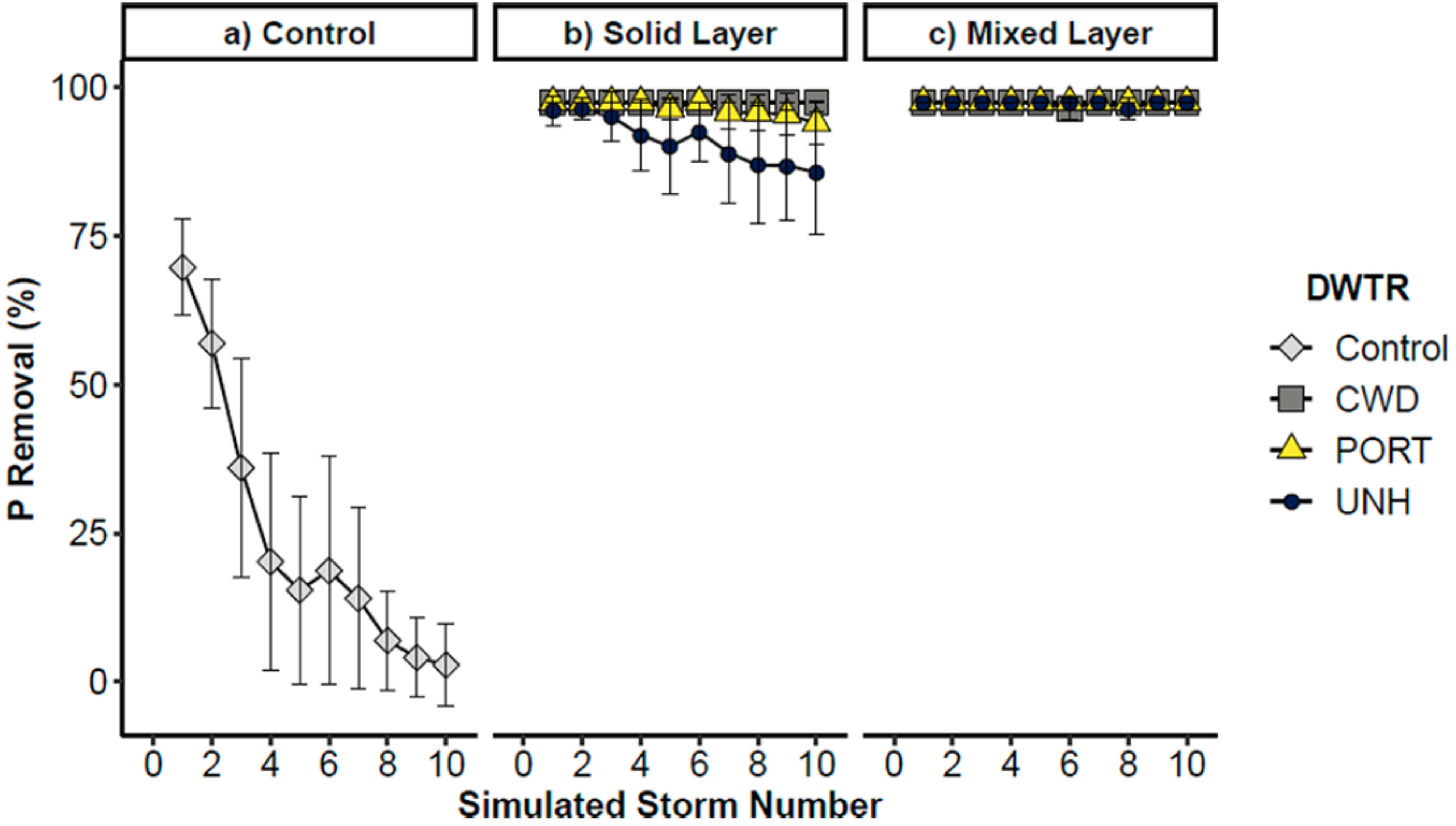
For each of 10 days, columns received a 15 L dose of synthetic stormwater:

0.5 mg L^{-1} NH_4-N, 0.5 mg L^{-1} NO_3-N, 0.2 mg L^{-1} PO_4-P in 0.01 M KCl, pH 7

Each storm was equivalent to a 2.5 cm rain event

Evidence from the lab (Ament et al. 2021 ACS ES&T Water)

