Spring-influenced rivers: Are they "ecological outliers" or can they be used to help us better understand rivers in a global context?

Dr. Weston Nowlin

Department of Biology

Aquatic Station

Texas State University

Acknowledgements

Students and Collaborators

Aaron Swink, Matthew Stehle

Benjamin Schwartz, Todd Swannack, Astrid Schwalb, Josh Perkin, Karl Cottenie, Tonya Ramey, Belize Lane, Mariana Perez Rocha, Benjamin Hutchins, Annette Engel, Rich Johansen, Christina Saltus

Funding

TCEQ

US Army Corps of Engineers®

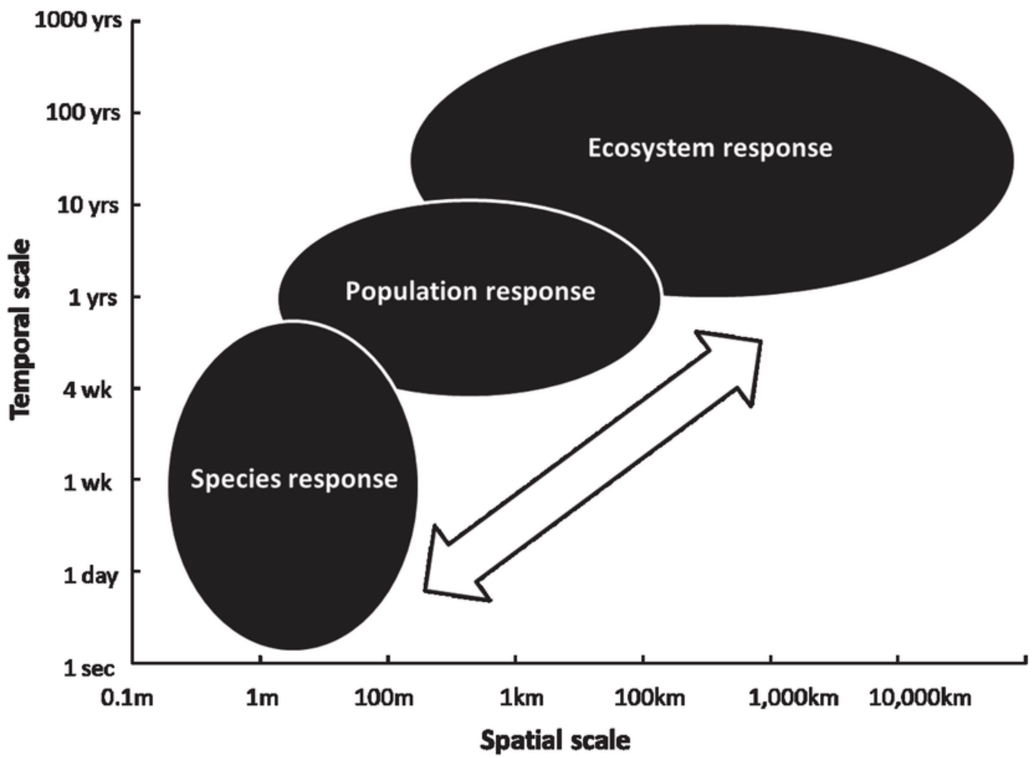
UtahStateUniversity

THE UNIVERSITY OF TENNESSEE KNOXVILLE

UNIVERSITY of GUELPH

TEXAS A&M UNIVERSITY 1876

Issues of Scale and Pattern in Ecology



Adapted from Suter (1993)

Long history in ecology

Scale of observations = Determines the outcome of observations

Hutchinson (1965) – interactions play out in an "ecological theatre" at various spatio-temporal scales

Scale of observations (grain and extent)

- Study organism or process
- Question

Issues of Scale are Pervasive

Ecology, 73(6), 1992, pp. 1943–1967

THE PROBLEM OF PATTERN AND SCALE IN ECOLOGY

THE ROBERT H. MACARTHUR AWARD LECTURE
Presented August 1989
Toronto, Ontario, Canada

by

SIMON A. LEVIN
Department of Ecology and Evolutionary Biology, Princeton University, Princeton, New Jersey 08544-1003 USA, and Section of Ecology and Systematics, Cornell University, Ithaca, New York 14853-2701 USA

Simon A. Levin
MacArthur Award Recipient

Abstract. It is argued that the problem of pattern and scale is the central problem in ecology, unifying population biology and ecosystems science, and marrying basic and applied ecology. Applied challenges, such as the prediction of the ecological causes and consequences of global climate change, require the interfacing of phenomena that occur on very different scales of space, time, and ecological organization. Furthermore, there is no single natural scale at which ecological phenomena should be studied; systems generally show characteristic variability on a range of spatial, temporal, and organizational scales. The observer imposes a perceptual bias, a filter through which the system is viewed. This has fundamental evolutionary significance, since every organism is an "observer" of the environment, and life history adaptations such as dispersal and dormancy alter the perceptual scales of the species, and the observed variability. It likewise has fundamental significance for our own study of ecological systems, since the patterns that are unique to any range of scales will have unique causes and biological consequences.

The key to prediction and understanding lies in the elucidation of mechanisms underlying observed patterns. Typically, these mechanisms operate at different scales than those on which the patterns are observed; in some cases, the patterns must be understood as emerging from the collective behaviors of large ensembles of smaller scale units. In other cases, the pattern is imposed by larger scale constraints. Examination of such phenomena requires the study of how pattern and variability change with the scale of description, and the development of laws for simplification, aggregation, and scaling. Examples are given from the marine and terrestrial literatures.

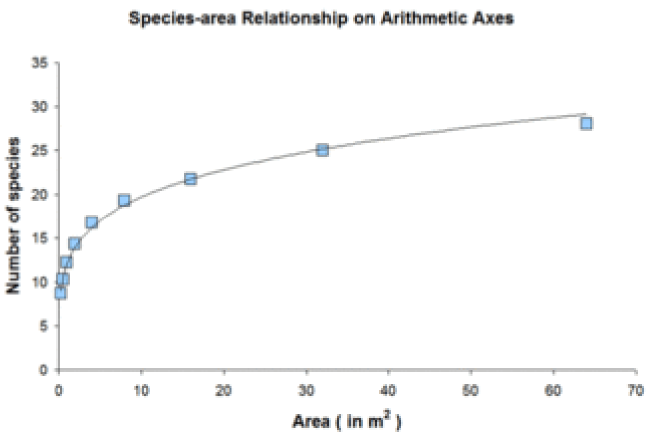
Key words: *heterogeneity; patchiness; pattern; scale; variability.*

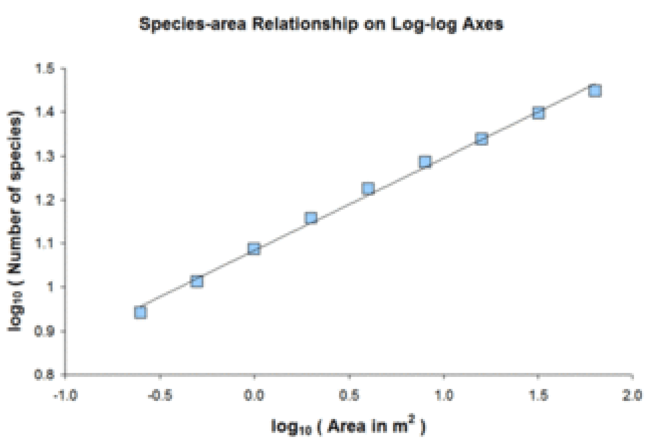
"The problem of pattern and scale is the central problem in ecology, unifying population biology and ecosystems science, and marrying basic and applied ecology…"

"To scale from the leaf to the ecosystem to the landscape and beyond, we must understand how information is transferred from fine scales to broad scales, and vice versa."

