National Research Program
Reston, VA

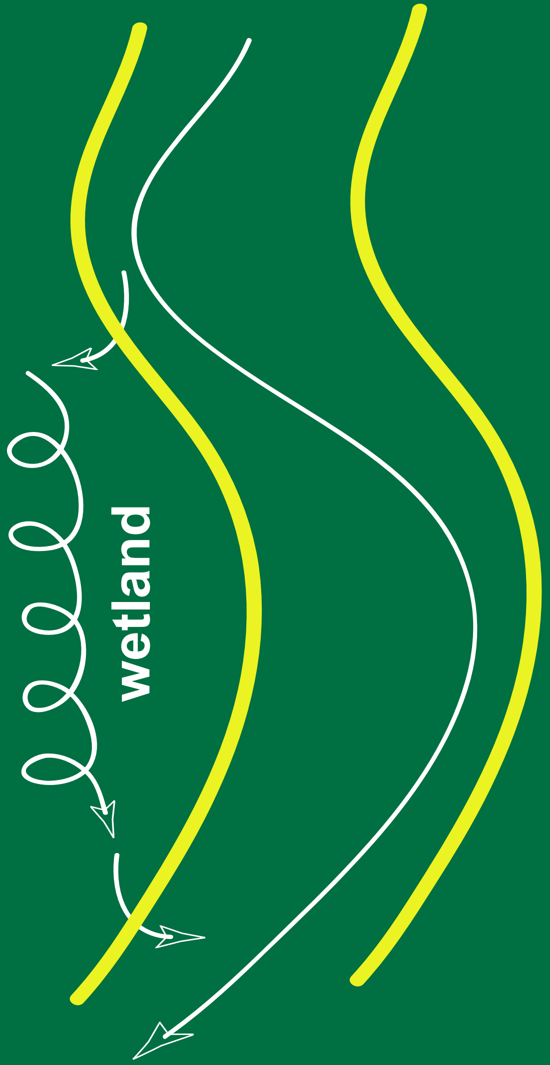
Nutrient transport and retention in wetland ecosystems

Greg Noe

Wetland nutrient processing

What controls
the transport and retention
of nutrients
in wetland hydroscapes?

Case studies:
Everglades & floodplains



Everglades is naturally oligotrophic, P starved

Flat, limestone basin – no terrigenous P loading

P enrichment

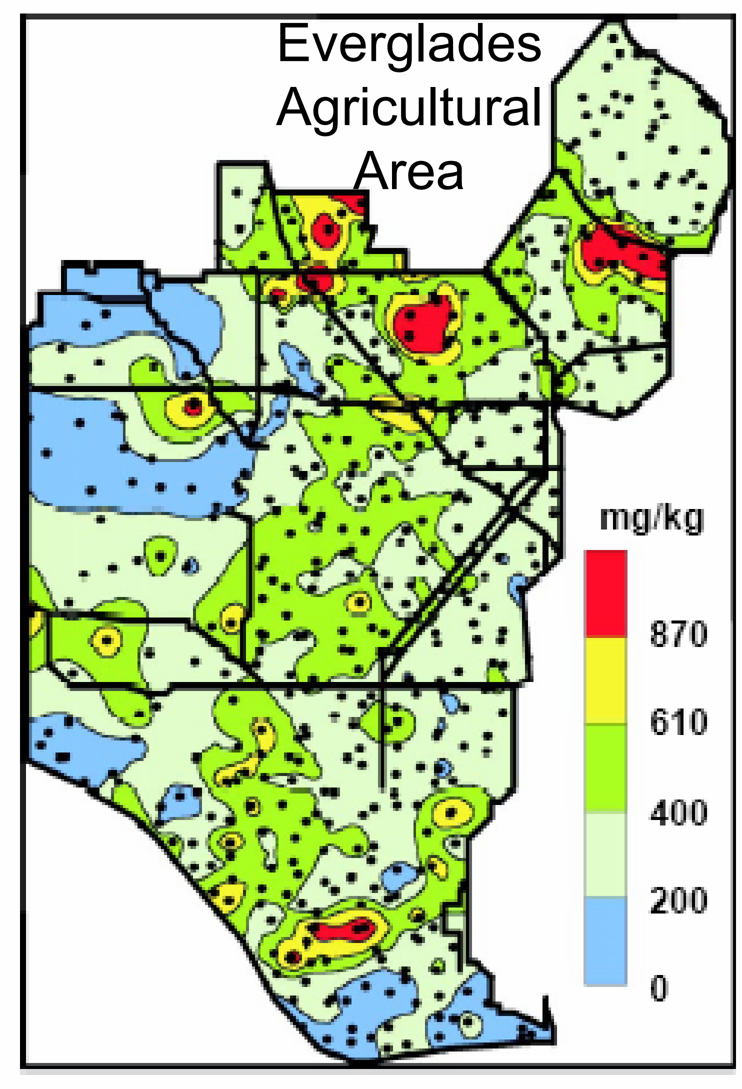
Decades of P loading from agricultural and urban lands

WCA's annual P load
Natural: 129 Mg/yr (11 upstream)
1990s: 376 Mg/yr (258 upstream)
(Davis 1994)

→ P accumulation, large changes in upstream ecosystem

Also hydrologic changes

USGS



South Florida Ecosystem Assessment, EPA 2000

Oligotrophic wet prairie/slough

Oligotrophic *Cladium*

Enriched *Typha*

Drastic changes to ecosystem structure and function

Everglades Forever Act:
“no imbalance in the flora or fauna”

Plentiful research on individual ecosystem component responses along P-enrichment gradient (SFWMD, UF, Duke, FIU)

→ Ecosystem approach

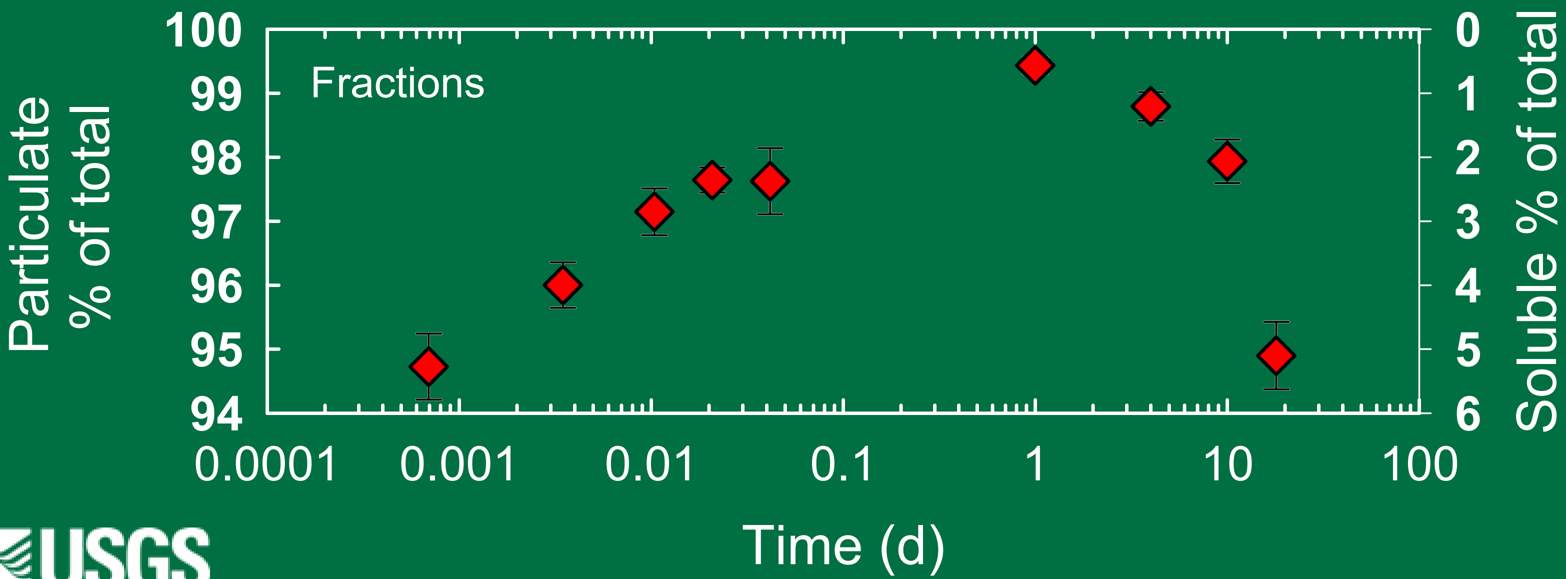
Research questions

- What is natural P cycling in oligotrophic Everglades?
  → ^{32}P radiotracer addition
- What level of P enrichment causes ecological changes?
  → Experimental dosing of P
- How does ecosystem change with P enrichment?
  → Whole-ecosystem P budgets
- How fast will P spread downstream?
  → Particulate P transport

- What is natural P cycling in oligotrophic Everglades?
  → ^{32}P radiotracer addition

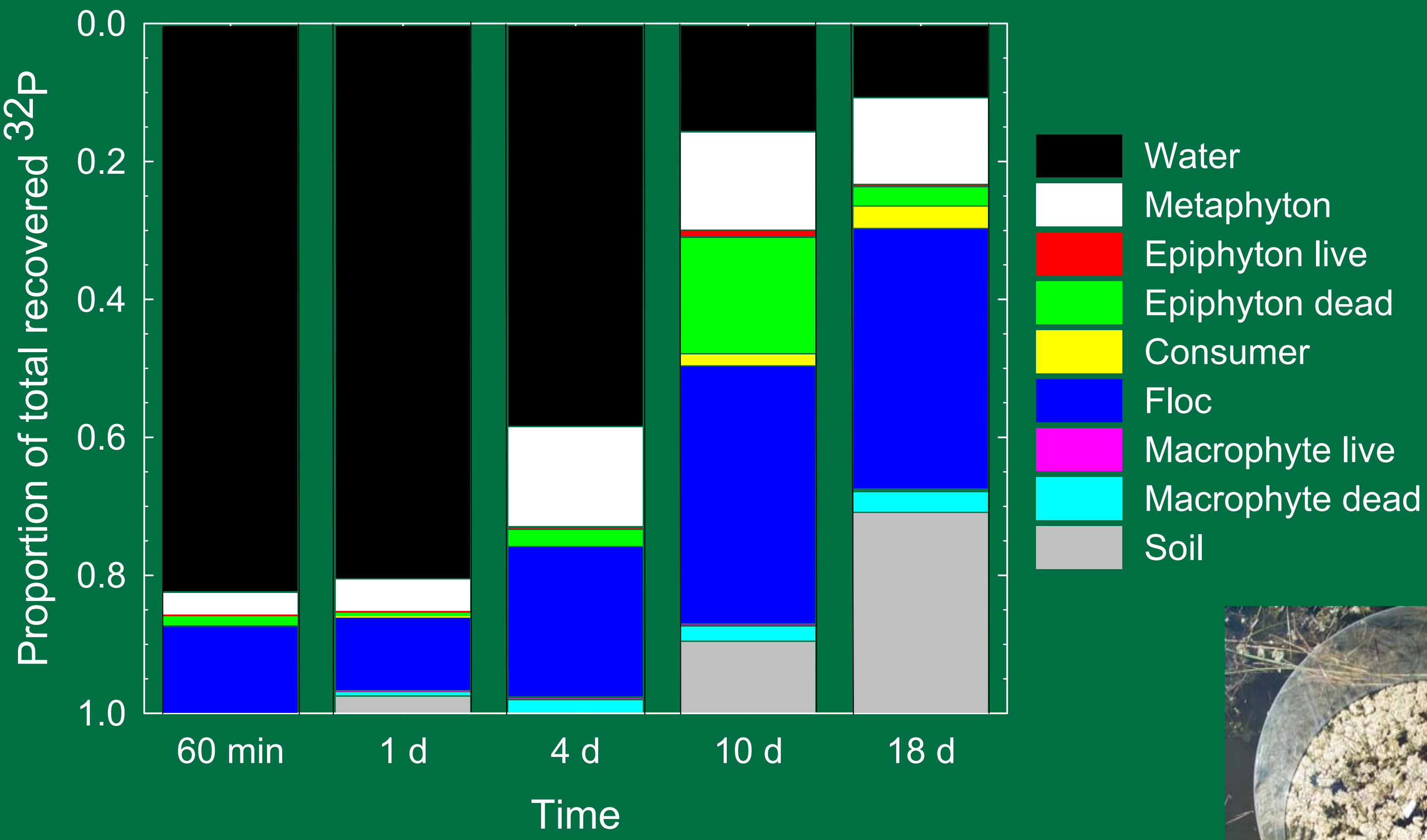
$^{32}PO_4$ added to 6 1-m^2 mesocosms

Initial P uptake by suspended particles



Noe et al. 2003. *Freshwater Biology*

^{32}P partitioning



P → particles → periphyton + floc → soil

- What level of P enrichment causes ecological changes?

→ Experimental dosing of P

3 FIU flow-through flumes in ENP, each w/ 4 100-m channels

0, 5, 15, and 30 µg/L PO_4

5 yrs dosing

Noe *et al*. 2002. *Biogeochemistry*
Gaiser *et al*. 2004. *Water Research*
Gaiser *et al*. 2005. *J. Env. Qual.*

Flume P retention (after 1 wet season)

	% Retention	
Treatment (μg L^{-1})	Mean	Range
5	24	10 to 40
15	8	-2 to 24
30	8	4 to 15

% Retention: g P recovered in flume / g P dosed

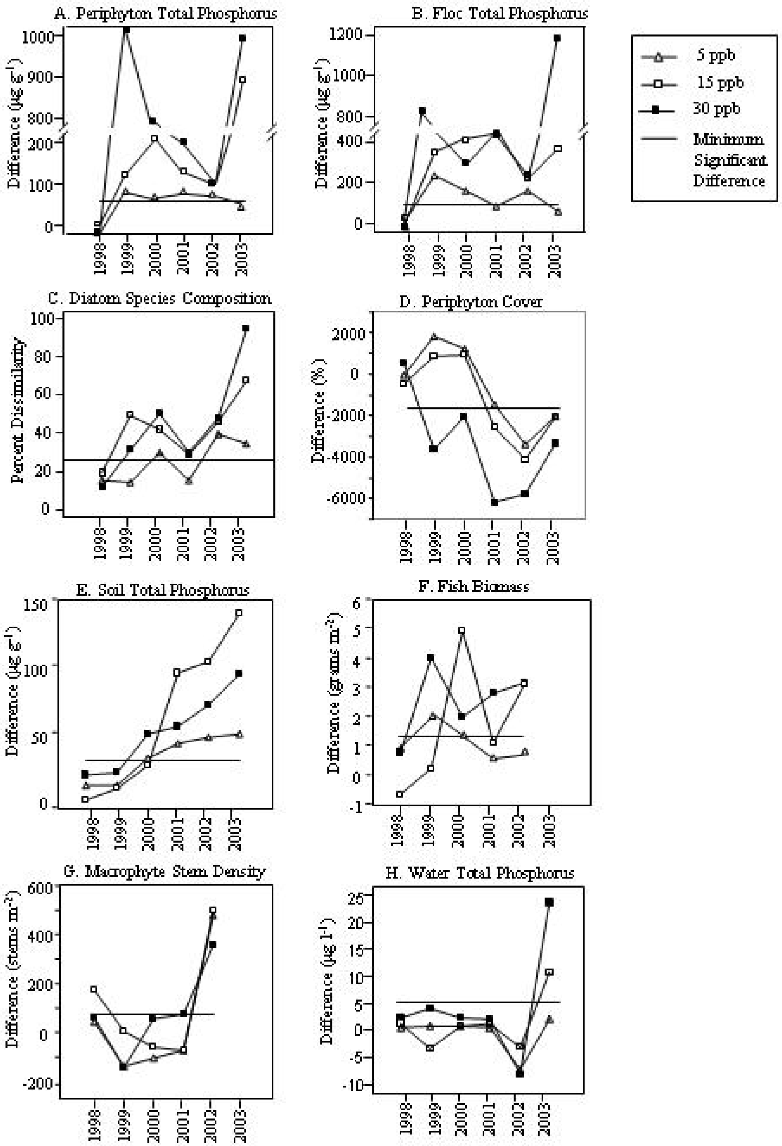
→ but most P exported

Cascade of responses through ecosystem:

1st: Periphyton
2nd: Floc
3rd: Consumers
4th: Soil
5th: Macrophytes
6th: Water

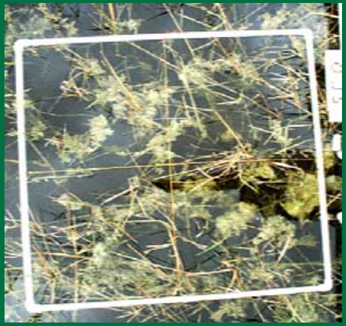
→ microbes respond first, water last

Figure 2



Site B - High Dose - Upstream

Dose Day 1



Dose Day 180

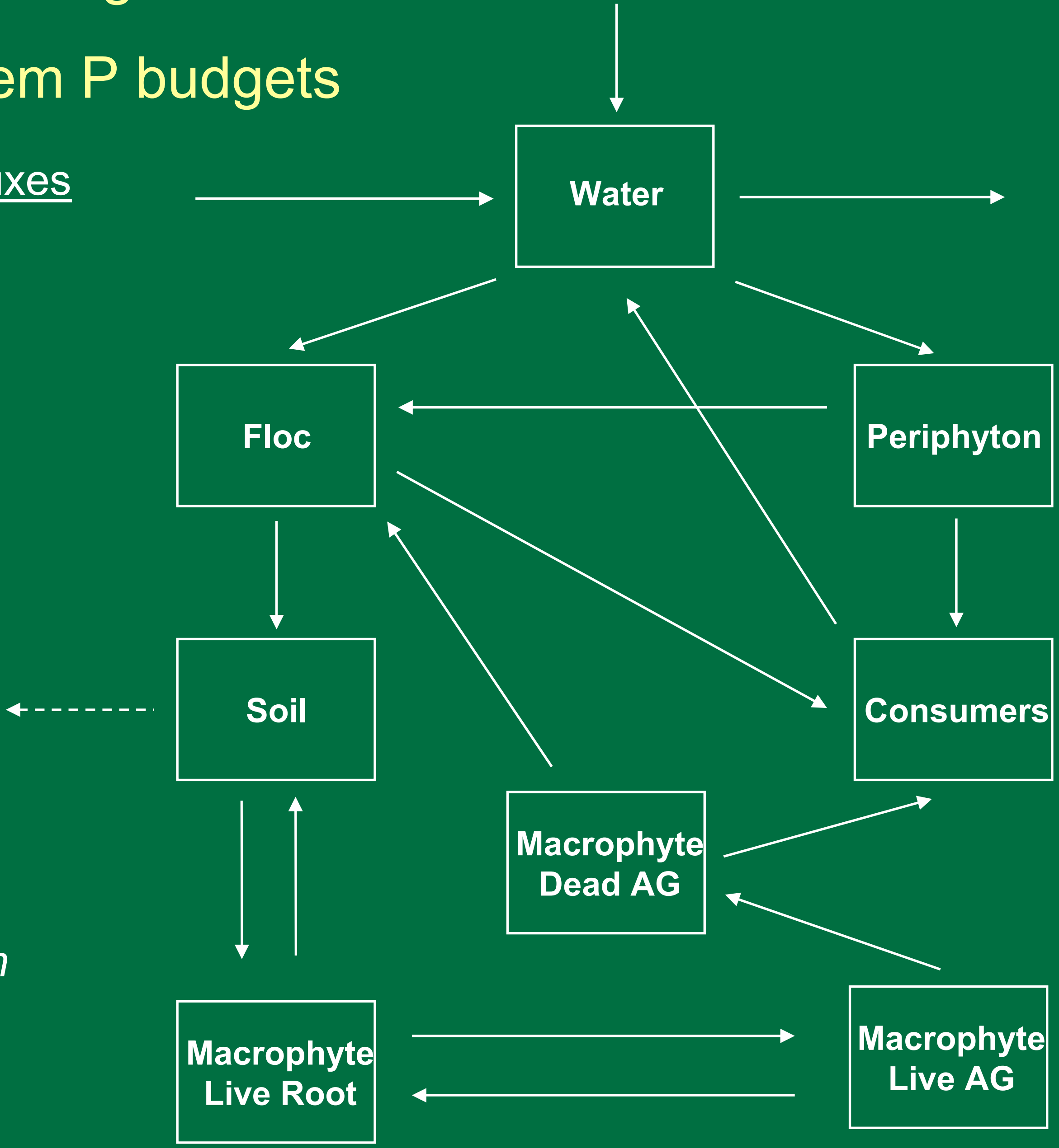
- How does ecosystem change with P enrichment?

→ Whole-ecosystem P budgets

General model of P pools and fluxes
Steady state, mass balance
Time step = 1 yr
Arrows are dominant, net fluxes
365 day hydroperiod

Parameterization:
Literature, unpublished, and ongoing research
Entire Everglades
System-specific budgets

Ecosystems:
Oligotrophic wet prairie
Oligotrophic *Cladium*
Partially enriched *Typha/Cladium*
Enriched *Typha*



Water

Floc

Periphyton

Soil

Consumers

Macrophyte Dead AG

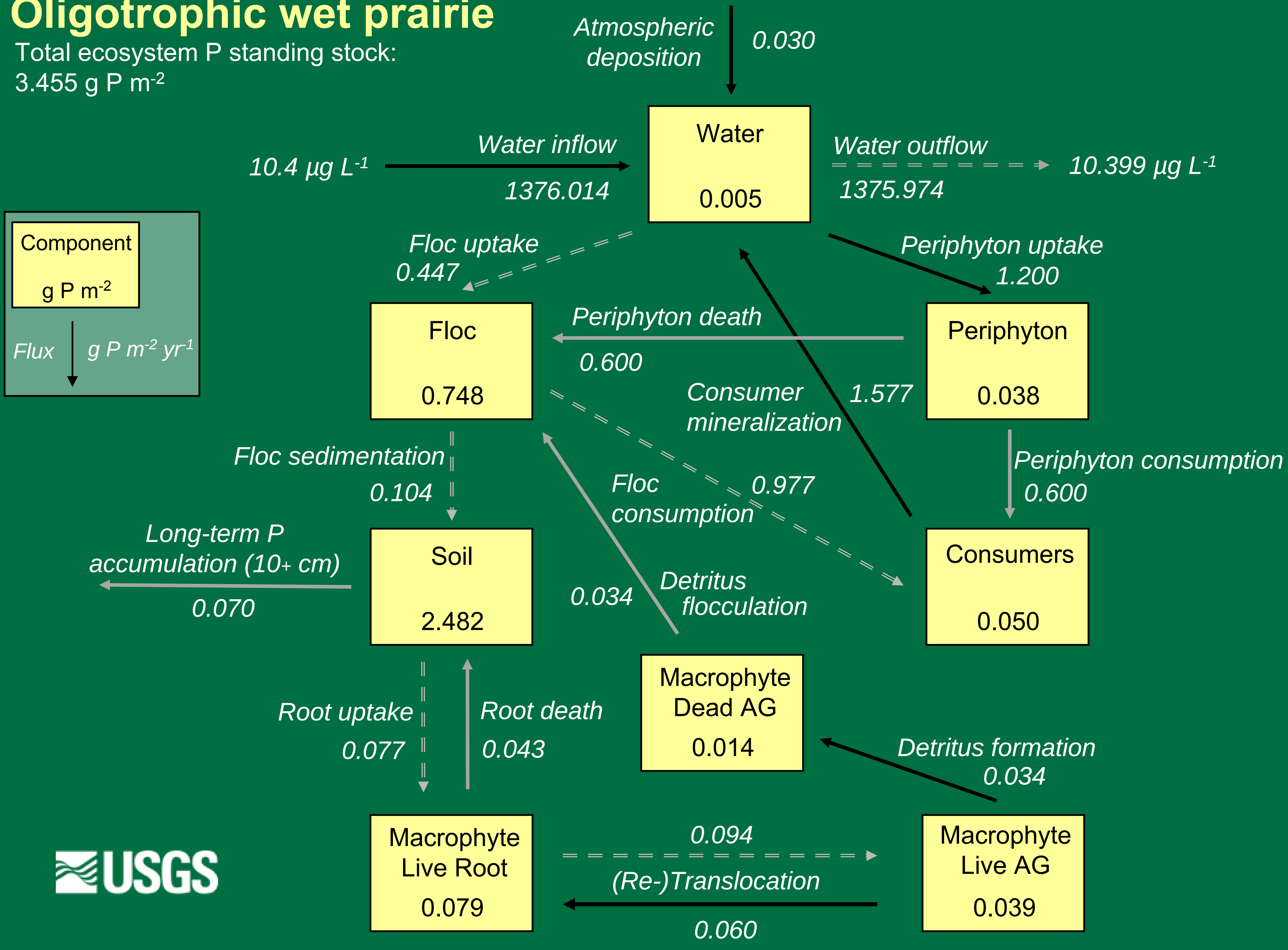
Macrophyte Live Root

Macrophyte Live AG

Noe & Childers 2007. *Wetl Ecol Manag*.

Oligotrophic wet prairie

Total ecosystem P standing stock:
3.455 g P m^{-2}



Component
g P m^{-2}

Flux
g P m^{-2} yr^{-1}

Atmospheric deposition
0.030

Water
0.005

Water inflow
10.4 µg L^{-1}
1376.014

Water outflow
1375.974
10.399 µg L^{-1}

Floc uptake
0.447

Periphyton uptake
1.200

Floc
0.748

Periphyton death
0.600

Periphyton
0.038

Consumer mineralization
1.577

Floc sedimentation
0.104

Floc consumption
0.977

Periphyton consumption
0.600

Long-term P accumulation (10+ cm)
0.070

Soil
2.482

Detritus flocculation
0.034

Consumers
0.050

Macrophyte Dead AG
0.014

Root uptake
0.077

Root death
0.043

Detritus formation
0.034

Macrophyte Live Root
0.079

(Re-)Translocation
0.094
0.060

Macrophyte Live AG
0.039

USGS

Plant P mining

Macrophyte detrital P flux (g P m^{-2} yr^{-1}):

Wet prairie
0.034
(1% of soil P)

Cladium
0.232
(8% of soil P)

→

Cladium/Typha
1.101
(20% of soil P)

→

Typha
1.589
(22% of soil P)

WCA-2A annual load:

Cladium/Typha + *Typha* macrophyte mining flux	~ 110 Mg P
External surface water input (2002)	18 Mg P

Large quantity of P leached to microbes and surface water
(Davis *et al*. 2006, *Hydrobiologia*)

USGS

→ internal eutrophication

Phosphorus in the Everglades: Too much of a good thing

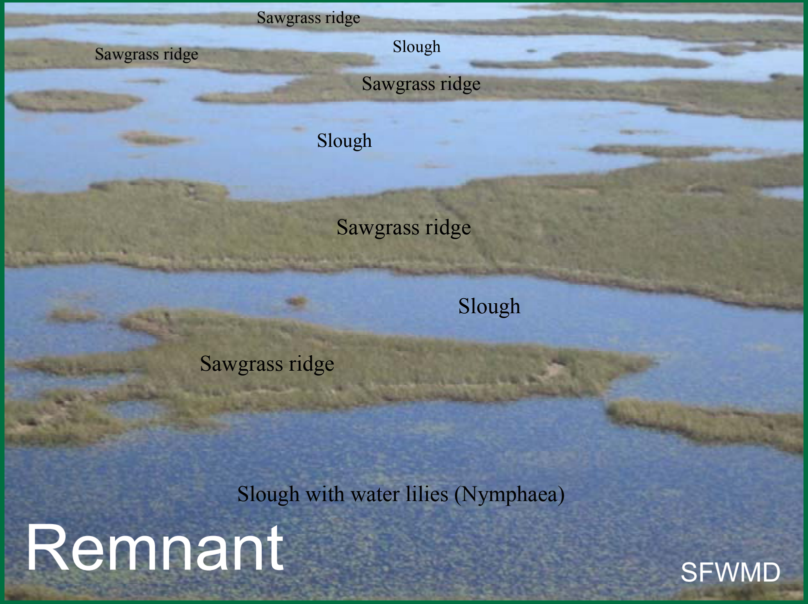
- PO_4 is quickly removed from water column in natural Everglades
- Low-level additions of PO_4 change the ecosystem
- Microbial ecosystem components (periphyton, floc) control P cycling in the short term
- Macrophytes become much more important to P cycling following P enrichment

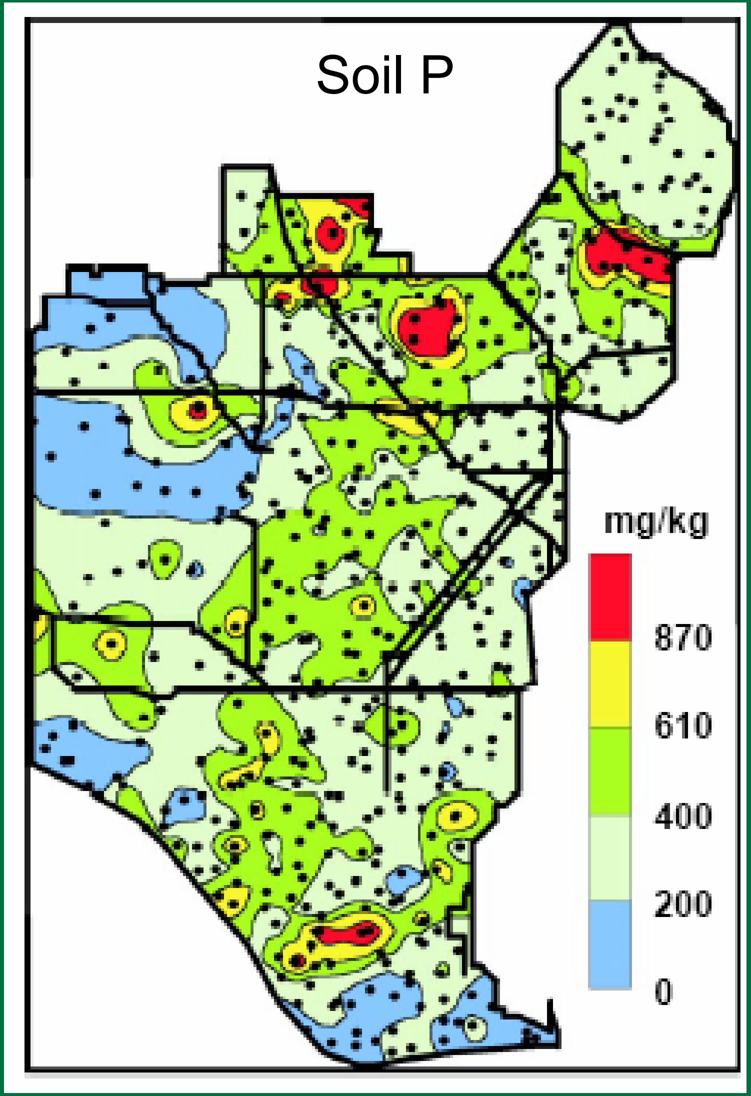
- How fast will P spread downstream?