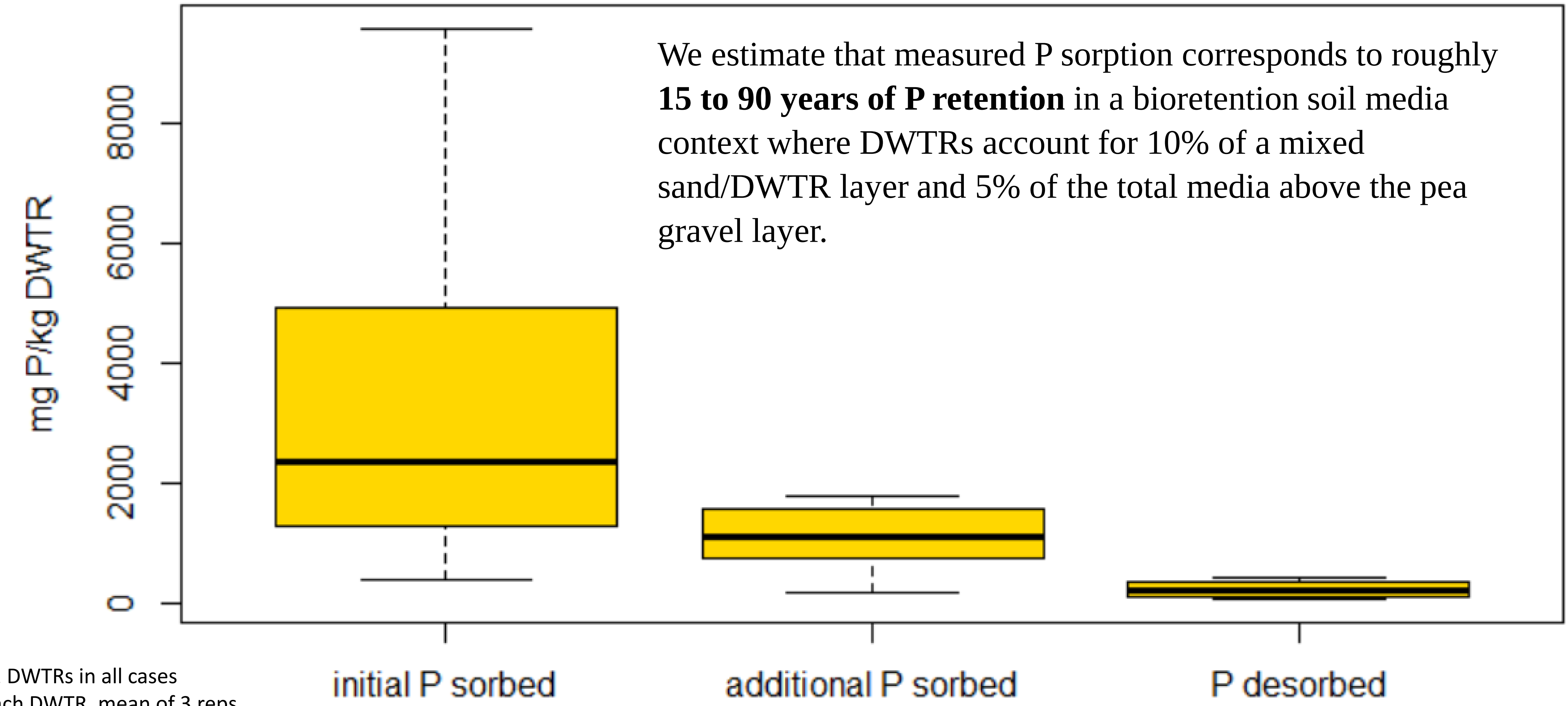
Large column studies of bioretention media designs



Evidence from the lab (Ament et al. 2021 & Roy et al. In Prep)

Low P/High flow small column studies of eleven DWTRs (1 mg P/L with ~3 min contact time)

load until Pout ~ Pin → **dry** → **load until Pout ~ Pin** → **P-free 0.01 M KCl for 7 d**



We estimate that measured P sorption corresponds to roughly **15 to 90 years of P retention** in a bioretention soil media context where DWTRs account for 10% of a mixed sand/DWTR layer and 5% of the total media above the pea gravel layer.

n = 11 DWTRs in all cases
For each DWTR, mean of 3 reps

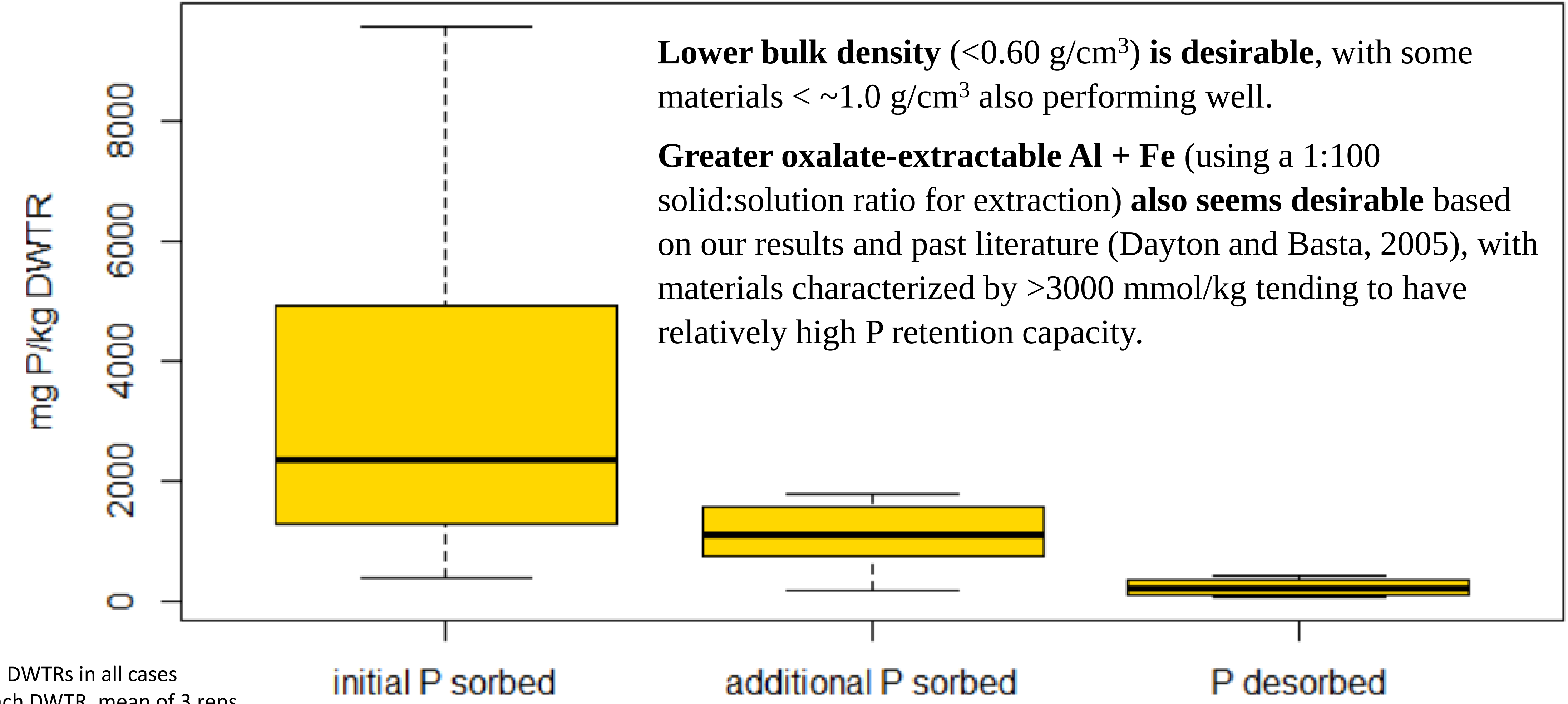
Evidence from the lab (Ament et al. 2021 & Roy et al. In Prep)