Scaling in Ecology and "Laws"

Species – Area Relationships





Metabolic Ecology

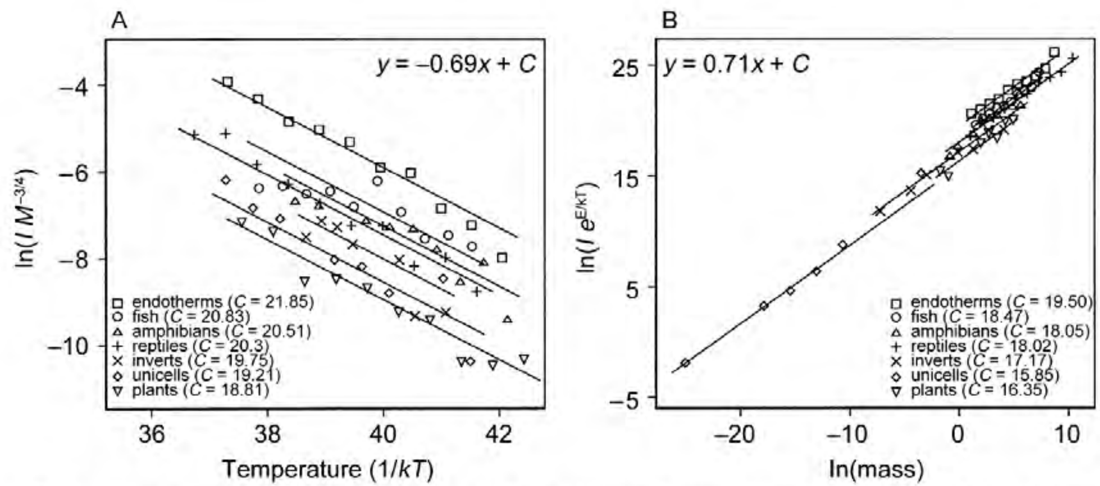
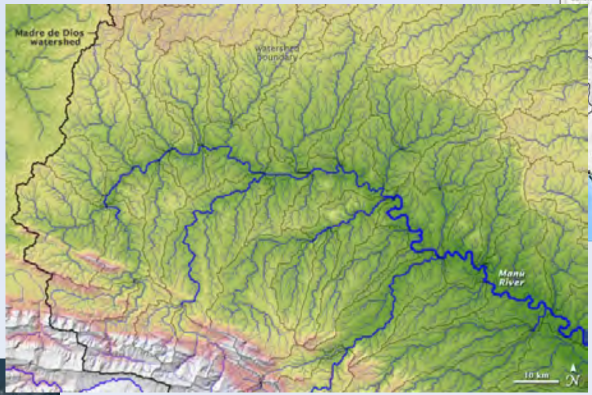


FIG. 1. Temperature and mass dependence of metabolic rate for several groups of organisms, from unicellular eukaryotes to plants and vertebrates (from Gillooly et al. 2001). (A) Relationship between mass-corrected metabolic rate, $\ln(IM^{-3/4})$, measured in watts/g$^{3/4}$, and temperature, $1/kT$, measured in K. The overall slope, calculated using ANCOVA, estimates the activation energy, and the intercepts estimate the normalization constants, $C = \ln(i_0)$, for each group. The observed slope is close to the predicted range of 0.60–0.70 eV (95% CI, 0.66–0.73 eV; SI conversion, 1 eV = 96.49 kJ/mol). (B) Relationship between temperature-corrected metabolic rate, $\ln(Ie^{E/kT})$, measured in watts, and body mass, $\ln(M)$, measured in grams. Variables are M, body size; I, individual metabolic rate; k, Boltzmann's constant; T, absolute temperature (in K). E is the activation energy. The overall slope, calculated using ANCOVA, estimates the allometric exponent, and the intercepts estimate the normalization constants, $C = \ln(i_0)$, for each group. The observed slope is close to the predicted value of ¾ (95% CI, 0.69–0.73). For clarity, data from endotherms (n = 142), fish (n = 113), amphibians (n = 64), reptiles (n = 105), invertebrates (n = 20), unicellular organisms (n = 30), and plants (n = 67) were binned and averaged for each taxonomic group to generate the points depicted in the plot.

Basin

Watershed

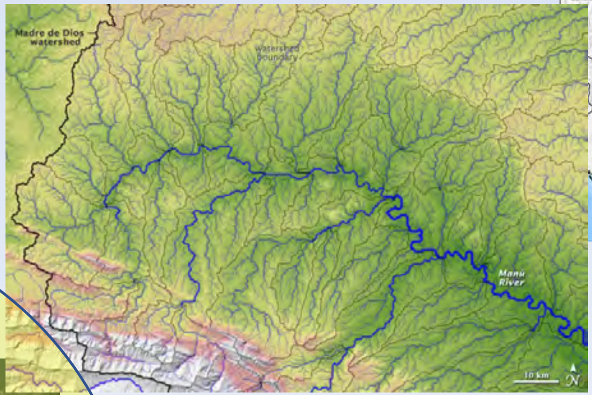


Reach

Habitat

Basin

Watershed



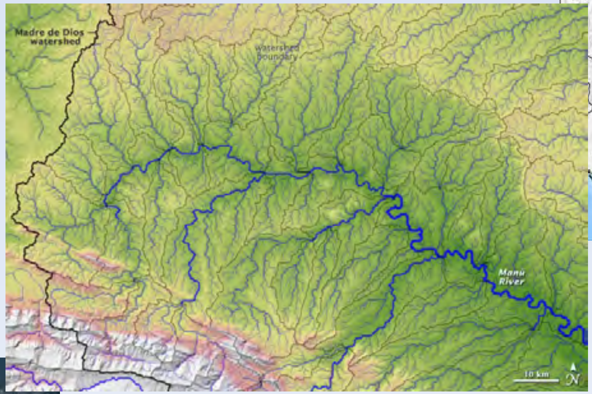
Reach

Habitat

Information Transfer?

Basin

Watershed



Reach

Habitat

Context dependent drivers?

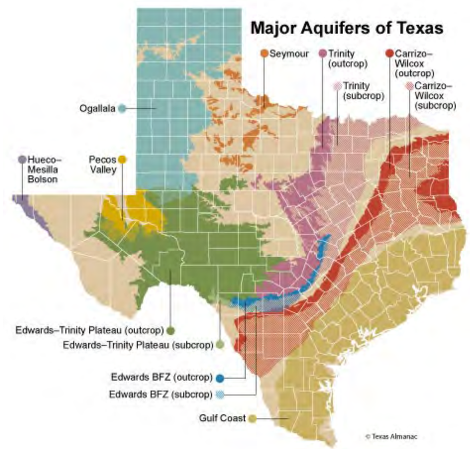
Today's Talk

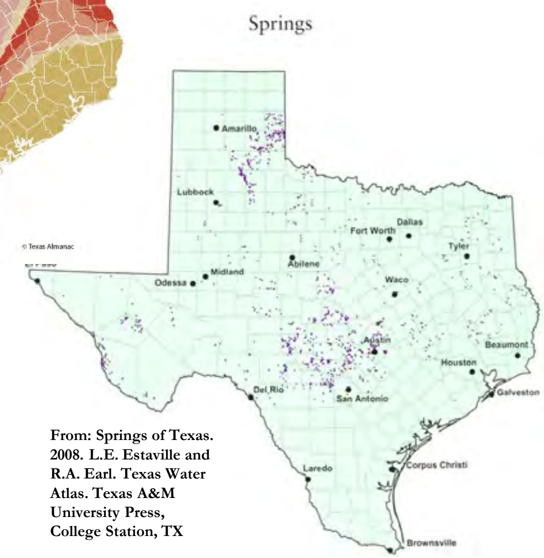
- Phosphorus uptake in groundwater dominated rivers
  - Retention of P in rivers and how does this scale across systems?
  - How do groundwater dominated rivers relate to a "global" river dataset?

- Metabolism of groundwater dominated rivers
  - Seasonal variation in production and respiration in a groundwater dominated river?
  - Role of macrophytes?
  - How do groundwater dominated rivers relate to a "global" dataset?