→ Particulate P transport

Clear water column of Everglades

Regional and Ridge vs. Slough differences in suspended particles





South Florida Ecosystem Assessment, EPA 2000

Research questions

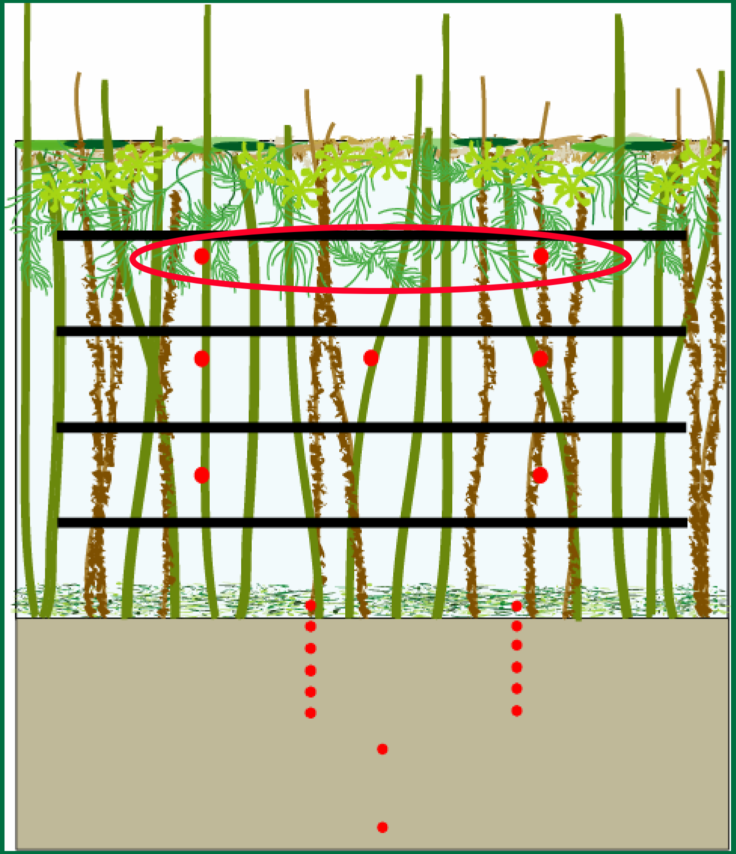
- How important are particles vs. solutes to P cycling and transport?

- What are the physical and biogeochemical characteristics of particles?

- Does differential particle transport maintain the characteristic ridge and slough topography of the Everglades?

Solute and particle transport: tracer studies

Dual Br^- and TiO_2 (0.3 µm) injection:
Transport, dispersion, and interception



Br^- tracer velocity retarded by 50% relative to velocity in 'dominant' water-column flow zone

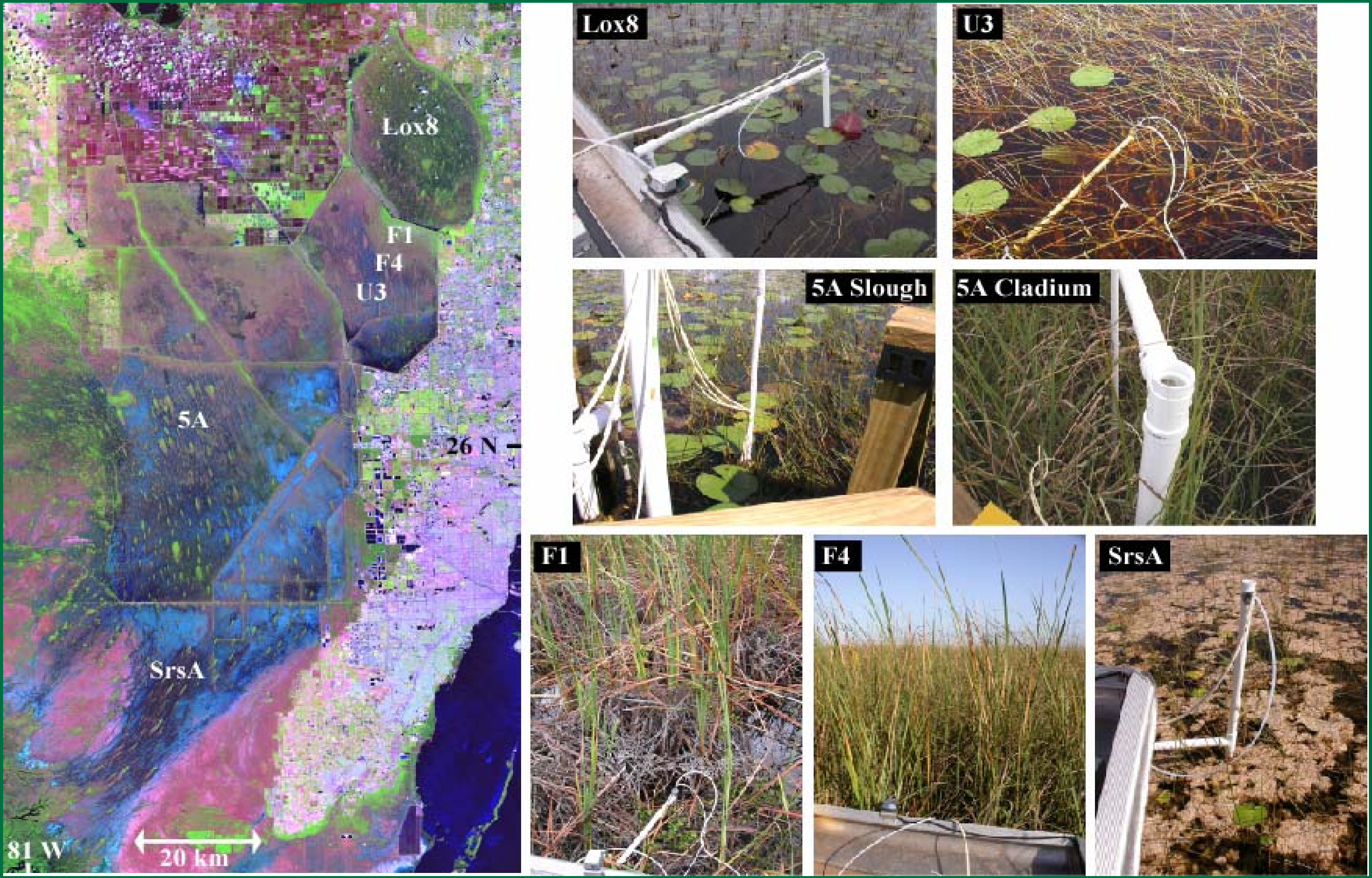
Quick exchange rate with floating vegetation (0.4 hr^{-1}), slow exchange rate with peat porewater (0.03 hr^{-1})

Very efficient particle filtration by floating vegetation (3.6 hr^{-1})

USGS

Saiers *et al.* 2003. *Geophysical Research Letters*
Harvey *et al.* 2005. *Water Resources Research*

Spatial patterns in suspended particles characteristics



Noe *et al*. *2007*. *L&O*

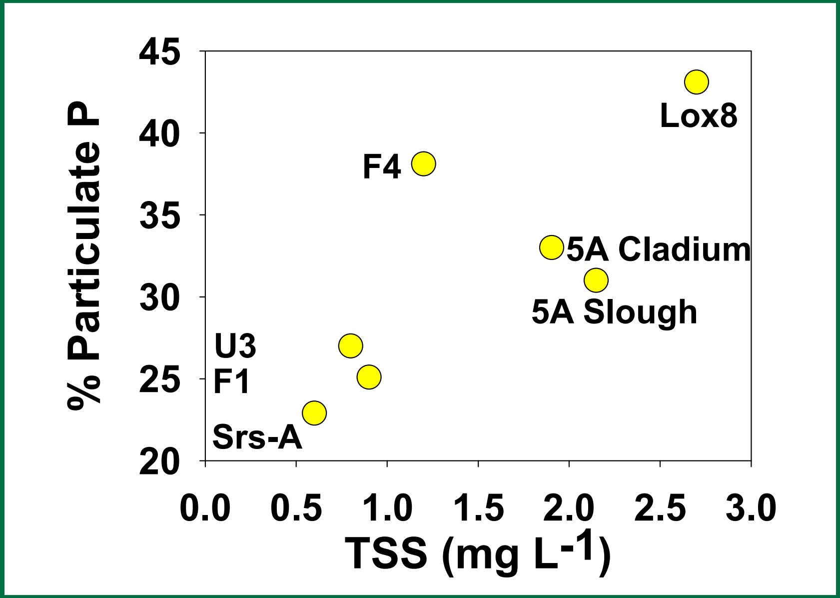
General particle characteristics

Site	Total suspended sediment (mg L^{-1})	Total particulate P (μmol L^{-1})	Total particulate N (μmol L^{-1})	Percent particulate P	Percent particulate N	Particulate N:P (molar)
Lox8	2.71 ± 0.09	0.19 ± 0.01	6.8 ± 0.2	43 ± 2	7 ± 0	36 ± 3
F1	0.85 ± 0.12	0.31 ± 0.02	4.8 ± 0.7	25 ± 2	3 ± 0	15 ± 1
F4	1.19 ± 0.41	0.18 ± 0.00	3.2 ± 0.1	38 ± 0	2 ± 0	18 ± 0
U3	0.81 ± 0.11	0.10 ± 0.01	3.7 ± 0.2	27 ± 0	2 ± 0	38 ± 0
5A Slough	1.90 ± 0.27	0.09 ± 0.01	6.5 ± 0.5	31 ± 3	10 ± 0	69 ± 1
5A Cladium	2.15 ± 0.30	0.11 ± 0.01	7.0 ± 0.3	33 ± 3	10 ± 1	66 ± 1
SrsA	0.69 ± 0.14	0.05 ± 0.00	3.1 ± 0.2	20 ± 2	3 ± 0	65 ± 1

TSS was low

31% of P was particulate

Particulate P was more abundant and more labile with P enrichment



USGS

Particle biogeochemical characteristics

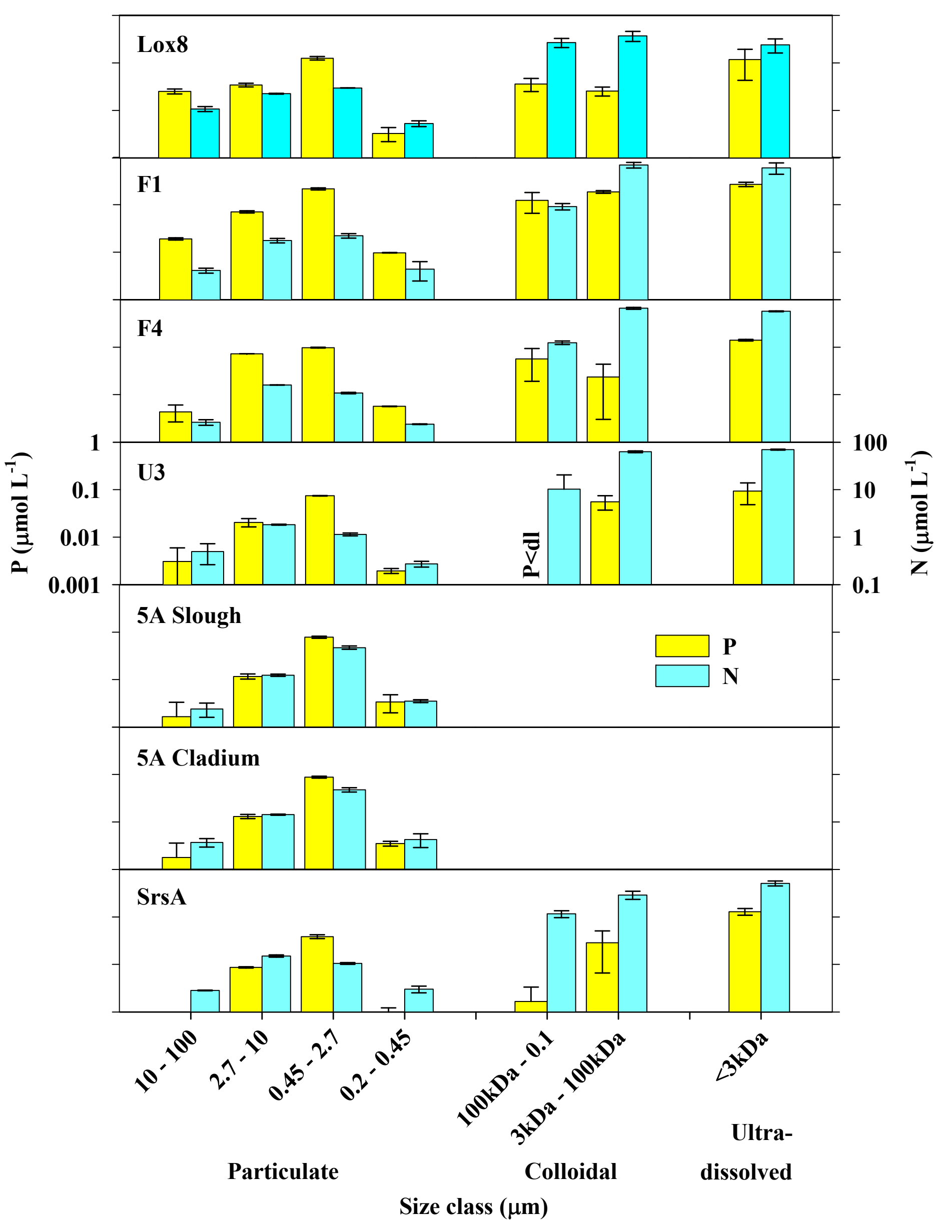
Size of most P: 0.45 to 2.7 µm

Particulate N bigger than P,
most N was colloidal

Most particulate P was acid-hydrolysable, not reactive P or refractory P

Particulate P and Fe (-) correlated

Particulate N and Ca (+) correlated



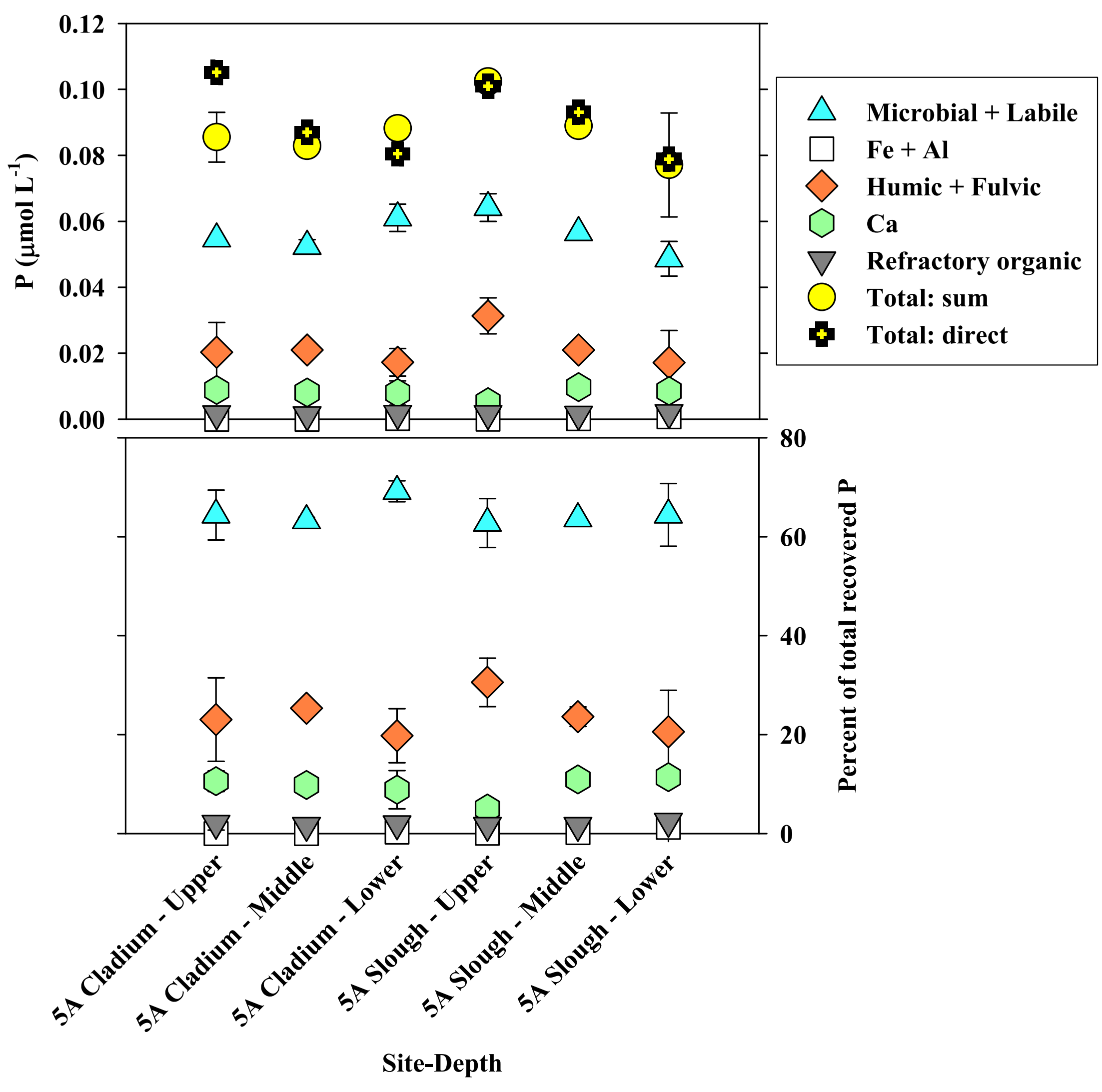
Particulate P sequential extraction: Dec 05