Low P/High flow small column studies of eleven DWTRs (1 mg P/L with ~3 min contact time)

load until Pout ~ Pin —dry→ **load until Pout ~ Pin** → **P-free 0.01 M KCl for 7 d**

Lower bulk density (<0.60 g/cm^3) **is desirable**, with some materials $<$ ~1.0 g/cm^3 also performing well.

Greater oxalate-extractable Al + Fe (using a 1:100 solid:solution ratio for extraction) **also seems desirable** based on our results and past literature (Dayton and Basta, 2005), with materials characterized by >3000 mmol/kg tending to have relatively high P retention capacity.



n = 11 DWTRs in all cases
For each DWTR, mean of 3 reps

Strategy 2: Use P metrics to guide site evaluation and BMP design

- **Study:** Stormwater subsurface gravel wetlands in Vermont

Collaborators: Marcos Kubow (UVM), Dr. Donna Rizzo (UVM), Andres Torizzo (Watershed Consulting LLC), Nisha Nadkarni (Watershed Consulting LLC)

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WATERSHED CONSULTING

Funding:
Lake Champlain Sea Grant

Sea Grant Lake Champlain

Potential P metrics to inform BMP material selection

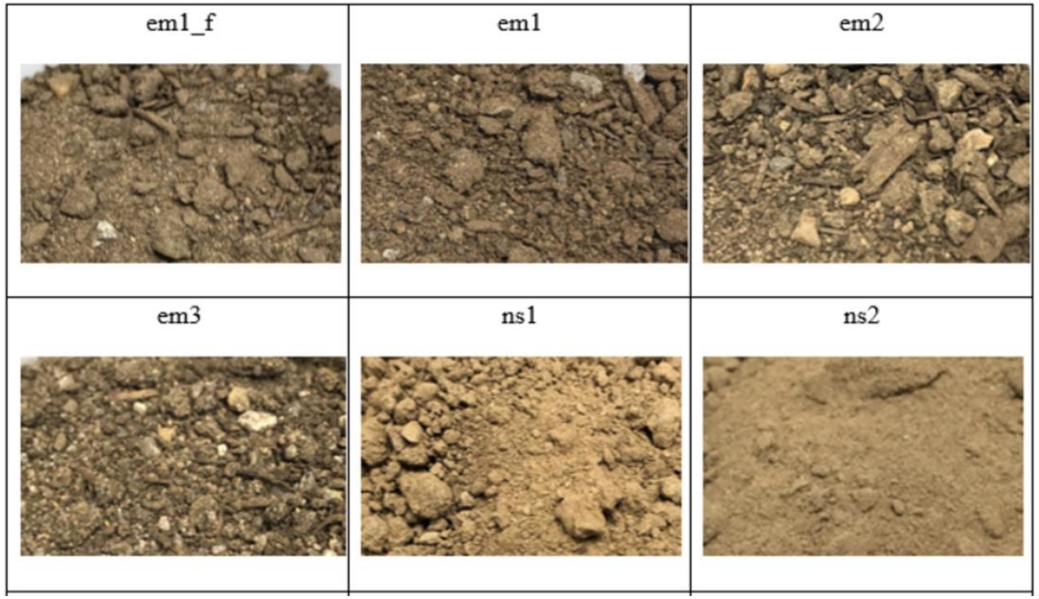
- **Phosphorus-only metrics**
  - Total phosphorus
  - Deionized water-extractable P
  - Soil test P (e.g., Mehlich-1, Mehlich-3, Modified Morgan, Bray)
- **Metrics that incorporate P, Al, and Fe**
  - P Saturation Ratio
  - Soil P Storage Capacity

My preference

Which "muck" materials are likely to leach P in stormwater subsurface gravel wetlands?