Groundwater Dominated Rivers

- Headwaters
  - Groundwater discharge
- Perennial flows
- Endemic fauna
  - Limited range; site-specific adaptation; high conservation priority
- Conservation issues
  - Pumping – "killer of springs"
  - Pollution (eutrophication)
  - Non-native species



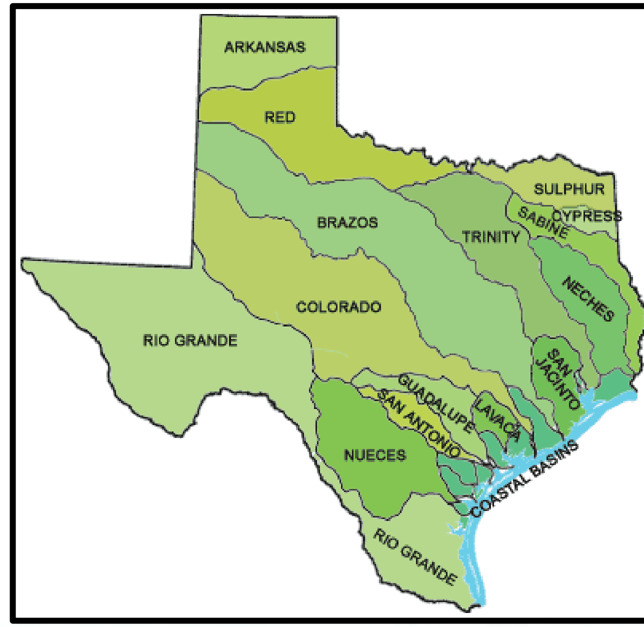


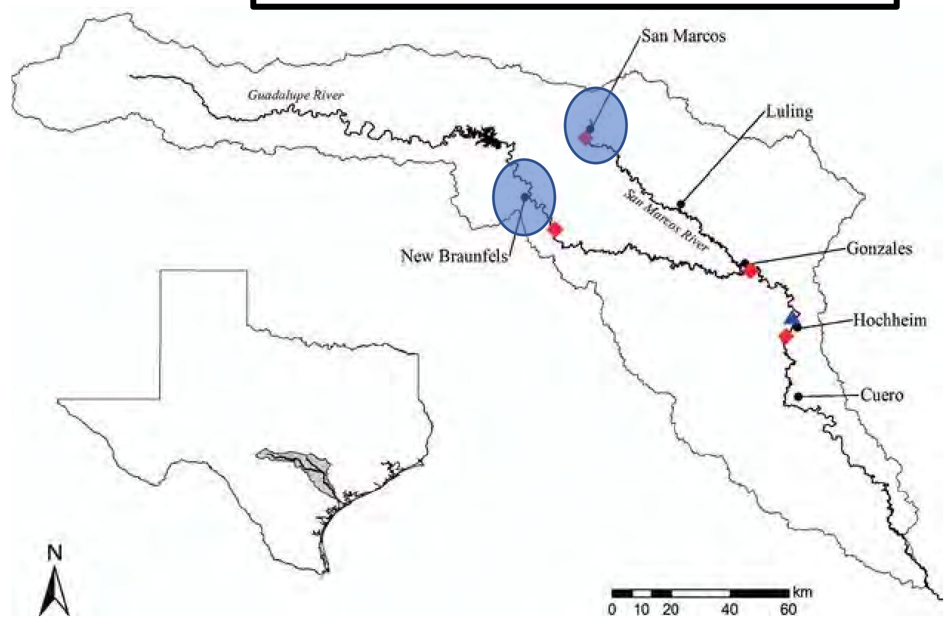
From: Springs of Texas. 2008. L.E. Estaville and R.A. Earl. Texas Water Atlas. Texas A&M University Press, College Station, TX

Unmack and Minckley 2006; Fensham et al. 2011; Bogan et al. 2014

Groundwater Dominated Rivers

- Headwaters
  - Groundwater discharge
- Perennial flows
- Endemic fauna
  - Limited range; site-specific adaptation; high conservation priority
- Conservation issues
  - Pumping – "killer of springs"
  - Pollution (eutrophication)
  - Non-native species





Groundwater Dominated Rivers

- Seasonal and interannual “stable” flows
- High water clarity
- Physicochemical consistency
- Higher *Q* than predicted by stream order

Groundwater Dominated Rivers

- Seasonal and interannual "stable" flows
- High water clarity
- Physicochemical consistency
- Higher *Q* than predicted by stream order

- Can GW rivers be used to understand scaling ecosystem processes?
- Are they "unique" ecosystems and can they inform us of processes in rivers, in general?

Today's Talk

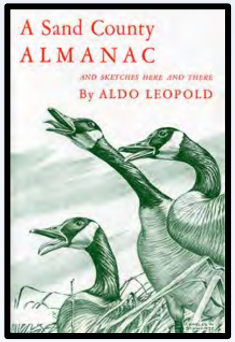
- Phosphorus uptake in groundwater dominated rivers
  - Retention of P in rivers and how does this scale across systems?
  - How do groundwater dominated rivers relate to a "global" river dataset?

- Metabolism of groundwater dominated rivers
  - Seasonal variation in production and respiration in a groundwater dominated river?
  - Role of macrophytes and epiphytes?
  - How do groundwater dominated rivers relate to a "global" dataset?

Nutrients in Rivers
Perspectives

Between each of his excursions through the biota, [Molecule] X lay in the soil and was carried by the rains, inch by inch, downhill… X rode down the spring freshet, losing more altitude each hour than heretofore in a century. He ended up in the silt of a backwater bayou, where he fed a crayfish, a coon, and then an Indian, who laid him down to his last sleep in a mound on the riverbank. One spring an oxbow caved the bank, and after one short week of freshet X lay again in his ancient prison, the sea.

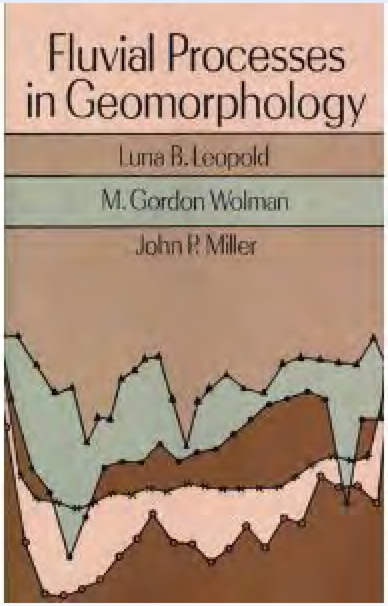
– Aldo Leopold (1949), "Odyssey" *in* A Sand County Almanac