Most particulate P was in microbial+labile fraction

Humic+Fulvic P also an important fraction

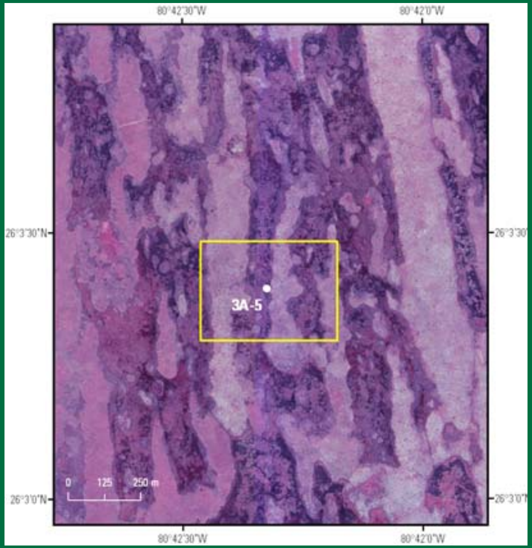
Ca P low

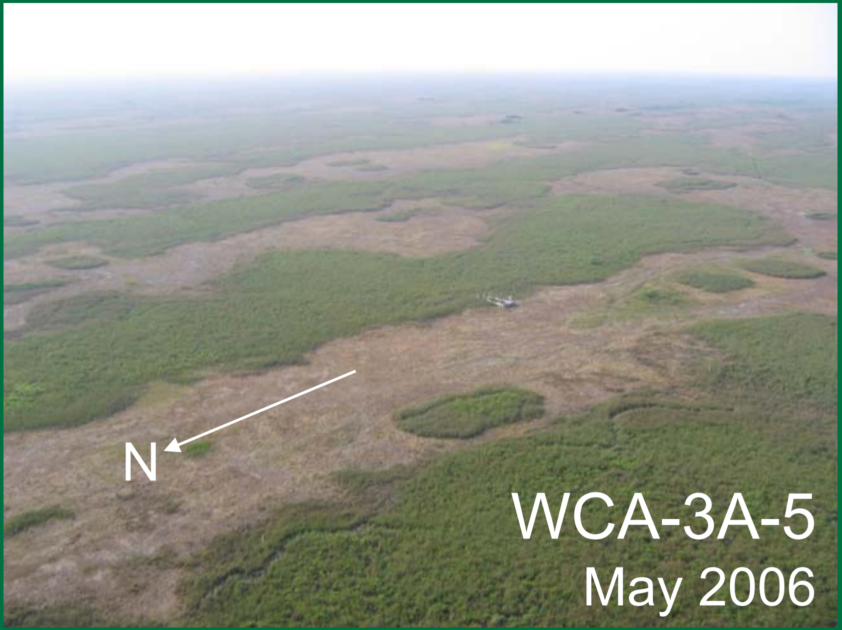
No site or depth differences



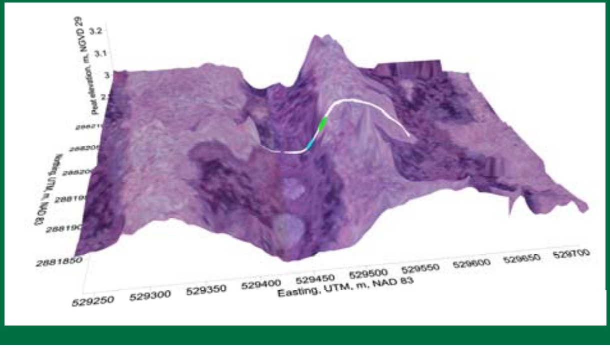
Ridge vs. Slough differences in suspended particles

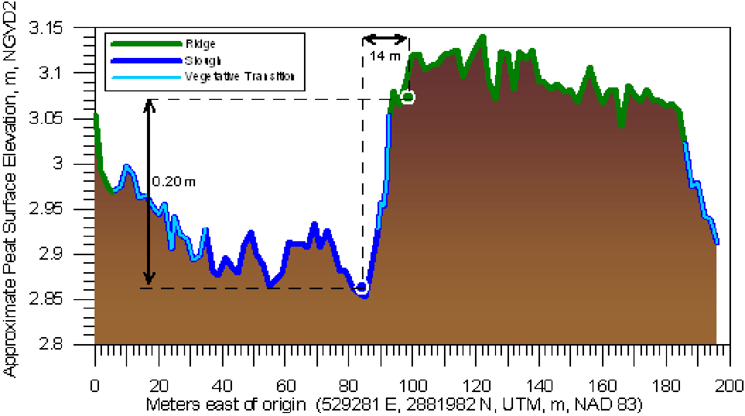
Space (ridge, slough)
Depth (upper, middle, lower)
Time (through wet season)





WCA-3A-5
May 2006





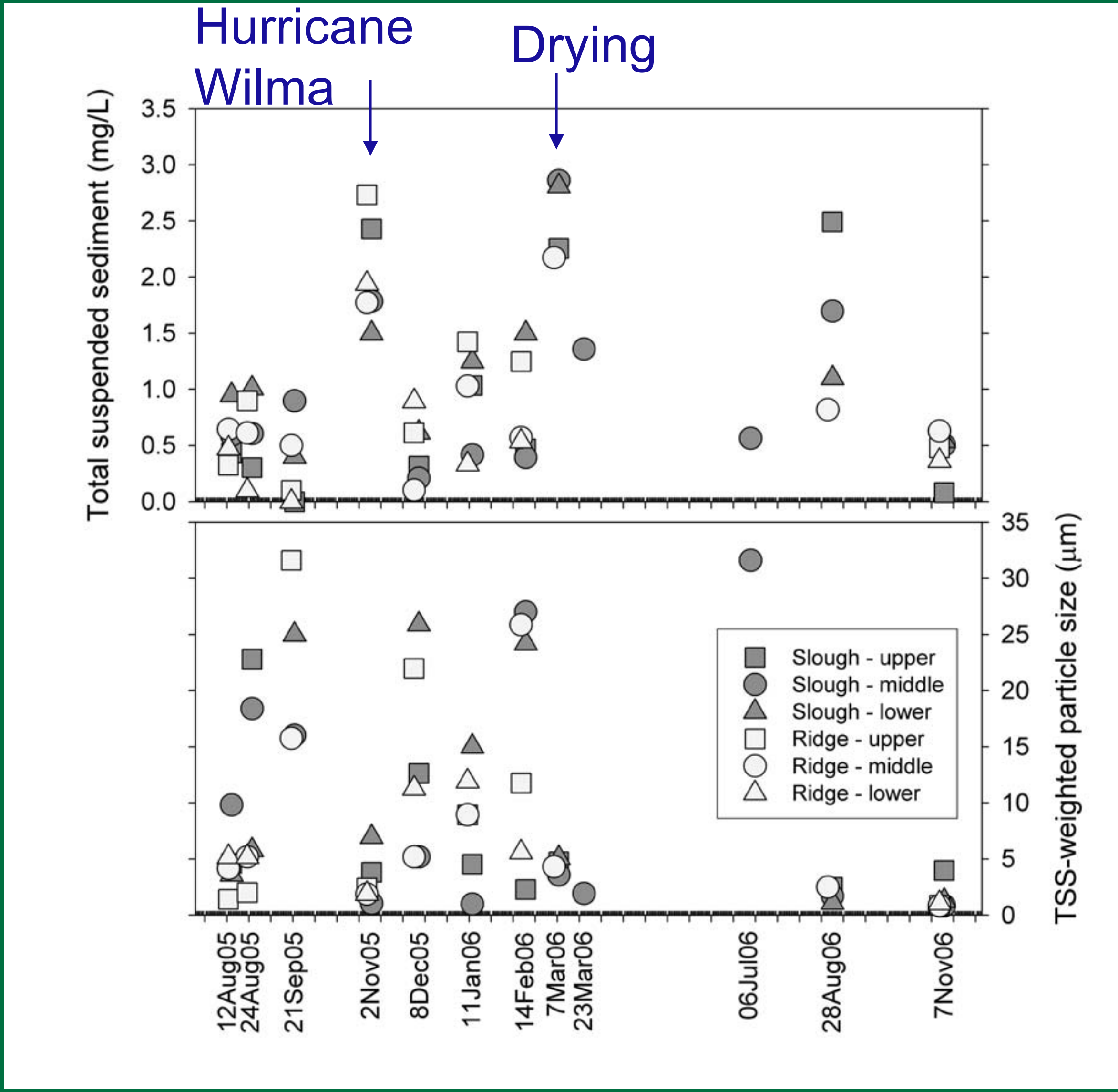
TSS

Concentration:
Time
Site*Depth interaction

Mean = 0.76 mg/L

Particle size:
Time

Mean = 9.4 µm


Hurricane Wilma

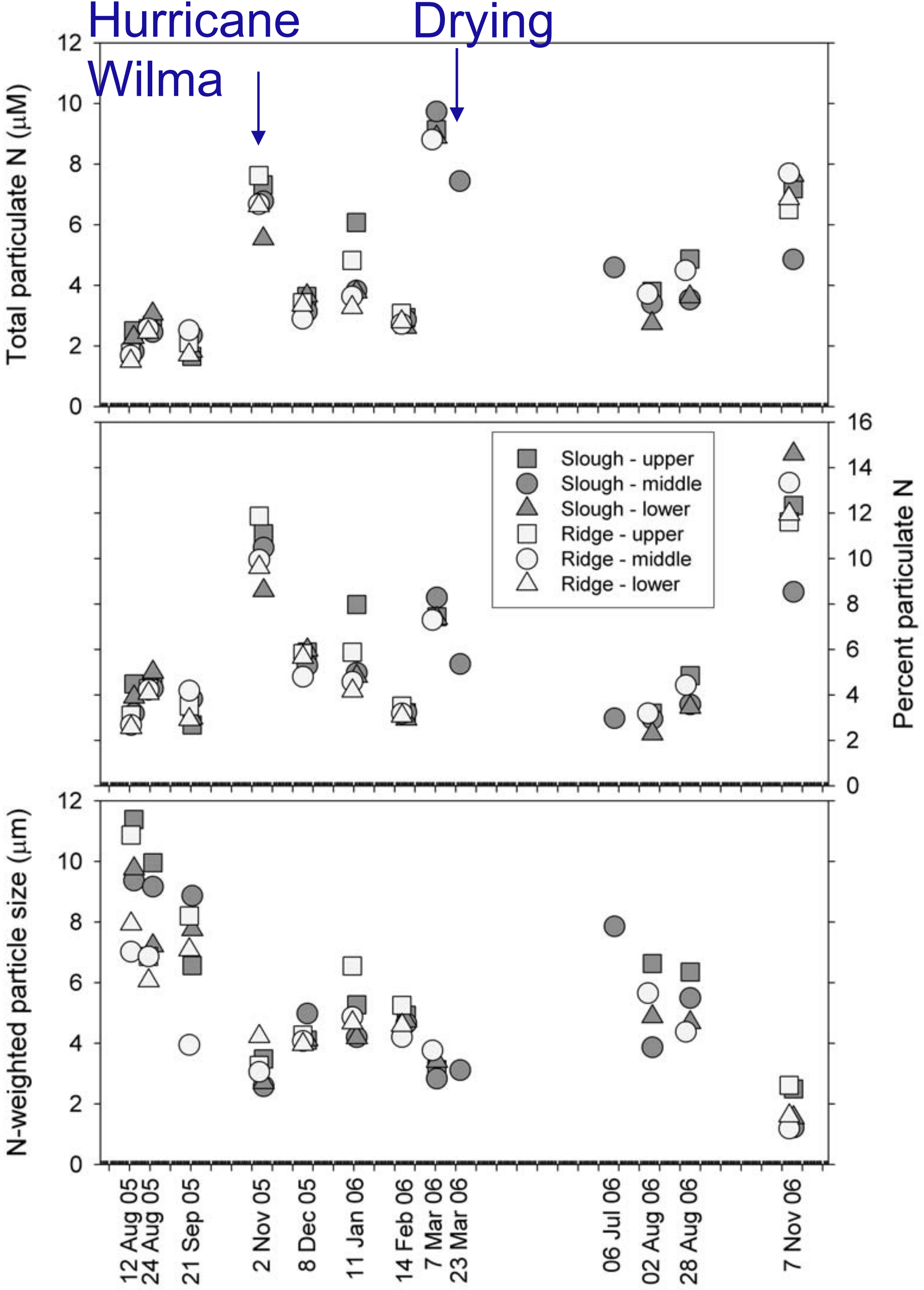
Drying

Particulate N

<u>Concentration</u>:
Time
Depth
~Time*Depth interaction
<u>Upper</u> = 4.1 µM
Middle = 3.7 µM
Lower = 3.7 µM

<u>%Particulate N</u>:
Time
Depth
~Time*Depth interaction
<u>Upper</u> = 6.4%
Middle = 5.7%
Lower = 5.8%

<u>Particle N size</u>:
Time
Depth
<u>Upper</u> = 6.0 µm
Middle = 5.0 µm
Lower = 5.1 µm



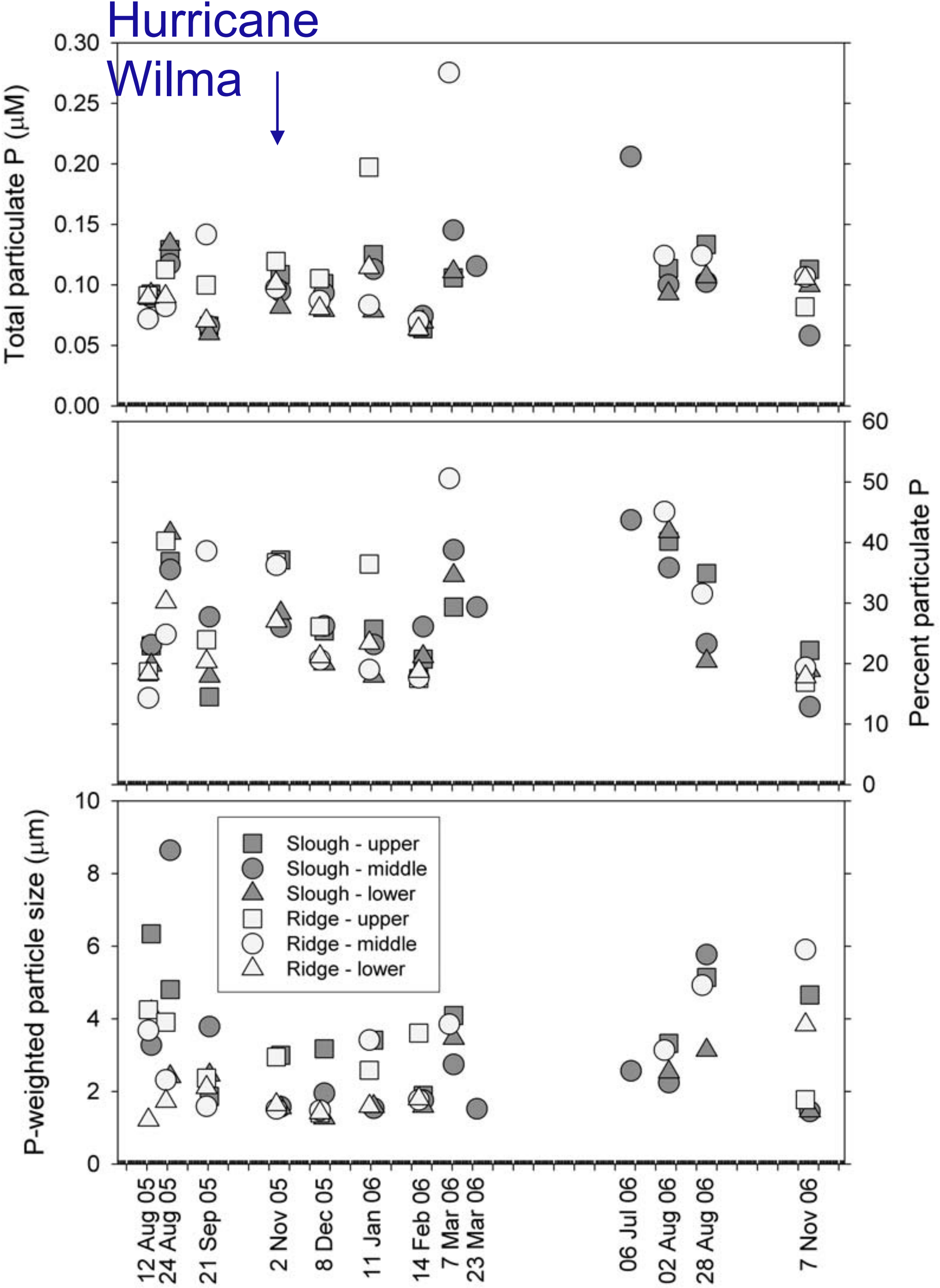
Particulate P

Concentration:
Time
~Depth
Upper = 0.104 µM
Middle = 0.090 µM
Lower = 0.088 µM

%Particulate P:
Time
Mean = 24.5%

Particle P size:
~Depth
Upper = 3.2 µm
Middle = 2.9 µm
Lower = 2.0 µm

USGS



Mass flux differences

Water flux:

Ridge = 1.4 x 10^8 cm^3
Slough = 2.9 x 10^8 cm^3
S/R = 2.06

Mass flux:

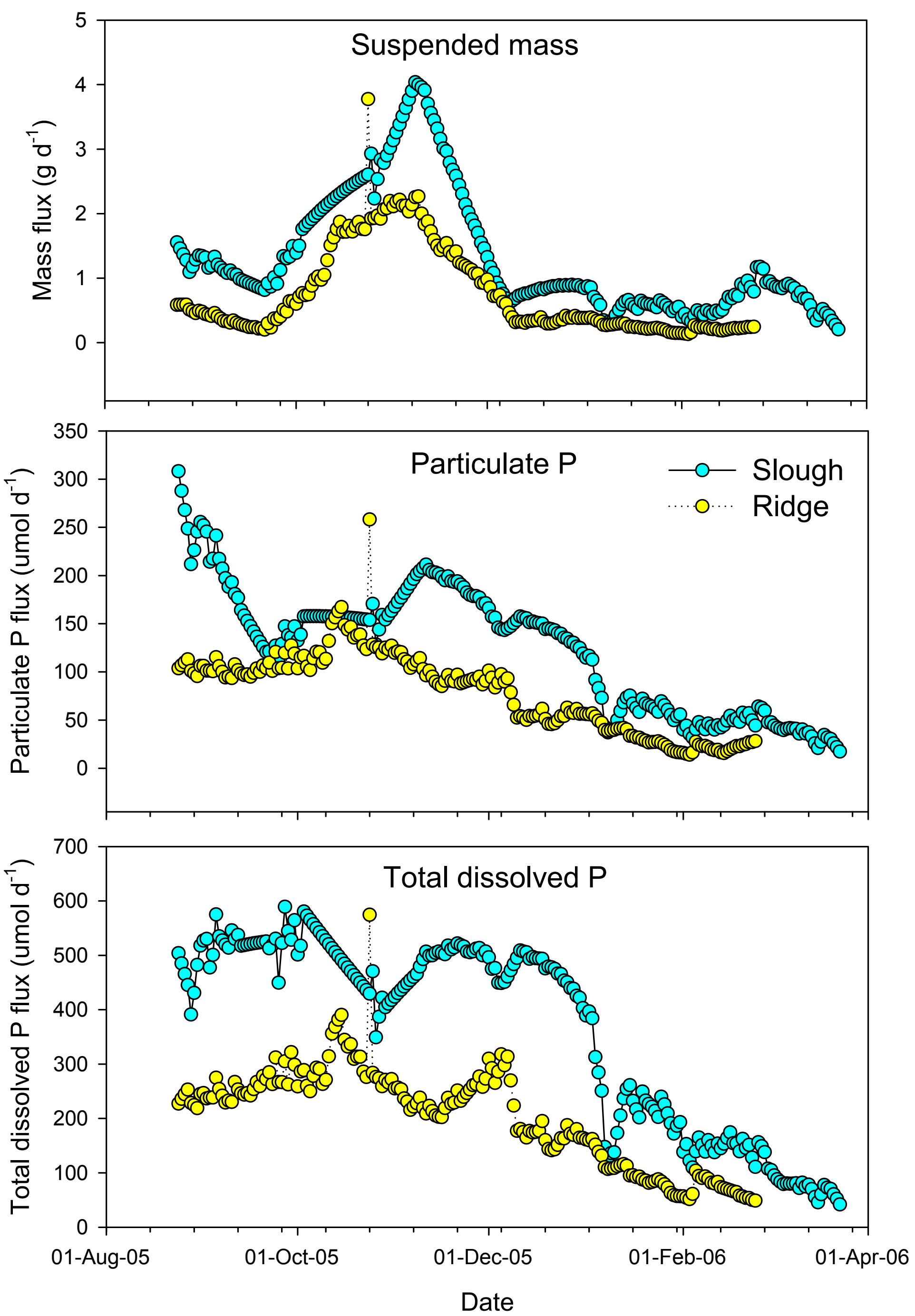
Ridge = 139 g
Slough = 281 g
S/R = 2.02

Particulate P flux:

Ridge = 14.6 mmol
Slough = 26.2 mmol
S/R = 1.79

Dissolved P flux:

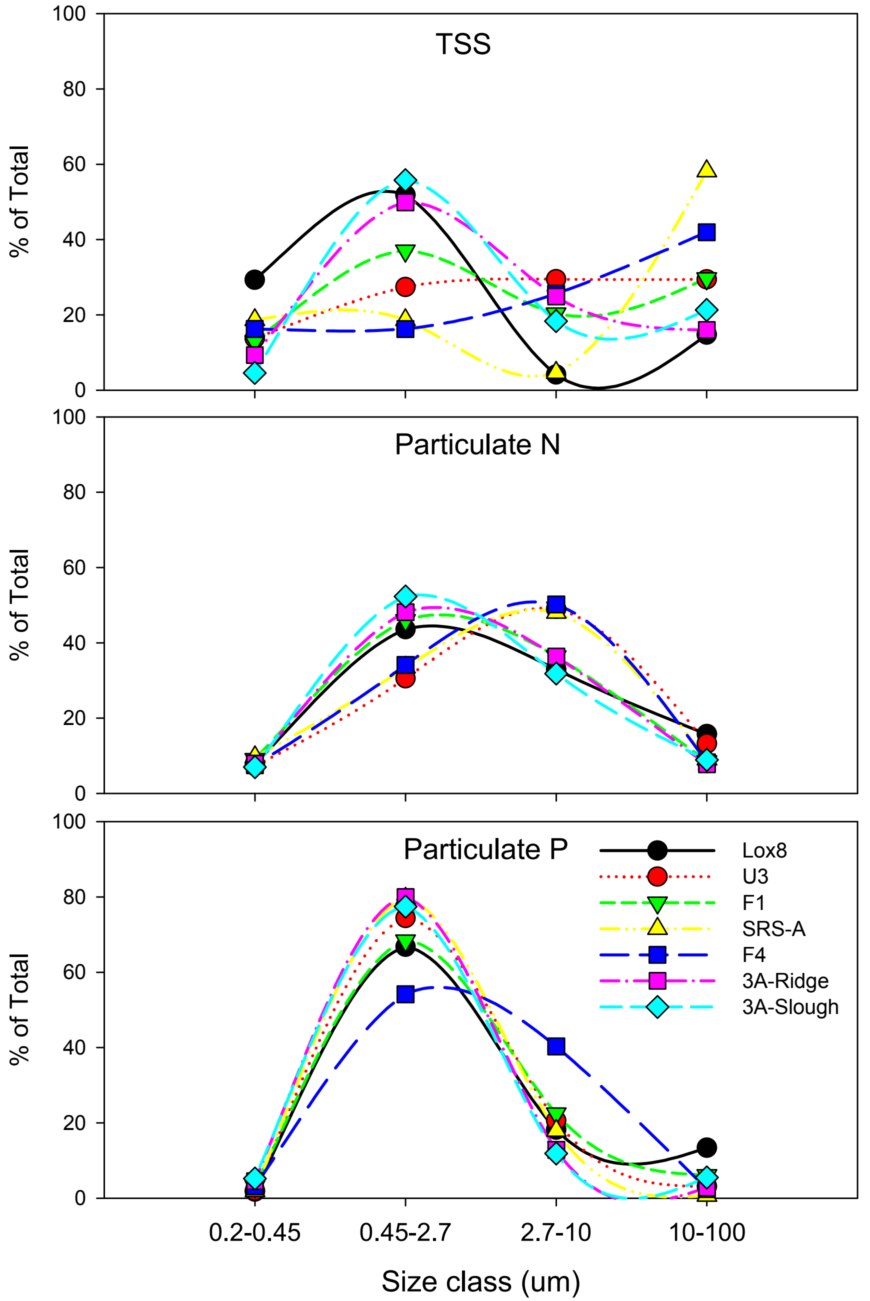
Ridge = 37.4 mmol
Slough = 76.6 mmol
S/R = 2.05



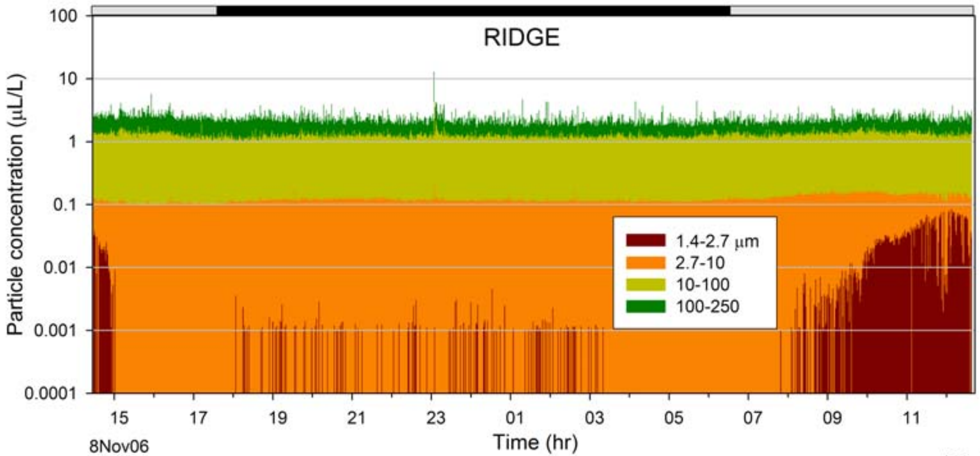
Suspended material size differences

Weighted average particle size:

TSS = 8.6 µm
Particulate N = 5.2 µm
Particulate P = 2.9 µm

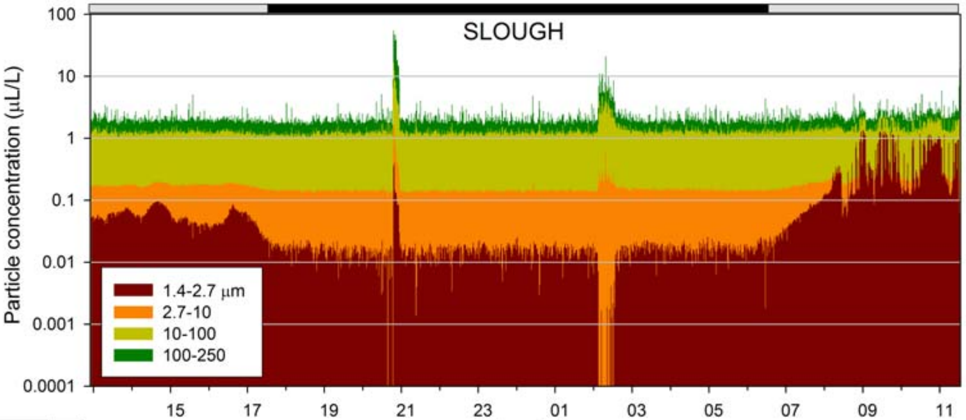


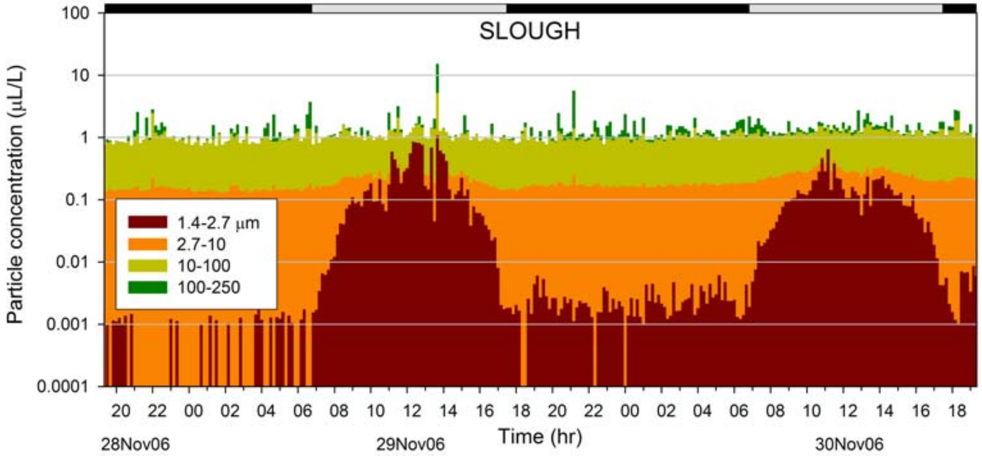
LISST-100X Suspended Sediment Analyzer



100-250 µm percent of total particle volume:

43%, 45%, 19%





100+ µm percent of total particulate nutrients:

10% of PP, 26% of PN,
P mixture of microbial and refractory organic P

Suspended particles in the Everglades

- Suspended particles are a large proportion of P in the water column, are quickest uptake component, and are intermediately labile … despite low TSS!

- P-rich particles were suspended bacteria, larger particles were more refractory

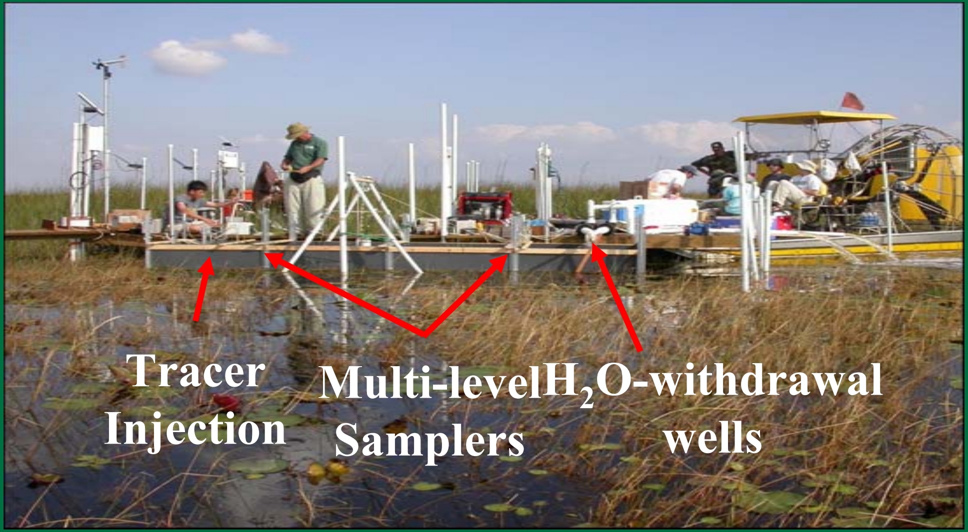
- Preliminary evidence suggests no difference in particle characteristics between ridge and slough

- Extreme flow events may be necessary to generate meaningful differences in particle mobilization, transport, and interception between ridge and slough.