P Saturation Ratio (PSR)

$$PSR = \frac{\left(\frac{P_{M3}}{31}\right)}{\left(\frac{Fe_{M3}}{56}\right) + \left(\frac{Al_{M3}}{27}\right)}$$



where,

P_{M3} = Mehlich-3 P in mg P per kg dry soil

Fe_{M3} = Mehlich-3 Fe in mg Fe per kg dry soil

Al_{M3} = Mehlich-3 Al in mg Al per kg dry soil

P Saturation Ratio (PSR)

$$PSR = \frac{\left(\frac{P_{M3}}{31}\right)}{\left(\frac{Fe_{M3}}{56}\right) + \left(\frac{Al_{M3}}{27}\right)}$$

- Can be used to evaluate a gravel wetland muck layer's potential to release P
- We have proposed that final mixes must have a **Phosphorus Saturation Ratio (PSR) less than or equal to 0.10 when using Mehlich-3 extraction**
- Soil studies have reported thresholds near 0.10 for M3-PSR, above which release of soluble reactive P is more likely to occur (Nair 2014, Dari et al. 2018)
- Mucks below this threshold did not release SRP during our column tests

Roy et al. (in prep)

where,
P_{M3} = Mehlich-3 P in mg P per kg dry soil
Fe_{M3} = Mehlich-3 Fe in mg Fe per kg dry soil
Al_{M3} = Mehlich-3 Al in mg Al per kg dry soil

muck & gravel column tests

Strategy 2: Use P metrics to guide site evaluation and BMP design

- **Study:** Restoring riparian wetlands on former agricultural land in Vermont

Collaborators: Dr. Adrian Wiegman (USDA ARS), Dr. Rebecca Diehl (UVM), Dr. Kristen Underwood (UVM), Dr. Breck Bowden (UVM), Harrison Myers (UVM), Maya Fein-Cole (UVM), Marcos Kubow (UVM), Tiffany Chin (UVM), Dr. Don Ross (UVM), Isabelle Augustin (UVM), Venesa Perillo (Instituto Argentino de Oceanografía)

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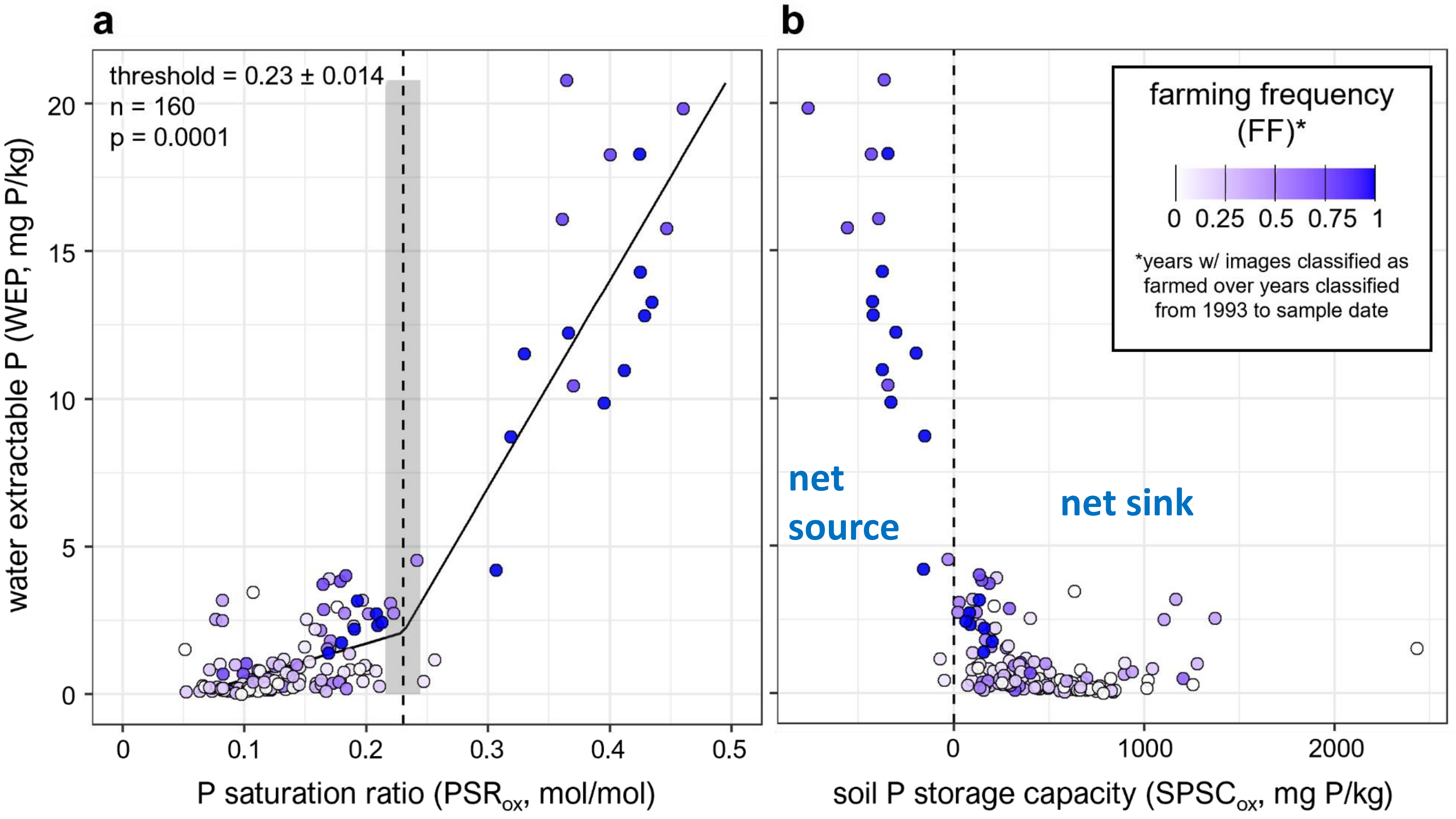
Funding:
Lake Champlain Basin Program
Vermont DEC
Gund Institute for Environment
USDA NRCS