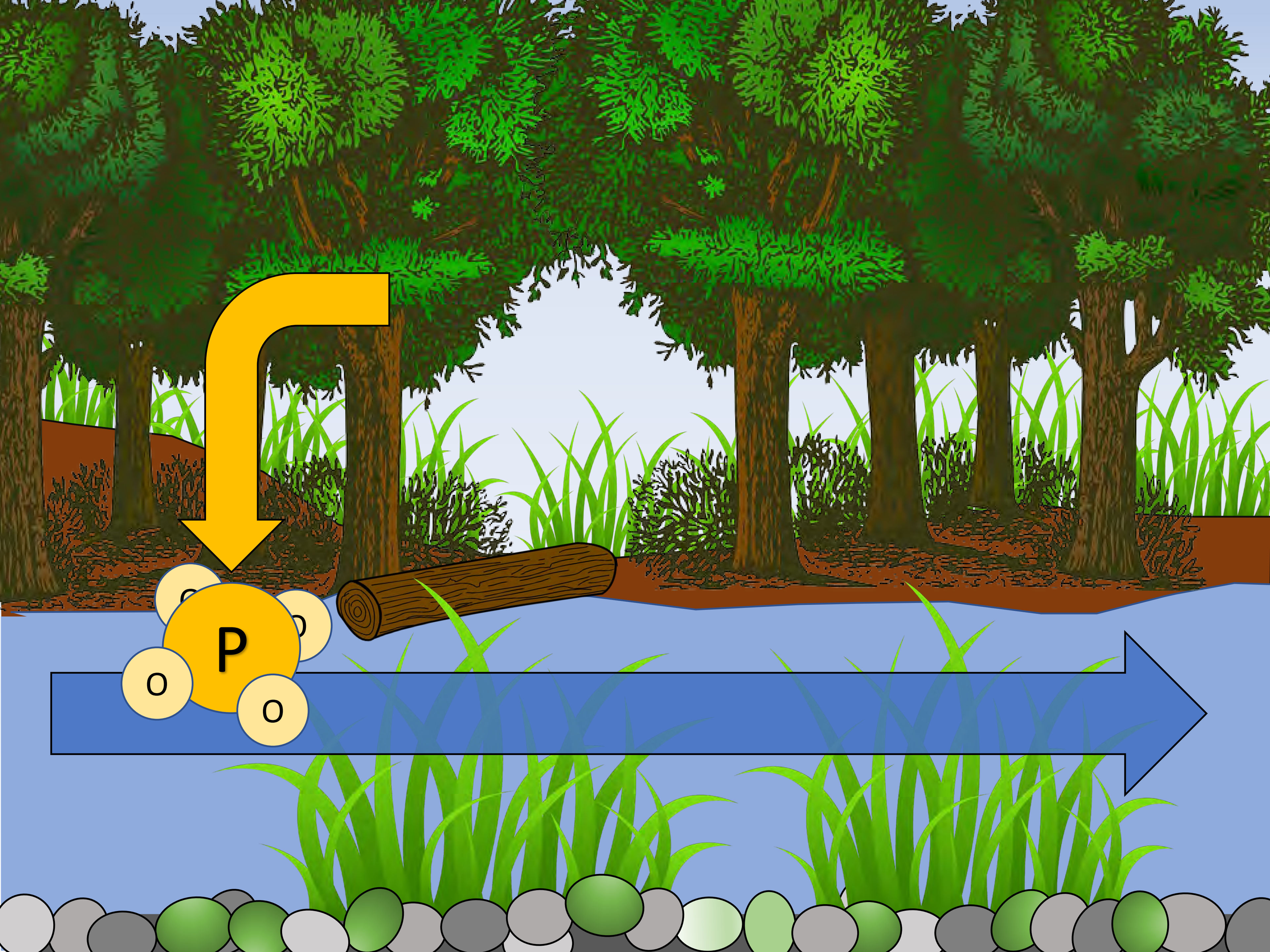


Nutrients in Rivers
Perspectives

It has been said that streams are the gutters down which flow the ruins of continents.

– Luna B. Leopold *et al*. (1964), *Fluvial Processes in Geomorphology*



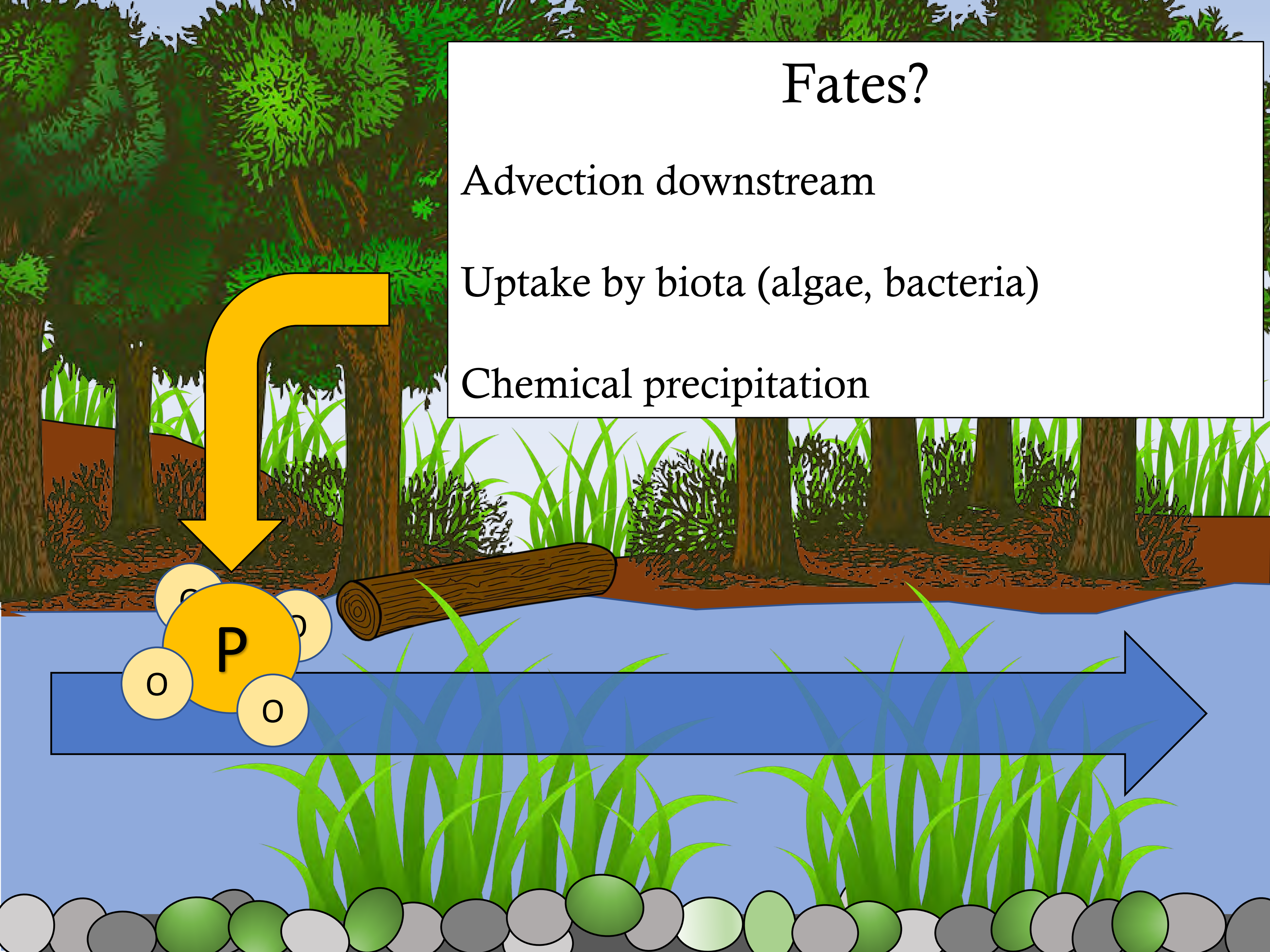

P
O
O

Fates?

Advection downstream

Uptake by biota (algae, bacteria)

Chemical precipitation

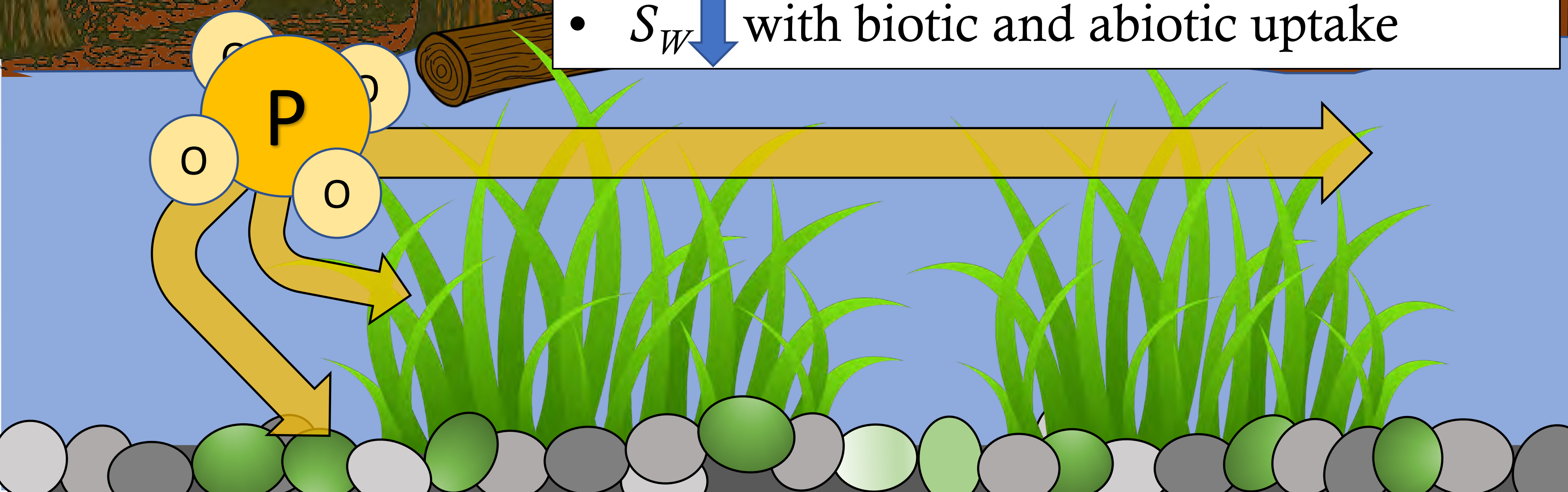


Uptake Length (S_W)