- Particles have different transport characteristics than solutes

- Suspended particles must be incorporated into Everglades ecosystem models

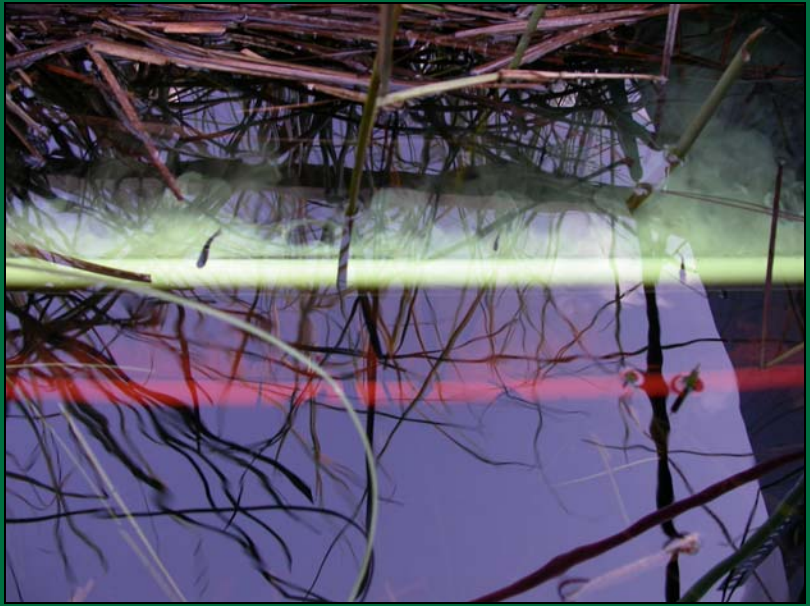
Particle tracer injections and flow enhancement experiments

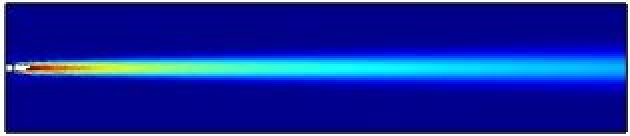


2005: Fluorescing 1 µm artificial particles

2007: Flow enhancement and mobilization of natural particles

2008: Tagging natural particles

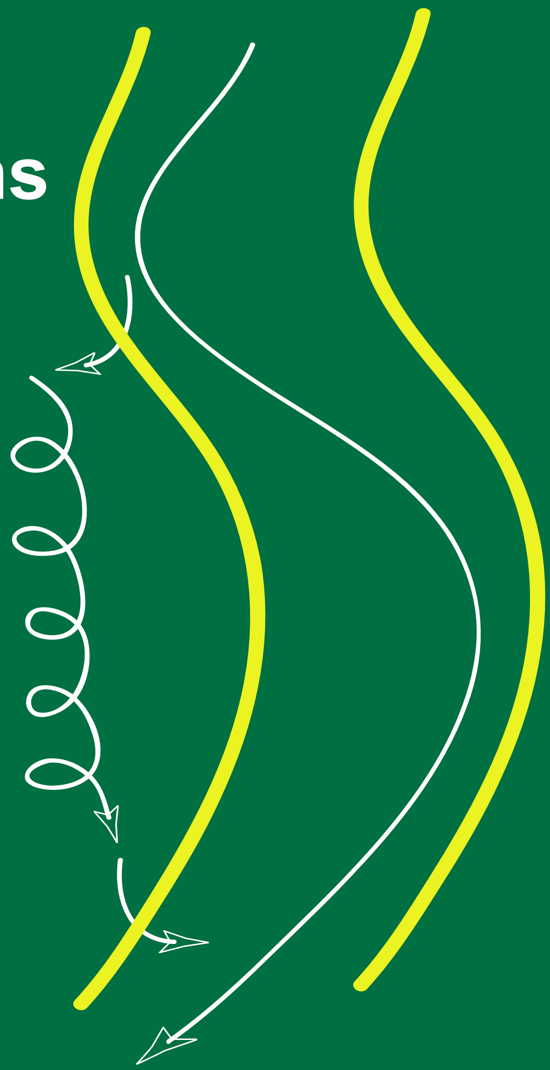




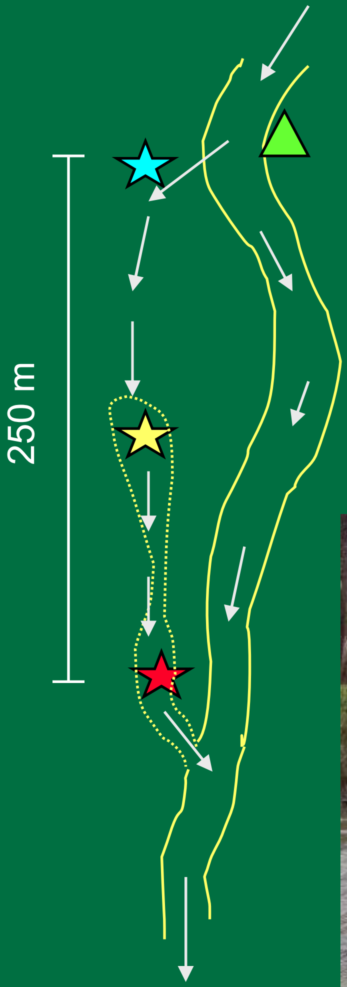
Floodplain nutrient processing

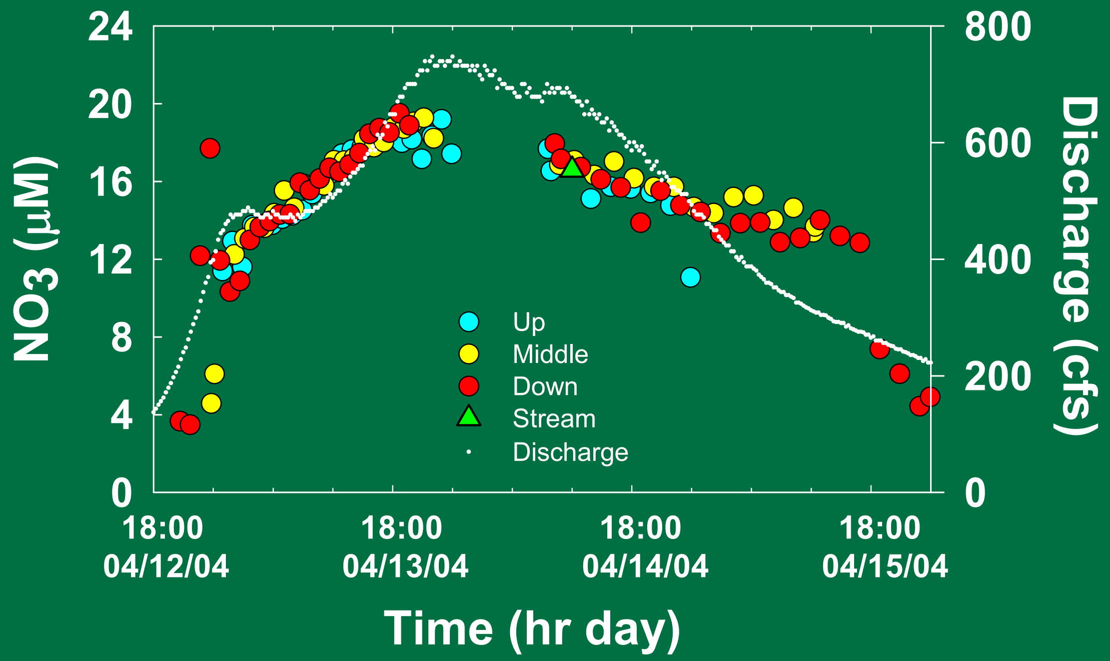
Quantifying
sinks, sources, and transformations
of nutrients in
river-floodplain ecosystems

What controls nutrient
processing?
- climate, geomorphology, hydrology?



Climate





Mattawoman Creek, MD
4th order
largely forested watershed
~ 45 min flowpath

Noe & Hupp. *In press. River Res Appl.*

	6-7 Feb 2004 (1 °C)		12-15 Apr '04 (9 °C)		29-30 Sep '04 (20 °C)		20-22 May 2005 (14 °C)	
	Concentration change	% change	Concentration change	% change	Concentration change	% change	Concentration change	% change
NO_2^- (µM)	**-0.14**	**-29**	0.00	0	0.11	33	0.05	8
NO_3^- (µM)	**-4.16**	**-16**	**-0.37**	**-2**	0.21	5	**-2.15**	**-12**
NH_4^+ (µM)	**-0.91**	**-9**	**0.33**	**8**	-0.46	-21	-0.34	-6
DON (µM)	-1.48	-16	-0.94	-4	1.89	8	**2.99**	**12**
PON (µM)	0.58	7	**3.39**	**25**	1.10	7	-4.10	-27
TN (µM)	-4.15	-8	2.25	4	**2.86**	**6**	-3.55	-5
DRP (µM)	**-0.13**	**-63**	-0.02	-9	-0.02	-7	0.01	5
DAHP (µM)	**-0.11**	**-192**	-0.04	-27	-0.03	-36	0.03	15
DOP (µM)	-0.07	-134	0.01	5	0.02	10	-0.01	-5
PRP (µM)	-0.05	-49	-0.02	-13	0.01	3	-0.02	-11
PAHP (µM)	-0.03	-5	0.05	5	0.03	2	0.16	11
POP (µM)	-0.20	-92	**0.13**	**32**	**0.21**	**85**	-0.34	-74
TP (µM)	**-0.51**	**-41**	**0.17**	**9**	0.26	10	-0.19	-8
ISS (mg L^{-1})	n.d.	n.d.	**4.31**	**27**	-2.24	-14	-2.42	-10
OSS (mg L^{-1})	n.d.	n.d.	0.55	12	-0.50	-17	3.43	38
TSS (mg L^{-1})	n.d.	n.d.	2.45	14	-2.77	-15	1.01	3
Conductivity (µU)	2.20	1	**-3.28**	**-3**	**-1.88**	**-2**	3.30	4

Up – Down; Source, Sink

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POP (μM)	-0.20	-92	**0.13**	**32**	**0.21**	**85**	-0.34	-74
TP (μM)	**-0.51**	**-41**	**0.17**	**9**	0.26	10	-0.19	-8
ISS (mg L^{-1})	n.d.	n.d.	**4.31**	**27**	-2.24	-14	-2.42	-10
OSS (mg L^{-1})	n.d.	n.d.	0.55	12	-0.50	-17	3.43	38
TSS (mg L^{-1})	n.d.	n.d.	2.45	14	-2.77	-15	1.01	3
Conductivity (μU)	2.20	1	**-3.28**	**-3**	**-1.88**	**-2**	3.30	4

Up – Down; Source, Sink

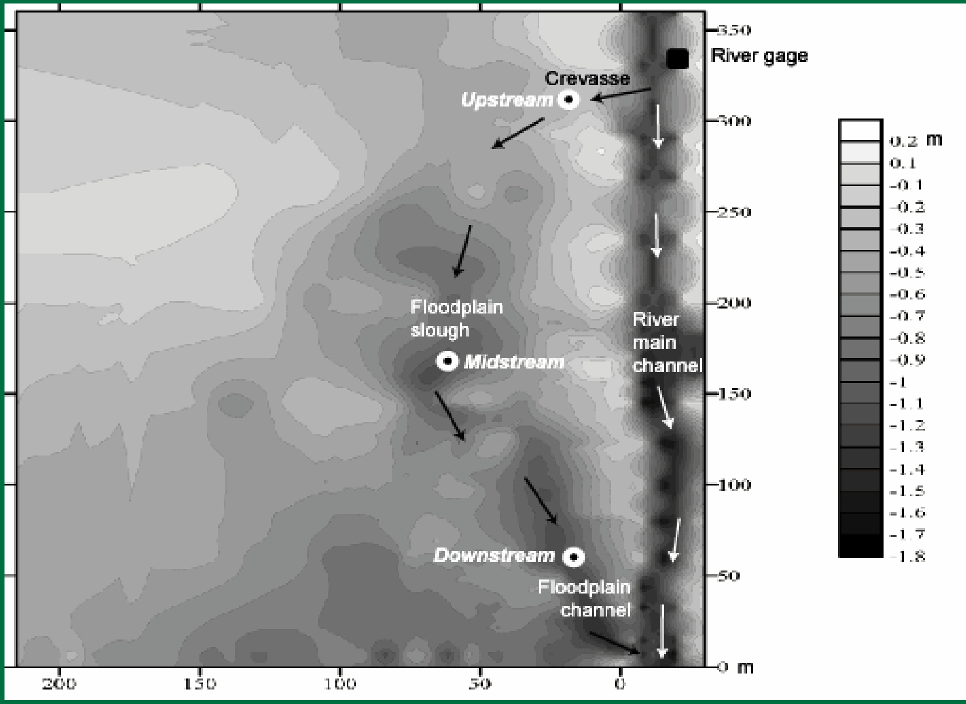
	6-7 Feb 2004 (1 °C)		12-15 Apr '04 (9 °C)		29-30 Sep '04 (20 °C)		20-22 May 2005 (14 °C)	
	Concentration change	% change	Concentration change	% change	Concentration change	% change	Concentration change	% change
NO_2^- (μM)	**-0.14**	**-29**	0.00	0	0.11	33	0.05	8
NO_3^- (μM)	**-4.16**	**-16**	**-0.37**	**-2**	0.21	5	**-2.15**	**-12**
NH_4^+ (μM)	**-0.91**	**-9**	**0.33**	**8**	-0.46	-21	-0.34	-6
DON (μM)	-1.48	-16	-0.94	-4	1.89	8	**2.99**	**12**
PON (μM)	0.58	7	**3.39**	**25**	1.10	7	-4.10	-27
TN (μM)	-4.15	-8	2.25	4	**2.86**	**6**	-3.55	-5
DRP (μM)	**-0.13**	**-63**	-0.02	-9	-0.02	-7	0.01	5
DAHP (μM)	**-0.11**	**-192**	-0.04	-27	-0.03	-36	0.03	15
DOP (μM)	-0.07	-134	0.01	5	0.02	10	-0.01	-5
PRP (μM)	-0.05	-49	-0.02	-13	0.01	3	-0.02	-11
PAHP (μM)	-0.03	-5	0.05	5	0.03	2	0.16	11
POP (μM)	-0.20	-92	**0.13**	**32**	**0.21**	**85**	-0.34	-74
TP (μM)	**-0.51**	**-41**	**0.17**	**9**	0.26	10	-0.19	-8
ISS (mg L^{-1})	n.d.	n.d.	**4.31**	**27**	-2.24	-14	-2.42	-10
OSS (mg L^{-1})	n.d.	n.d.	0.55	12	-0.50	-17	3.43	38
TSS (mg L^{-1})	n.d.	n.d.	2.45	14	-2.77	-15	1.01	3
Conductivity (μU)	2.20	1	**-3.28**	**-3**	**-1.88**	**-2**	3.30	4

Up – Down; Source, Sink

Likely mechanisms

<u>Upper flowpath</u>:
Steeper slope
NH_4^+ export (nitrified to NO_3^-)
Low sedimentation (1.6 mm/yr)

<u>Lower flowpath</u>:
Shallower slope
Particulate nutrient sink
Suspended sediment sink
More sedimentation (3.5 mm/yr)