PSR concept illustrated for VT riparian soils



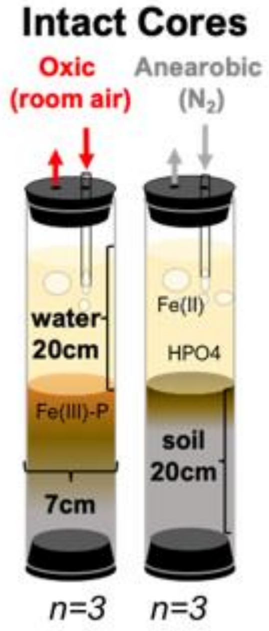
Wiegman et al. (2022) Biogeochemistry

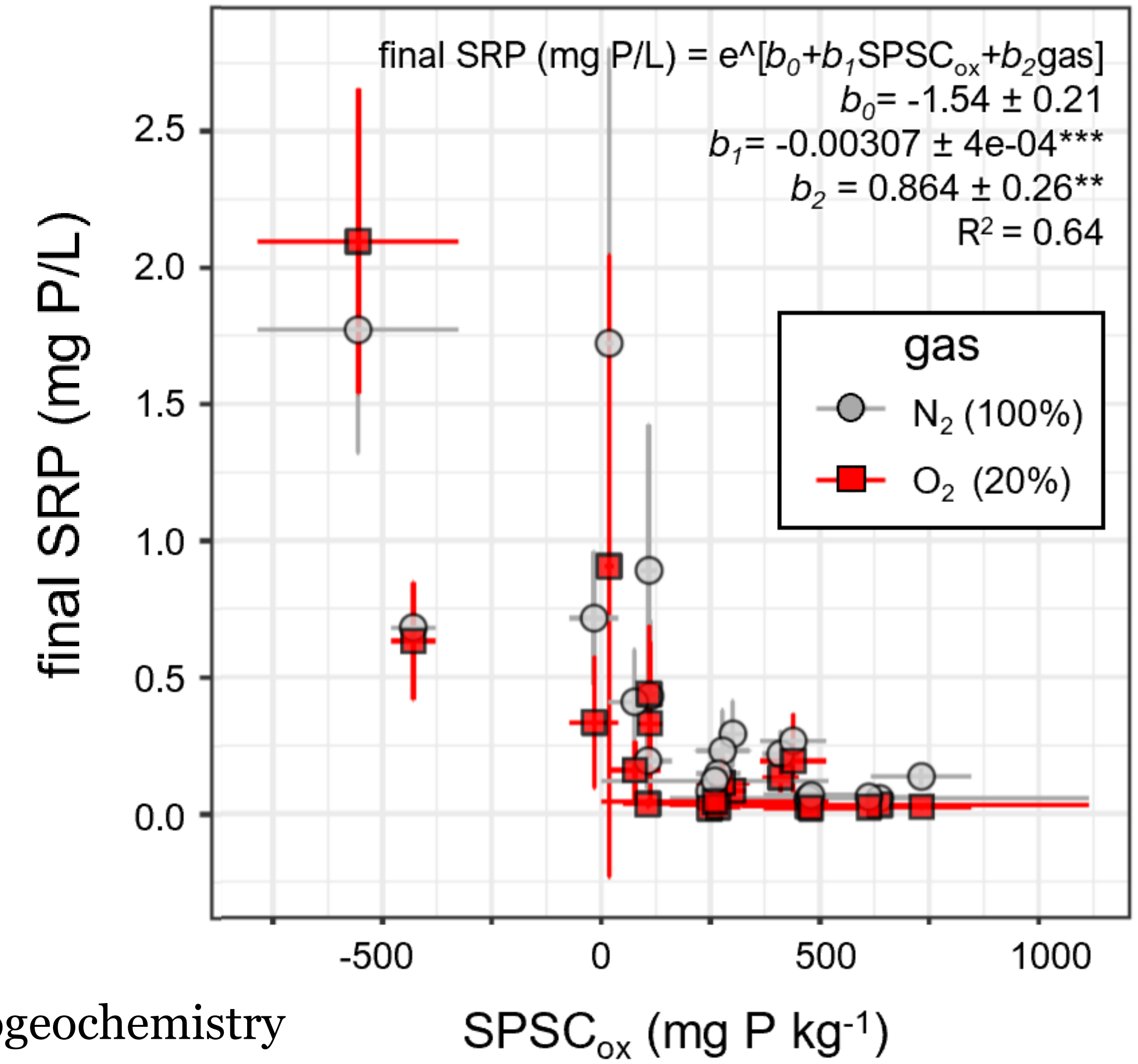
P saturation (PSR) threshold for P release based on oxalate-extractable P, Fe, and Al of ~0.23