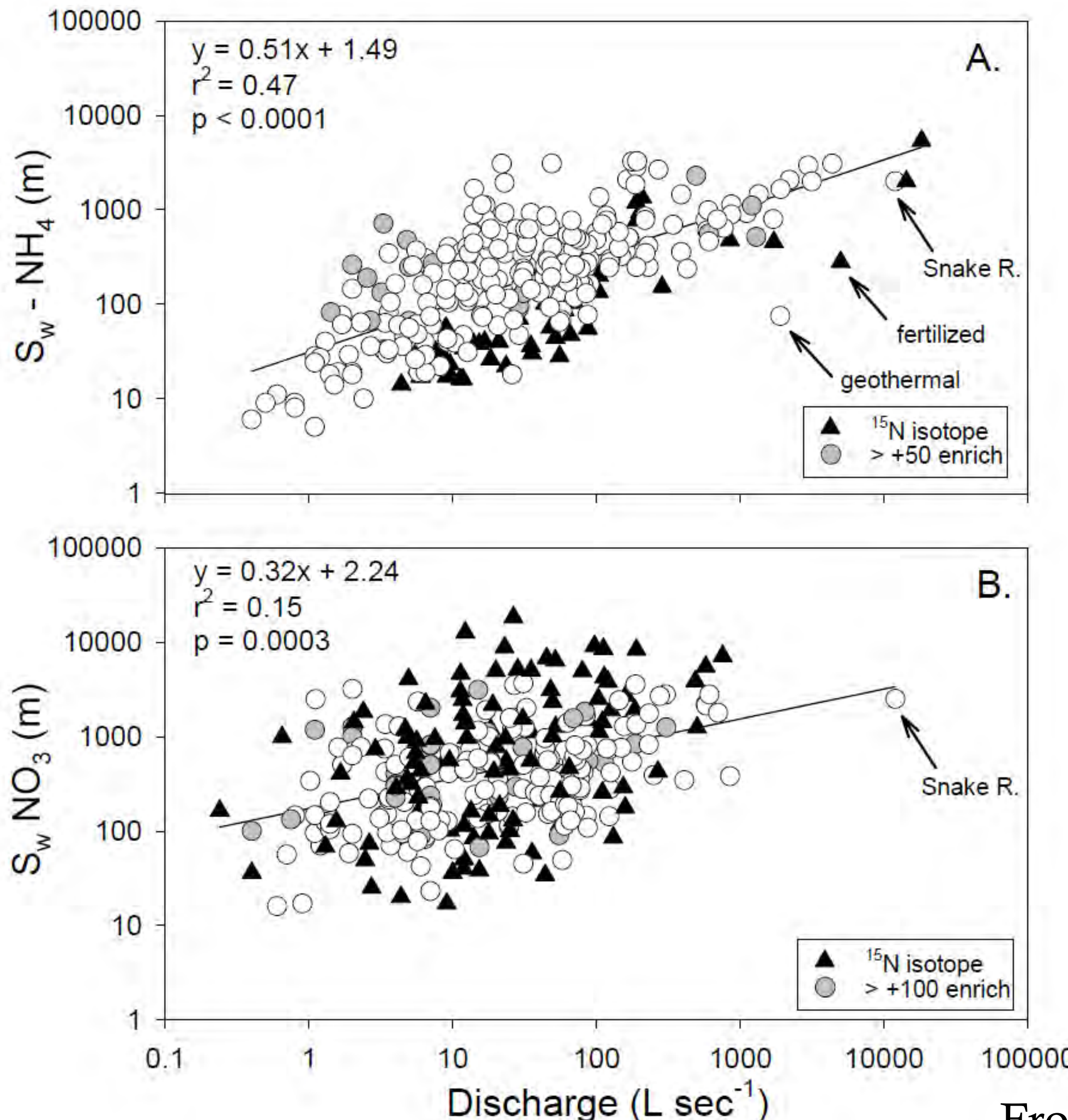
Average distance traveled before being removed from the water column (in meters)

- <u>Advection</u>
- <u>Uptake and assimilation</u>

- S_W ↑ with depth and velocity
- S_W ↓ with biotic and abiotic uptake



Nutrient Uptake Scales with Discharge

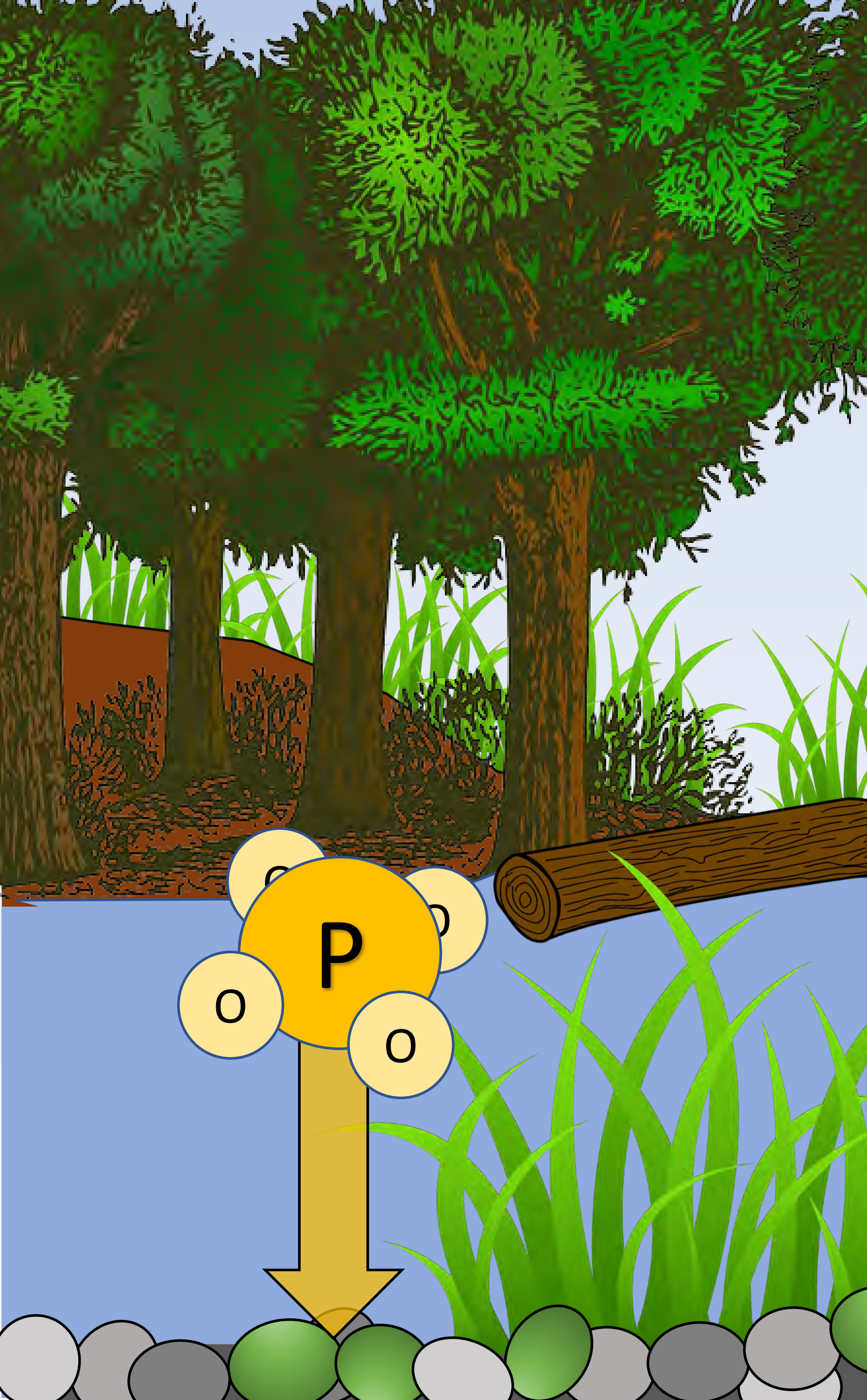


From Tank et al (2008)