Geomorphology → hyporheic discharge or particle settling

Short-hydroperiod floodplain

- Seasonality (temperature) affects N and P processing
- Source of inorganic, sink of organic N and P
- Geomorphology within floodplain influences nutrient processing
- → complexity

  floodplains variable in short term

USGS

Pocomoke River, MD

Mattaponi River, VA

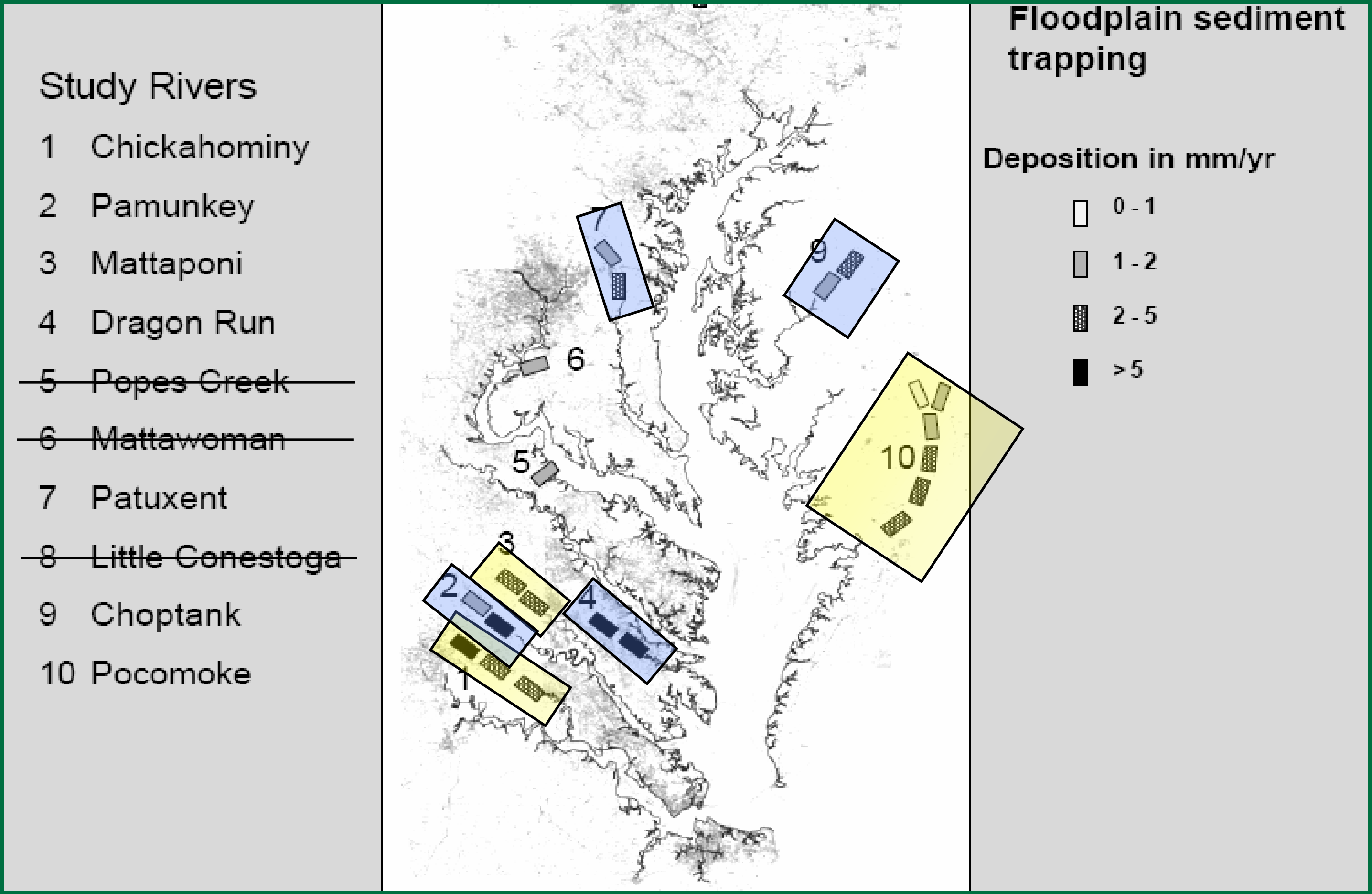
Chickahominy River, VA

Geomorphology & River Load

Noe & Hupp 2005, *Ecol. Applications*

3-6 yr net sediment accumulation rates

Extrapolate nutrient accumulation to wider network of sediment deposition sites



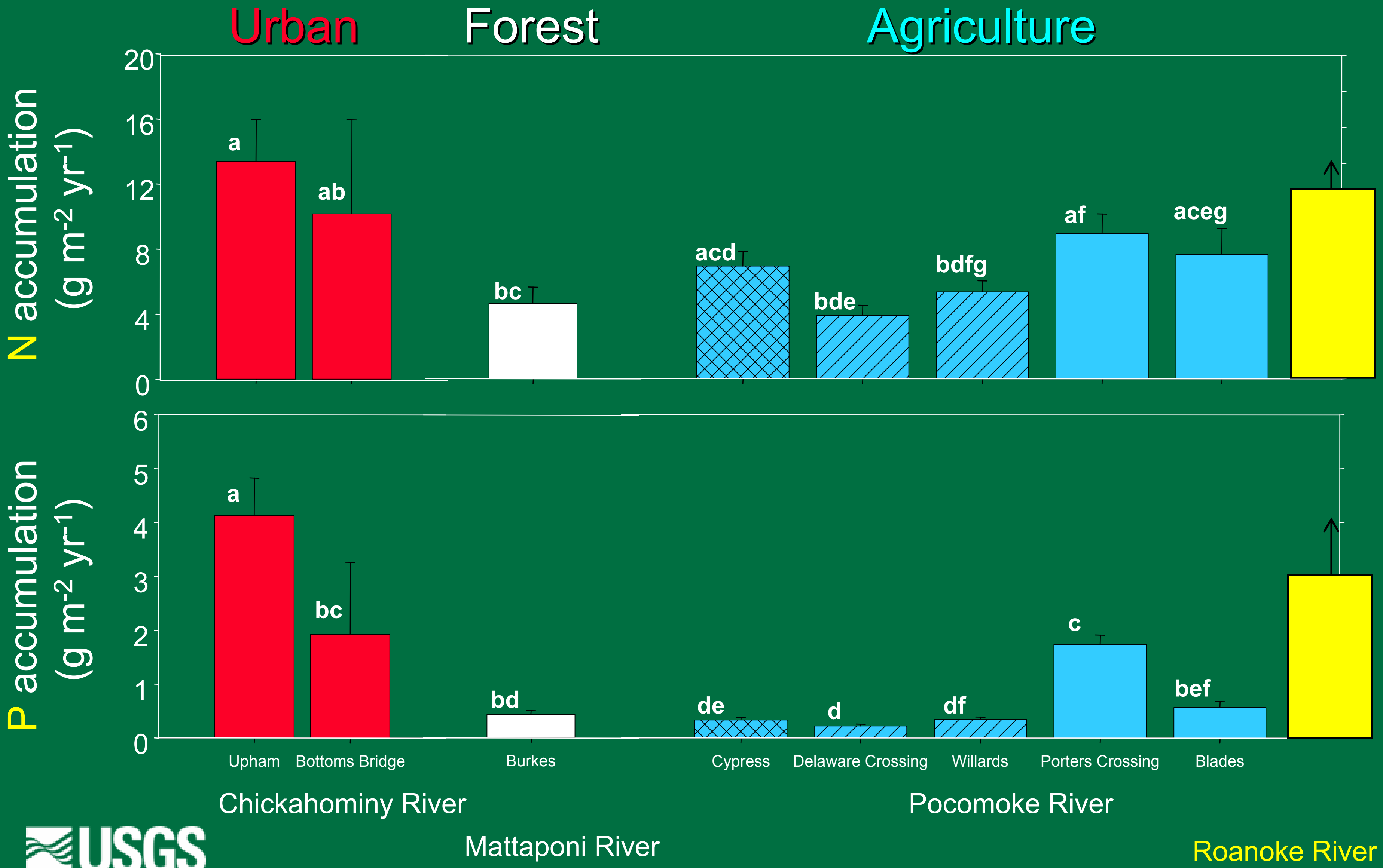
nutrients
n = 71

\+

sediment
n = 114

→ n = 185

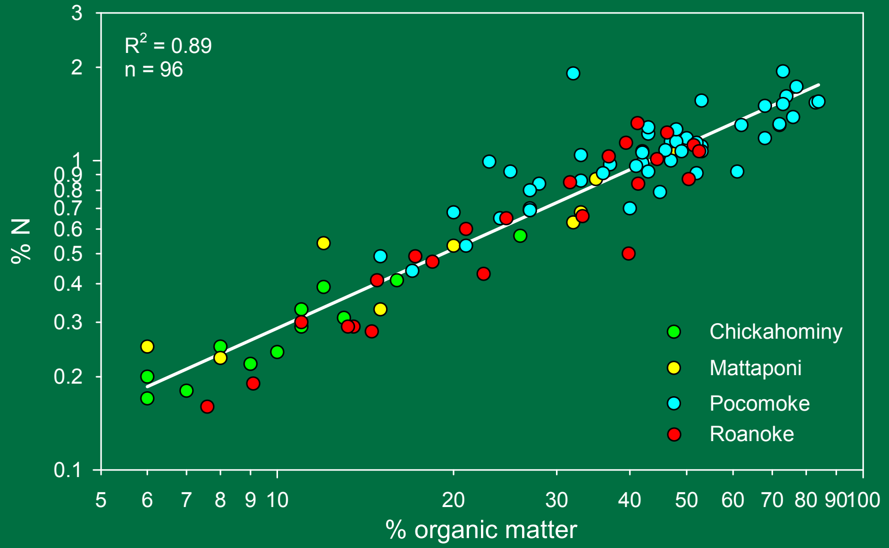
N and P net accumulation rates

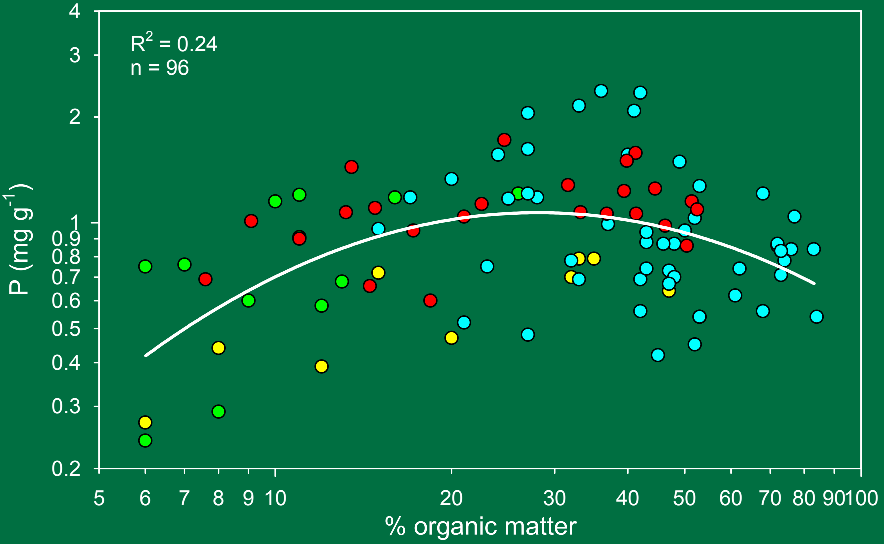


Geomorphology and River Load effects

- Nutrient accumulation rates in floodplains were controlled by
  - River-floodplain **hydraulic connectivity**
  - Watershed **land-use**

Extrapolate nutrient accumulation to wider network of sediment deposition sites





(Sediment deposition) x (bulk density) x ($[\hat{N}]$ or $[\hat{P}]$) x (age) = Mean (± CI) accumulation rate per site (g m^{-2} yr^{-1})

→ Accumulation rate per site x floodplain area per site = River retention rate (kg yr^{-1})

Percent retention summary statistics

	N			P			Sed		
	Mean	-90%	+90%	**Mean**	-90%	+90%	**Mean**	-90 %	+90%
Chickahominy	**104**	49	305	**245**	121	840			
Choptank	**5**	3	7	**14**	9	22	**85**	56	130
Dragon Run	**150**	85	265	**587**	333	1035			
Mattaponi	**56**	43	75	**66**	51	87	**476**	360	632
Pamunkey	**12**	8	17	**22**	15	32	**53**	35	82
Patuxent	**17**	14	21	**59**	47	74	**119**	94	149
Pocomoke	**22**	17	30	**21**	16	27	**690**	529	911

If disconnected Pocomoke floodplains were restored, projected 23% N, 25% P retention

Atchafalaya: 5% N, 27% P (Hupp & Noe 2006 ASABE)

Assumptions

\-

- Permanent sink
- Deposited material is allochthonous and riverine
- Load data is accurate

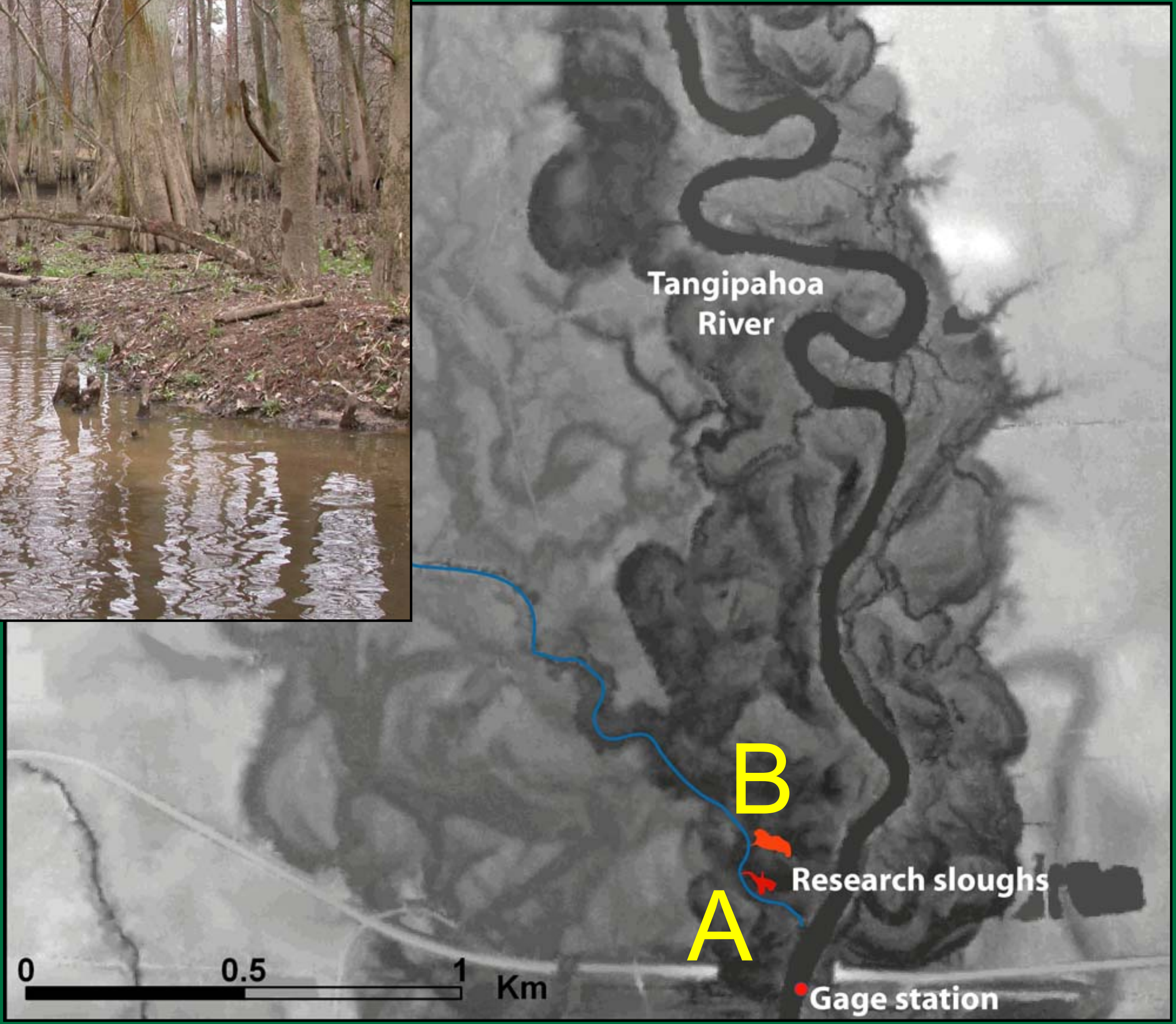
\+

- Other removal fluxes not measured

?