PSR can be used to calculate **soil P storage capacity (SPSC)**

Farming history can affect SPSC

SPSC & Gas Treatment predict SRP flux during incubations





Wiegman et al. (2022) Biogeochemistry

Strategy 3: Facilitate soil development that eventually results in lesser potential for dissolved P loss (and be patient)

- **Study:** Restoring riparian wetlands on former agricultural land in Vermont

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Soil Development Theory

- In restored wetland ecosystems, SRP losses from agricultural soils should decline over time as readily available SRP is flushed from soils and recently added soil P is converted to more stable forms (Ardón et al. 2010a; Cross and Schlesinger 1995; Walker and Syers 1976)
- Stable forms can be both inorganic and organic
- Over time, we expect more P in recalcitrant organic forms

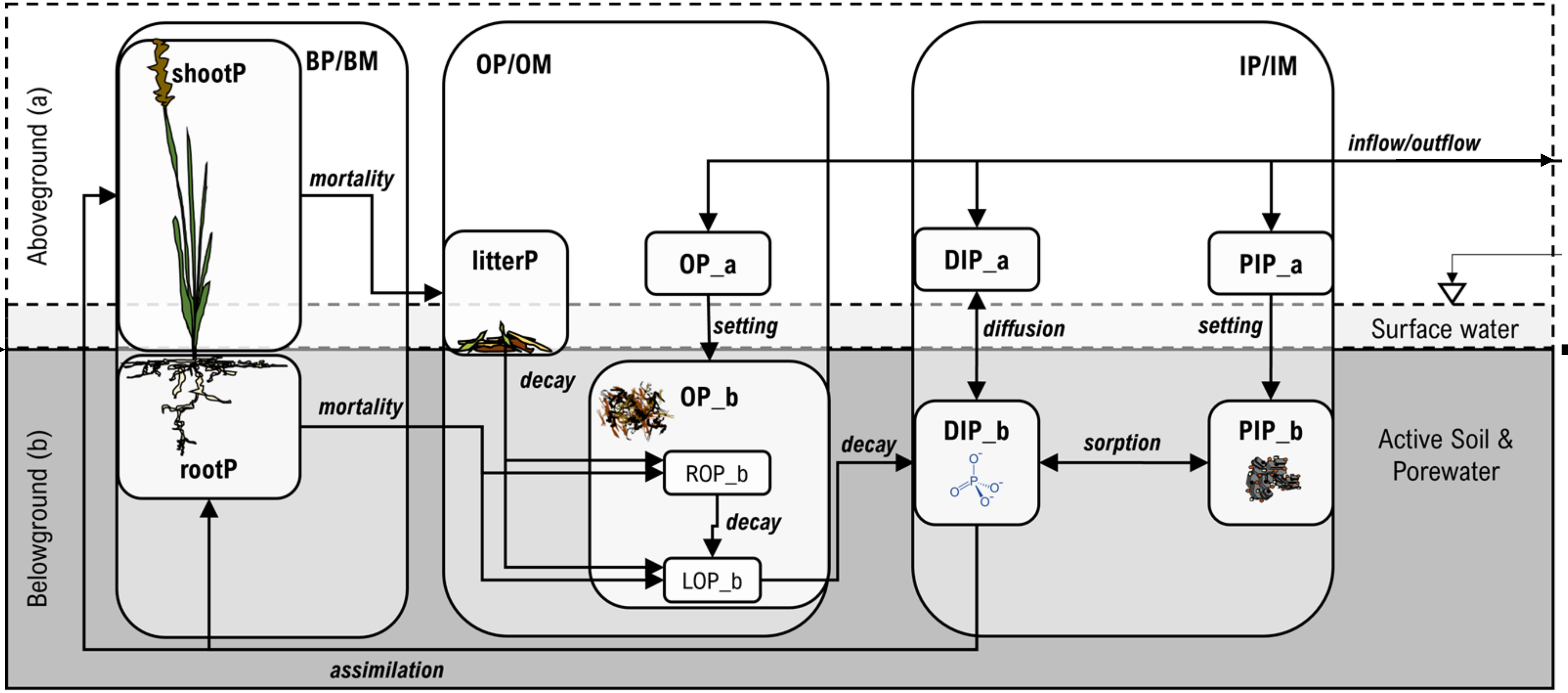
Soil Development Theory

- This theory is holding up so far in our study of restored riparian wetlands in Vermont.
- Our results suggest that soil SRP release will decline exponentially with time since farming at a mean rate of roughly 7% to 10.5% per year in our study region.
- At that rate soil SRP release would decrease by 50% after ~ 7–10 years (since farming) and by 90% after ~ 22–32 years