Uptake Velocity (v_f)

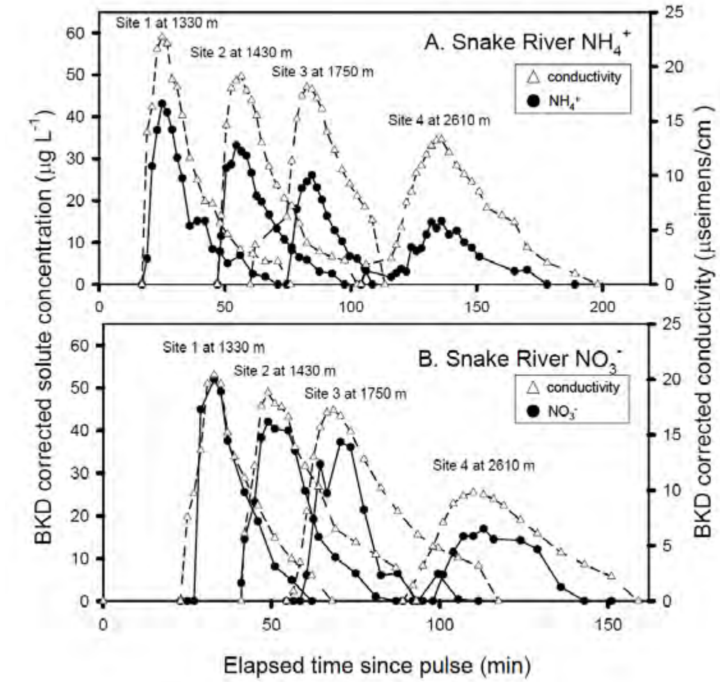
Allows "normalization" of uptake for depth and velocity

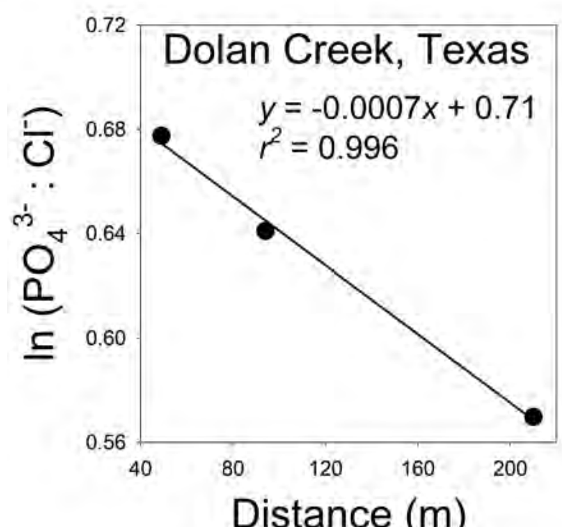
- $(Q/w)/S_W$
- Vertical velocity of molecule into the benthos
  - mm/min
- <u>Compare streams of different size or discharge</u>



How to Estimate This?

- Can model it
  - e.g., OTIS-P by USGS
- Empirically measure it with an addition experiment
  - Add a “conservative” tracer with a “reactive” tracer
    - Cl^-
    - PO_4^{3-}
  - Points downstream
  - $1/|k| = S_W$

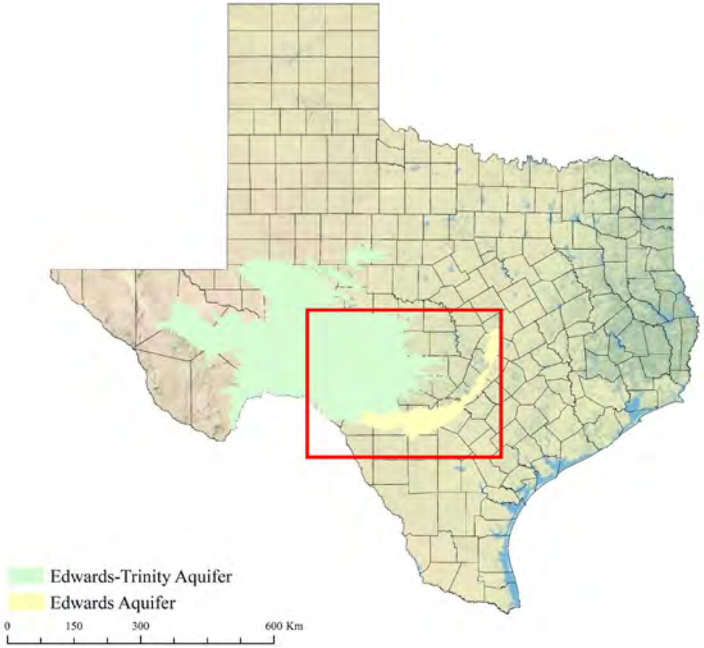




Study Questions and Goals

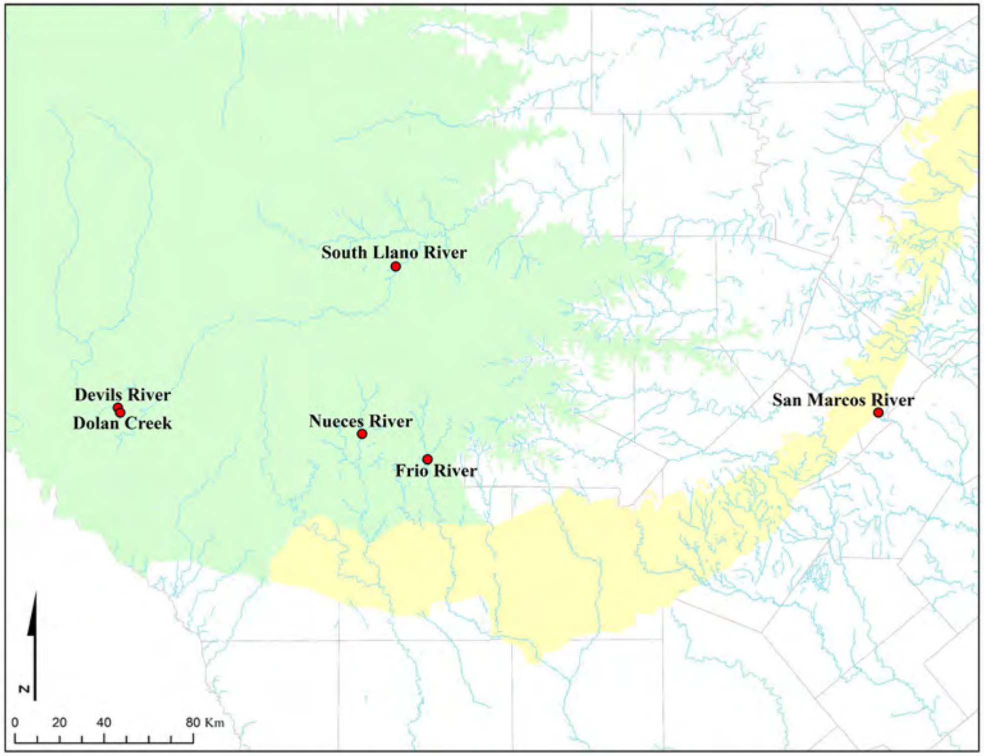
- Uptake and sequestration of P in groundwater dominated systems
- Most studies conducted in small *Q* systems
  - <20 L/s
- Most studies focused on N
  - P is often limiting

- What factors influence uptake rates of P in the EP?
- How do groundwater systems compare to surface water dominated systems?