- Nutrient concentration is accurately predicted
- Sampling network representative
- Floodplain area estimation is accurate

Hydrology



Tangipahoa River, LA

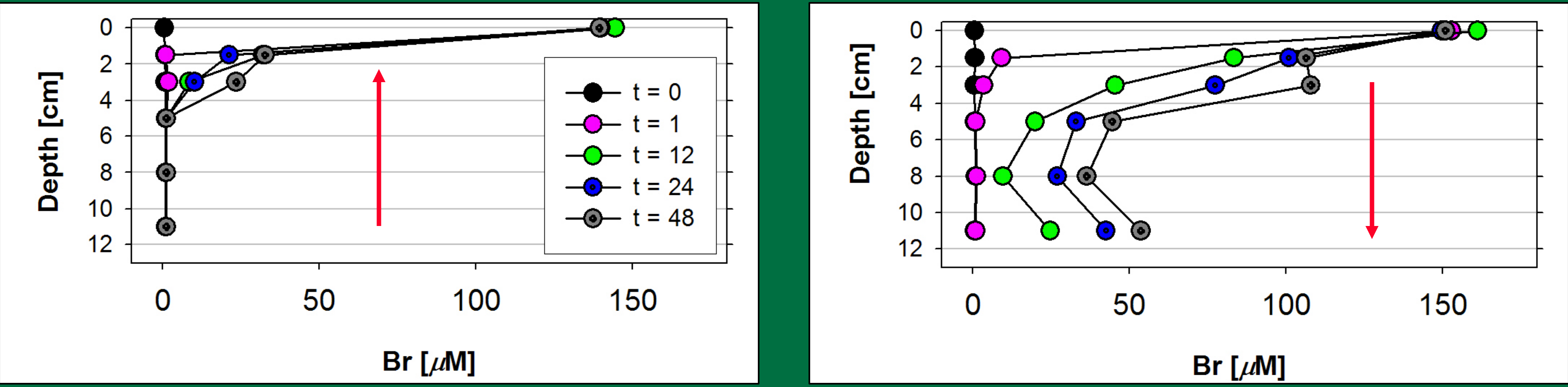
Scott et al., *in prep.*

Surface-subsurface exchange: March flood

Br$^-$ tracer addition to mesocosms

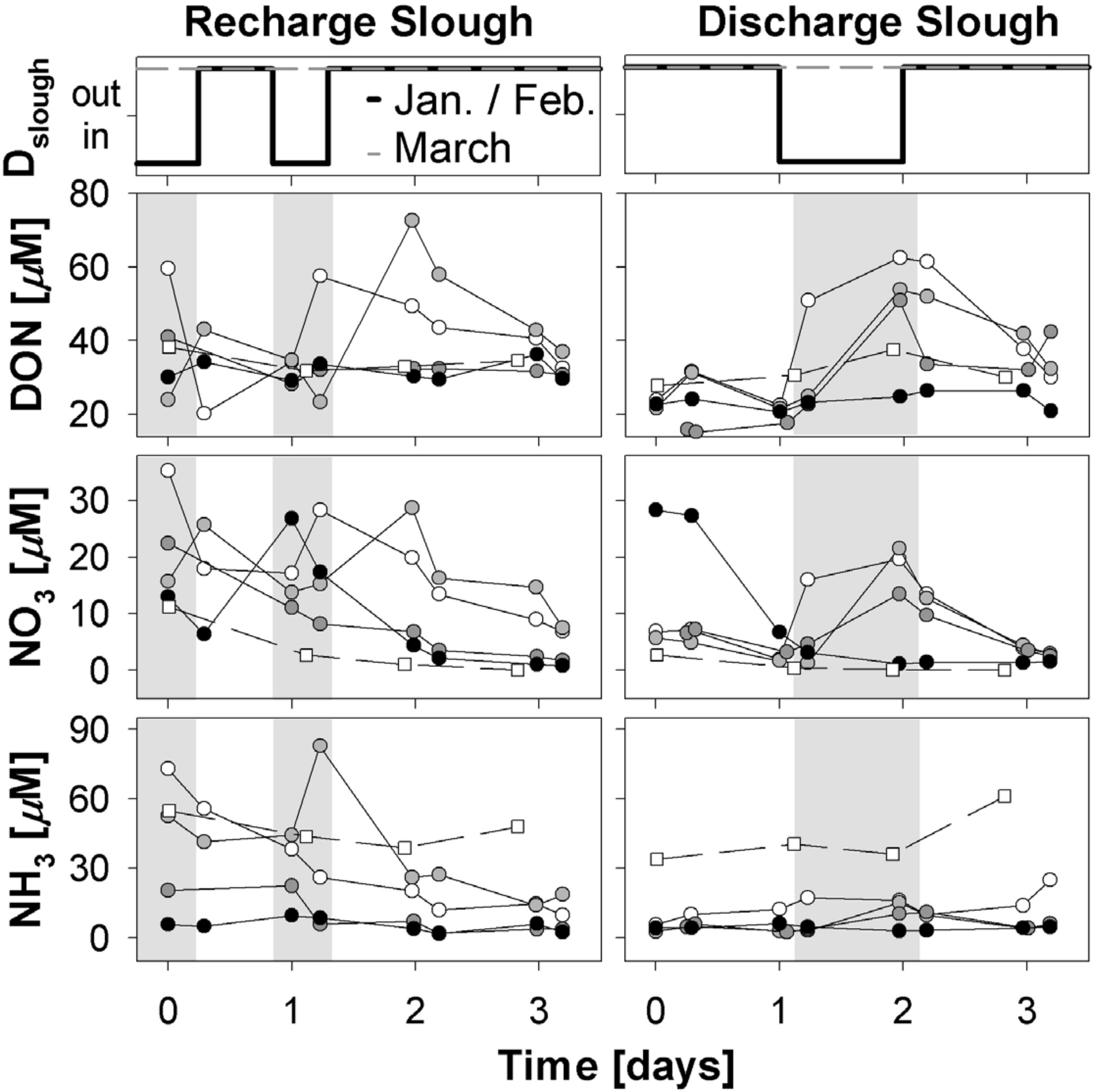
Slough A

Slough B



→ discharging

→ recharging


Recharge Slough
Discharge Slough
D_{slough}
out
in
Jan. / Feb.
March
DON [μM]
80
60
40
20
NO_3 [μM]
30
20
10
0
NH_3 [μM]
90
60
30
0
0
1
2
3
Time [days]

USGS

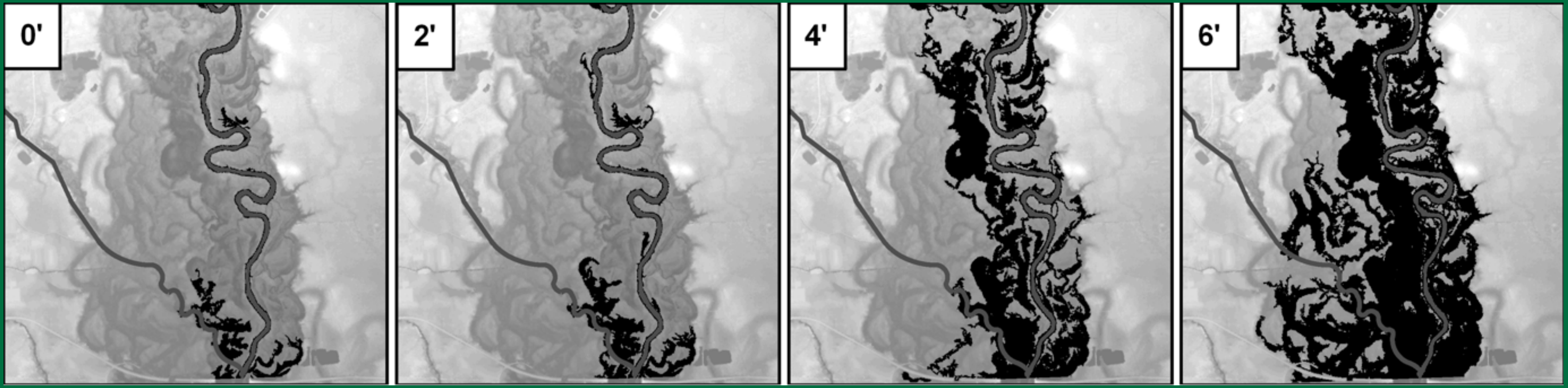
1st-order coupled N removal, constrained by hydrologic mass balance

$$DON \longrightarrow NH_3 \longrightarrow NO_3 \longrightarrow N_2$$

Flood	Location	GW-SW Hydrology	DON	NH_3	NO_3
			k_{DON} [day^{-1}]	k_{NH3} [day^{-1}]	k_{NO3} [day^{-1}]
Jan	SI – B	discharge	-0.3	-0.3	-1.6
	SI – A	discharge	-0.8	-0.6	-2.6
Mar	SI – B	recharge	-0.2	0	-1.8
	SI – A	discharge	0.1	0	-2.0

Source, Sink

20-km reach scale NO_3^- removal



- Estimate percent inundation and residence time (DEMInundate)
- Apply measured denitrification rates

- Floodplain removes 9% of the annual N load (16% of NO_3^-) (does not include PON)

Hydrology effects

- Surface-subsurface hydrologic exchange controls O_2 and nitrification

- Denitrification removes most NO_3 in surface and subsurface water (~9% of annual riverine NO_3 load?)

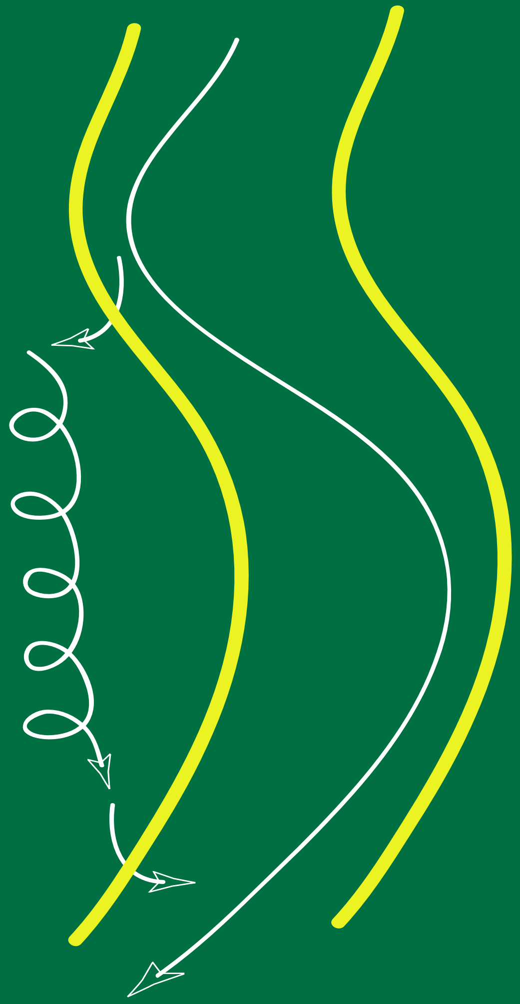
- DON and PON flux dominates N load
  - what is fate of ON?

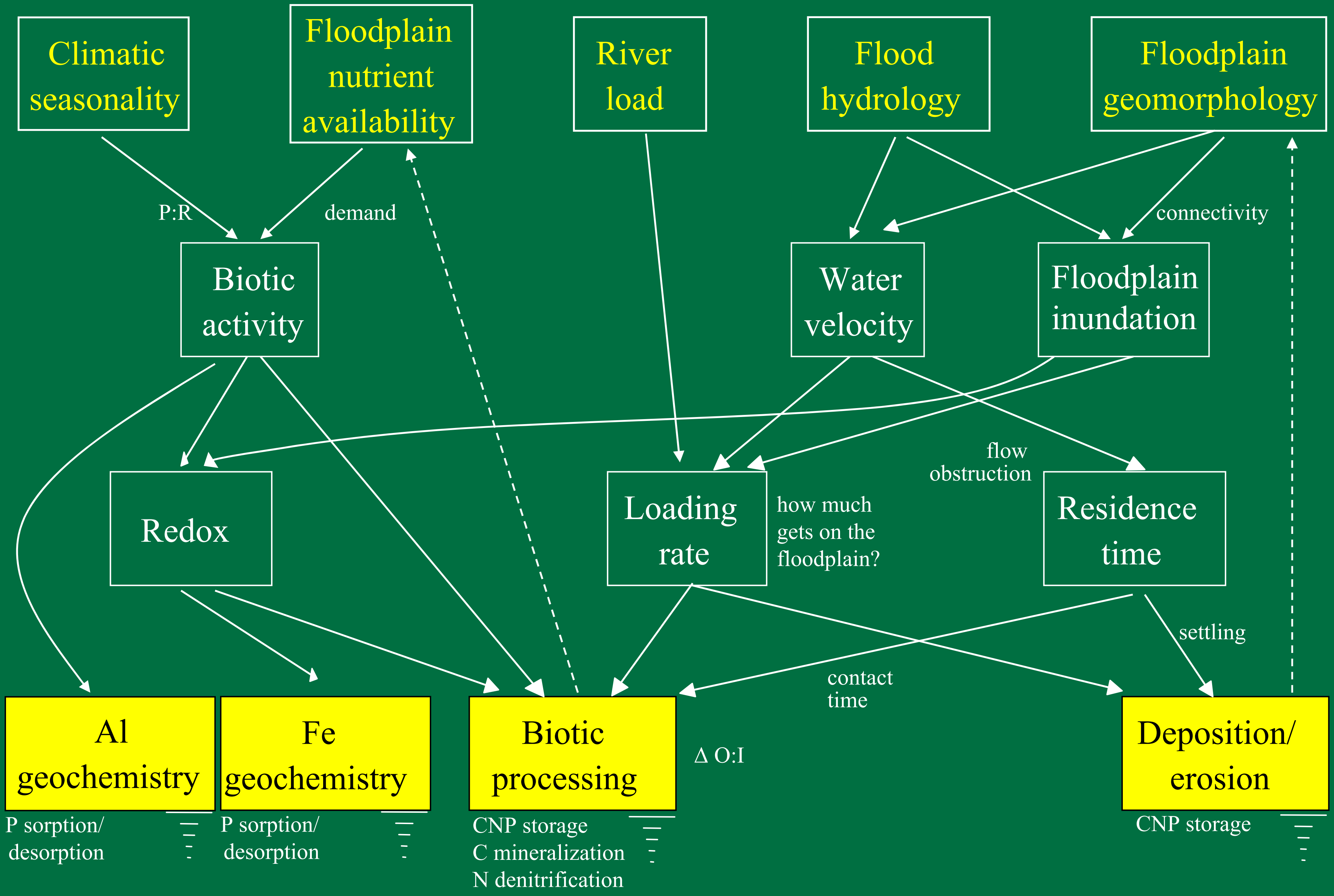
- Coupled mineralization – nitrification – denitrification important process in Southeastern US floodplains

Conclusions

- Nutrient processing in floodplains was controlled by:
  - river load
  - geomorphology and hydraulic connectivity
  - climate
  - hydrology

→ Adds up to meaningful nutrient and sediment retention





Climatic seasonality

Floodplain nutrient availability

River load

Flood hydrology

Floodplain geomorphology

P:R

demand

connectivity

Biotic activity

Water velocity

Floodplain inundation

Redox

Loading rate

how much gets on the floodplain?

flow obstruction

Residence time

settling

contact time

Al geochemistry

P sorption/ desorption

Fe geochemistry

P sorption/ desorption

Biotic processing

CNP storage
C mineralization
N denitrification

Δ O:I

Deposition/ erosion

CNP storage

Noe & Hupp. *In press. River Res Appl.*

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