Wiegman et al. (2022) Biogeochemistry

Modeling P dynamics in riparian wetlands

model input parameters

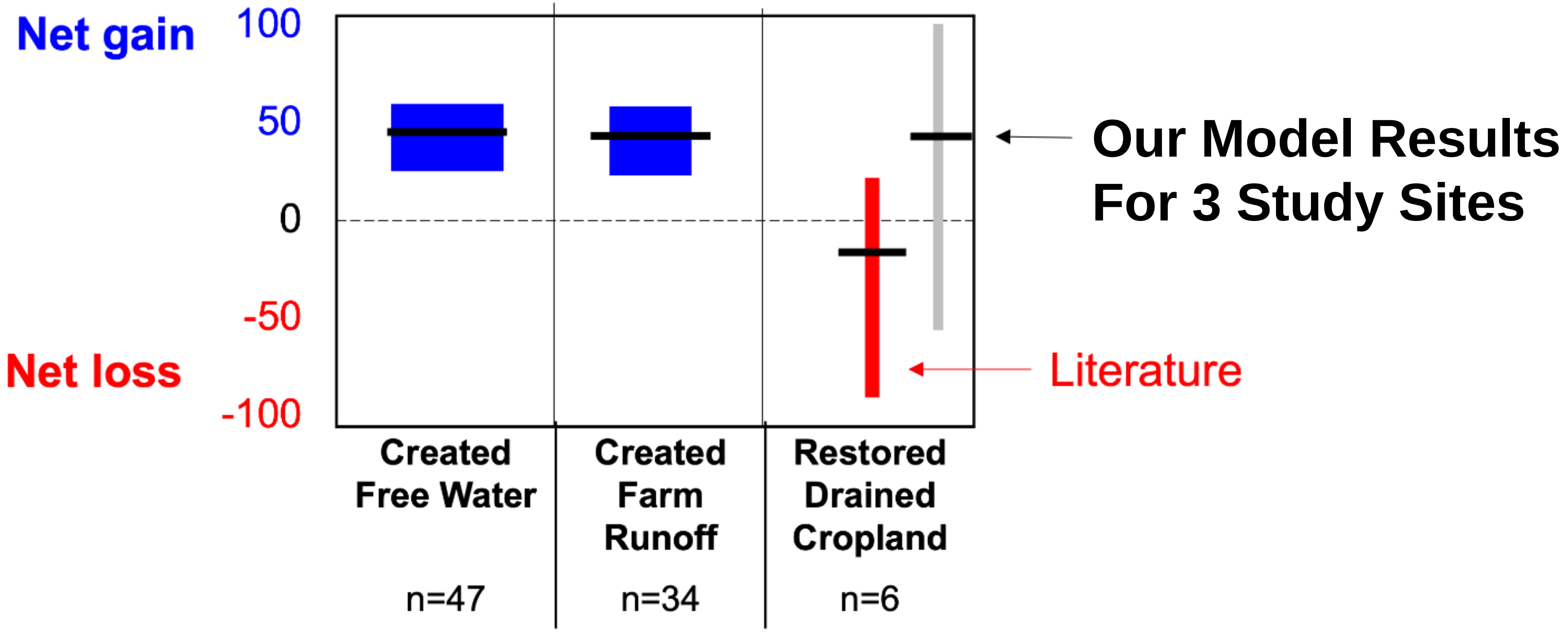


net P balances

Wiegman (2022)

Wetland Total P
Retention Efficiency

$$r(\%) = 100 * \left(1 - \frac{\text{TP out}}{\text{TP in}}\right)$$



Vertical bar = range, Width of vertical bar proportional to n, black horizontal line = median

Wiegman (2022)

Literature estimates in blue and red come from Land et al. (2016)

At this stage in their development (>10 years post-restoration), the three riparian wetlands we studied are behaving more like functioning wetlands than active farm fields

net P source

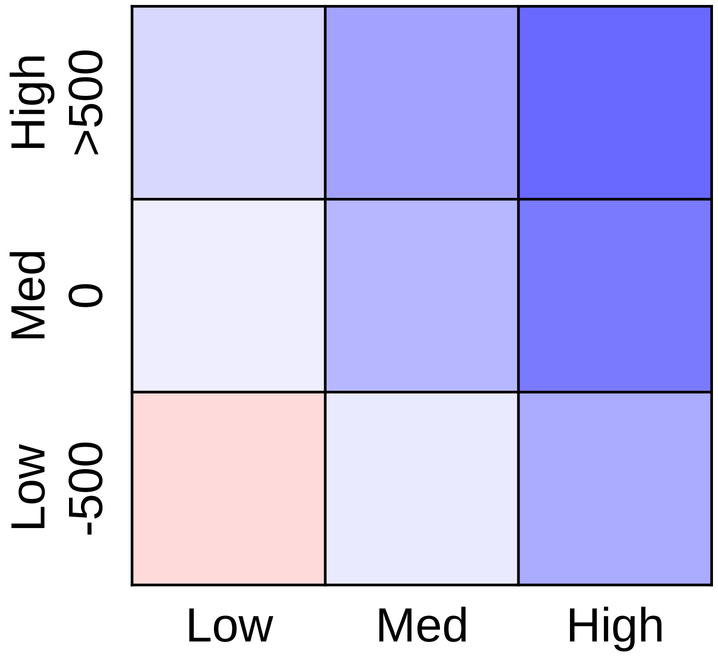
Greater erosion
Lower soil P sorption capacity
Lower organic matter

net P sink

More sediment trapping
Greater soil P sorption capacity
Greater organic matter

Restored wetlands are likely net P sinks under most combinations of plausible soil and water conditions in VT riparian zones

Soil P Storage Capacity
(mg P kg^{-1})



Inflow Concentrations**
(TSS, TP, SRP)

Net total P Balance*
(lbs. acre yr^{-1})