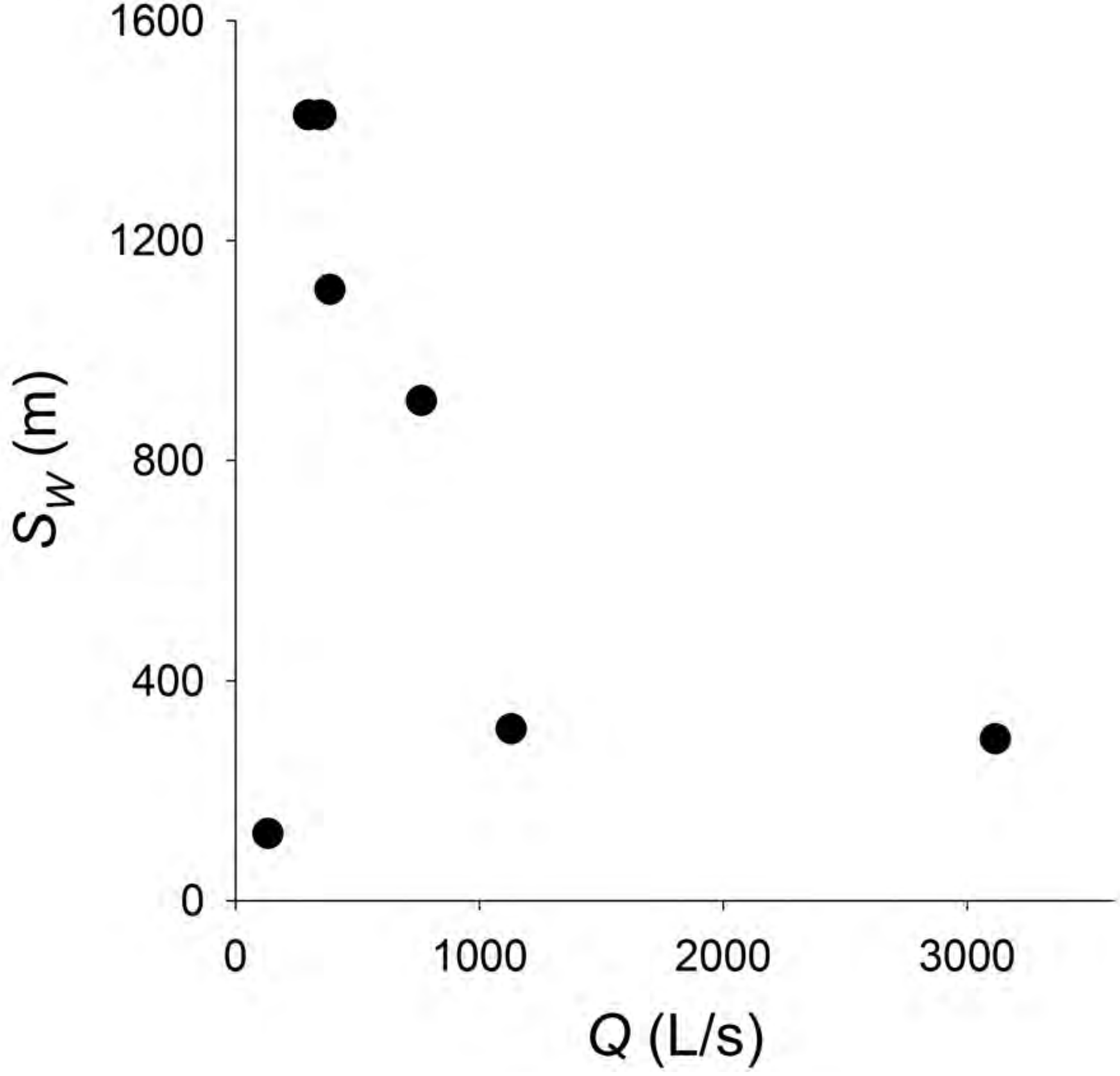


Methods

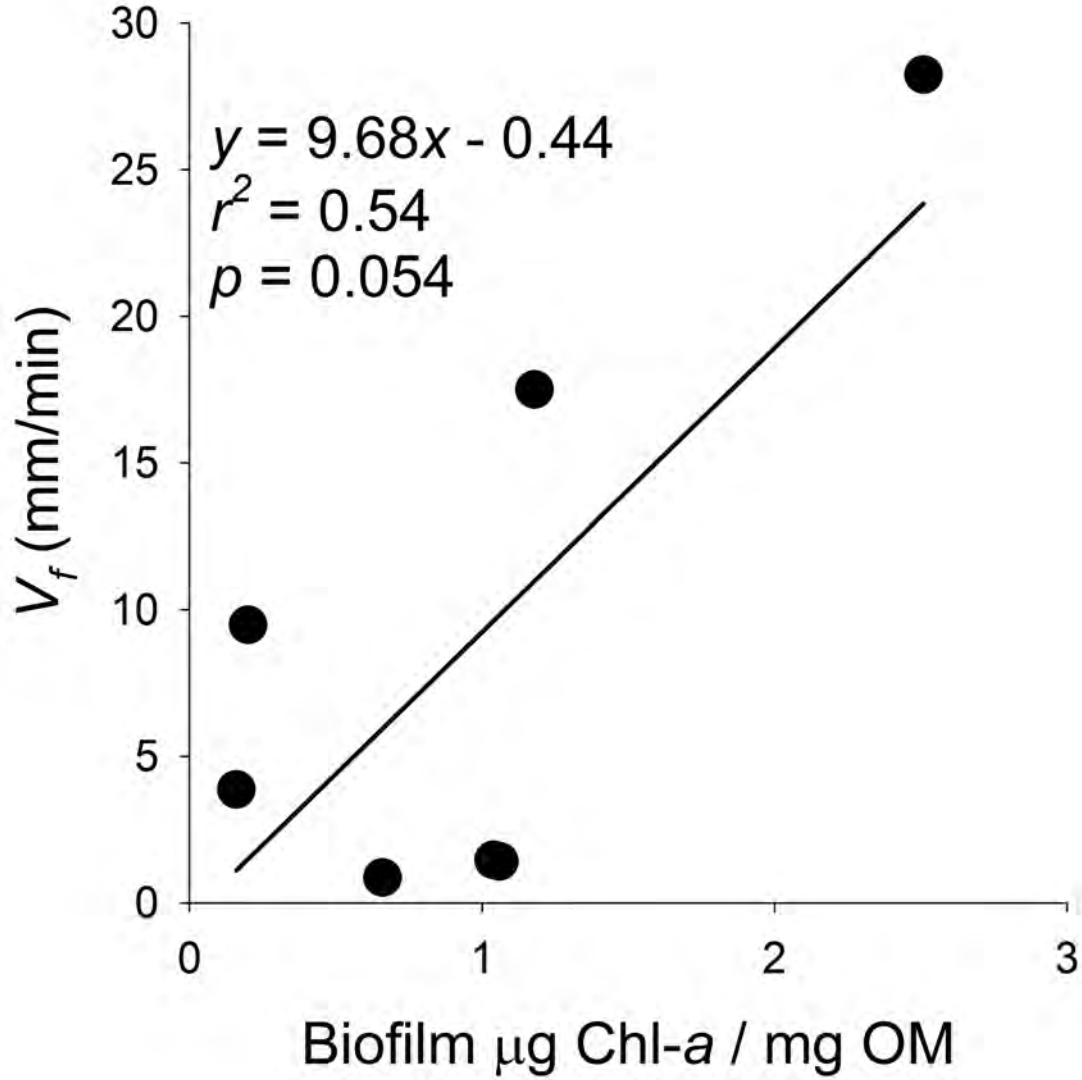
- Seven experiments
  - 6 rivers
  - Edwards Plateau
  - Edwards and E-T Aquifers
- Range in Q and in-stream conditions
- Pulsed tracer addition experiments
  - Estimated S_W and v_f
- Suite of stream conditions
- Literature review of P addition experiments
  - 352 experiments from 111 different systems