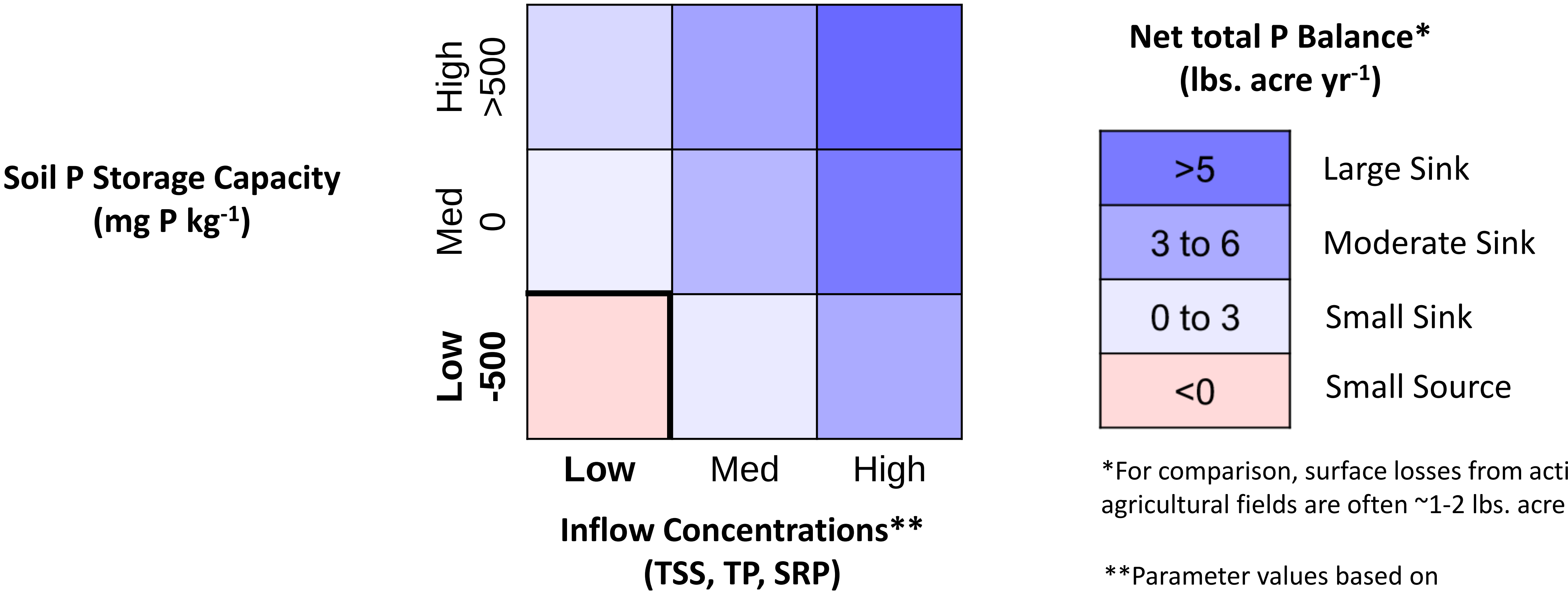
>5	Large Sink
3 to 6	Moderate Sink
0 to 3	Small Sink
<0	Small Source

*For comparison, surface losses from active agricultural fields are often ~1-2 lbs. acre yr^{-1}

**Parameter values based on representative sampling within the Vermont lake Champlain Basin

Preliminary Model Results
Wiegman, Roy et al. (in prep)

Only under the low soil P storage capacity and low inflow concentrations were wetlands net TP sources in our model



*For comparison, surface losses from active agricultural fields are often ~1-2 lbs. acre yr^{-1}

**Parameter values based on representative sampling within the Vermont lake Champlain Basin

Preliminary Model Results
Wiegman, Roy et al. (in prep)

Conclusions

- Effective retention of dissolved P is challenging in green infrastructure
- Low P sorption capacity of sand substrates, P leaching from organic substrates, and existing legacy soil P can potentially compromise water quality goals
- We can improve performance with design:
  - Geochemical augmentation of substrates in BMPs (e.g., drinking water treatment residuals)
  - Effective use of P metrics to guide material selection and site evaluation
- In some cases (e.g., riparian wetland restoration), patience may be required to observe full benefits – our goal should be reductions in P loading over decadal time scales, while creating co-benefits

Acknowledgements

- **Many co-authors have contributed to research included in this presentation, including:**
  - **Drinking water treatment residuals & bioretention** – Dr. Stephanie Hurley (UVM), Dr. Michael Ament (Minn. Pollution Control Agency), Dr. Yongping Yuan (EPA), Mark Voorhees (EPA), Eric Perkins (EPA), Andrea Traviglia (EPA)
  - **Stormwater gravel wetlands** – Marcos Kubow (UVM), Donna Rizzo (UVM), Andres Torizzo (Watershed Consulting LLC), Nisha Nadkarni (Watershed Consulting LLC)
  - **Riparian wetland restoration** – Dr. Adrian Wiegman (USDA ARS), Dr. Rebecca Diehl (UVM), Dr. Kristen Underwood (UVM), Dr. Breck Bowden (UVM), Harrison Myers (UVM), Maya Fein-Cole (UVM), Tiffany Chin (UVM), Dr. Don Ross (UVM), Isabelle Augustin (UVM), Venesa Perillo (Instituto Argentino de Oceanografía)

and more…

Acknowledgements

- This research was supported by:
  - EPA RARE Program (2 grants)
  - Lake Champlain Sea Grant
  - Lake Champlain Basin Program
  - USDA NRCS
  - Vermont DEC
  - Gund Institute for Environment

Questions?

- **Contact:** Eric Roy, eroy4@uvm.edu

Nutrient Cycling & Ecological Design Lab
Team Photos