Uptake Length in the Edwards

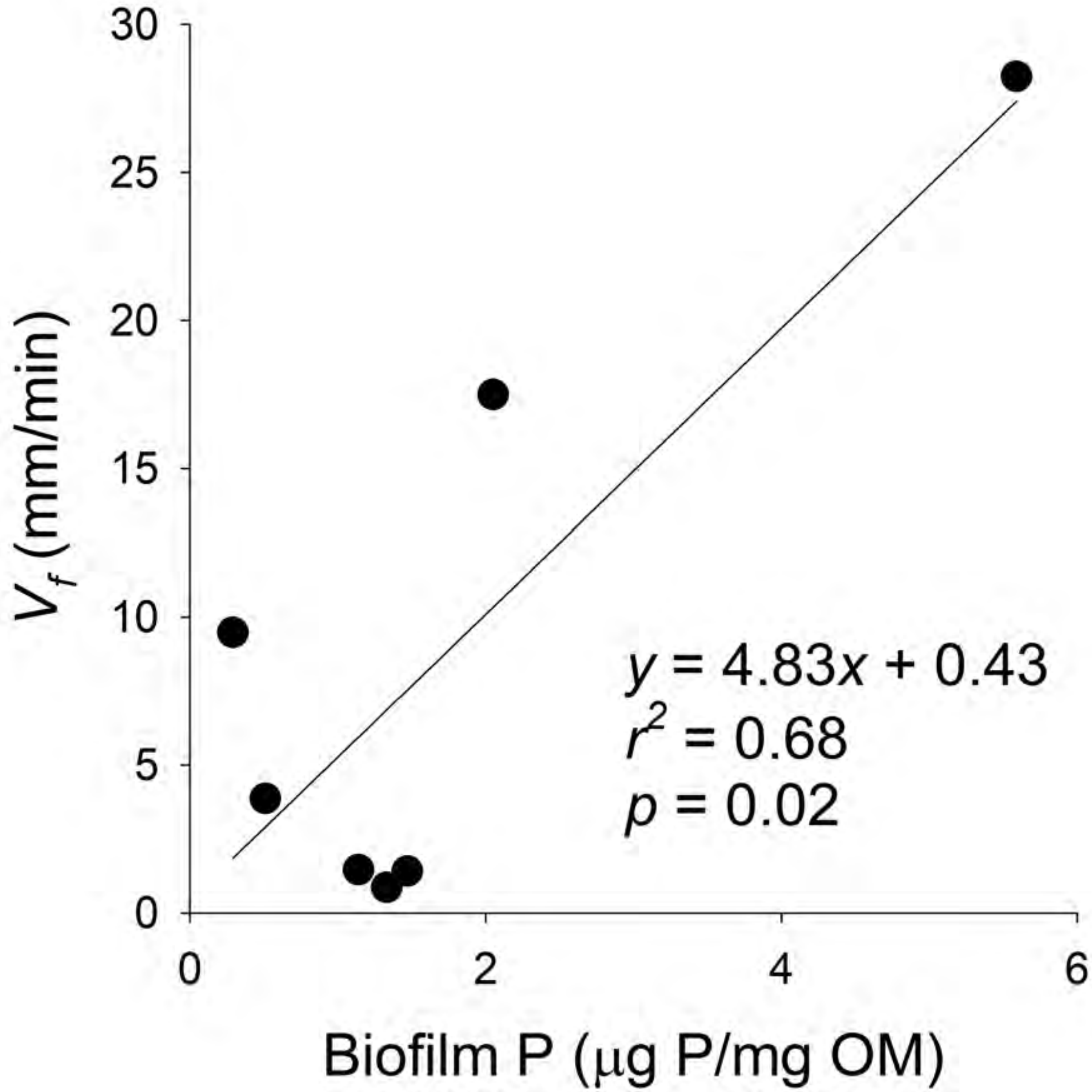


Uptake Velocity in the Edwards

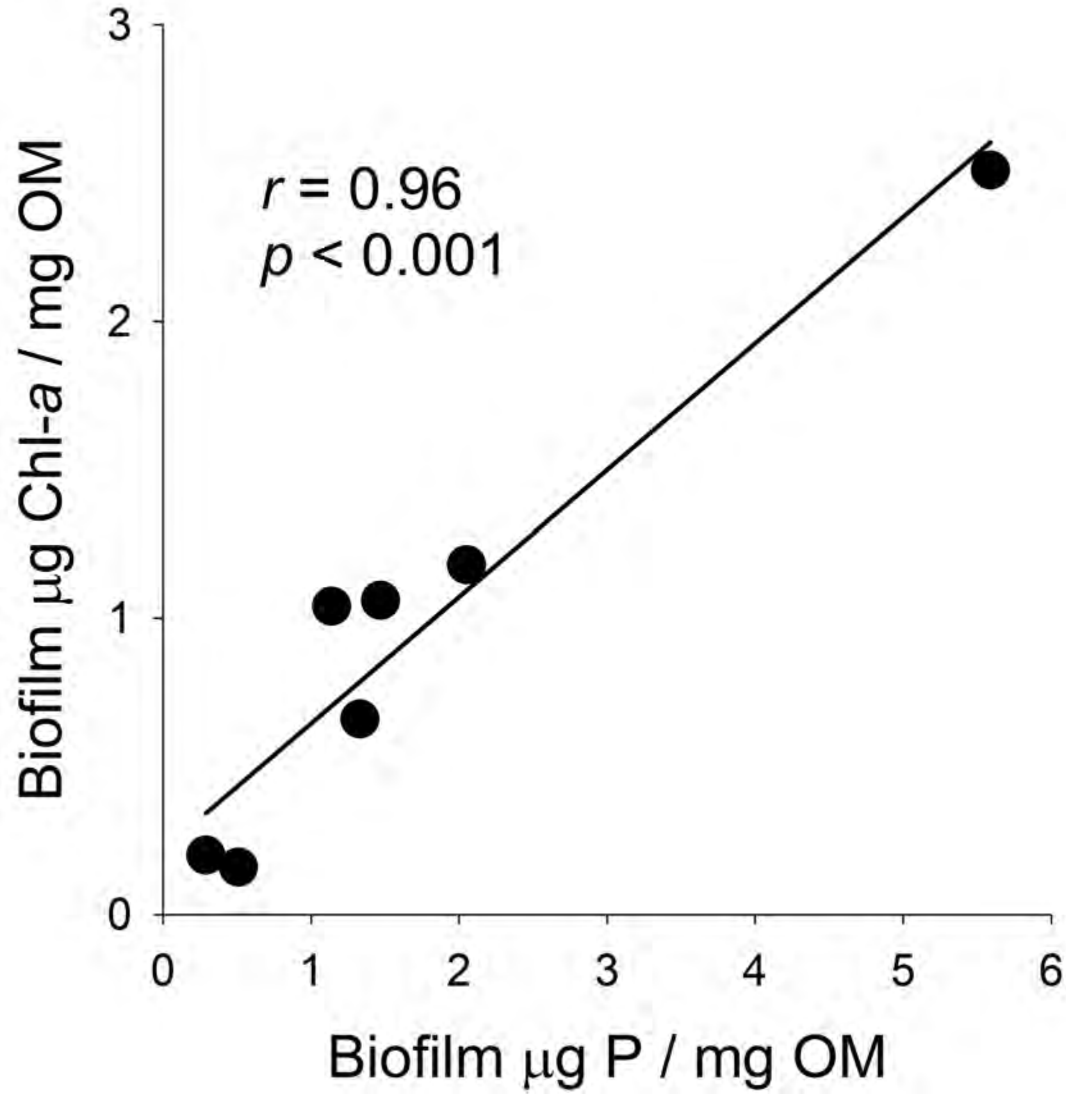


Uptake Velocity in the Edwards

Uptake Velocity in the Edwards



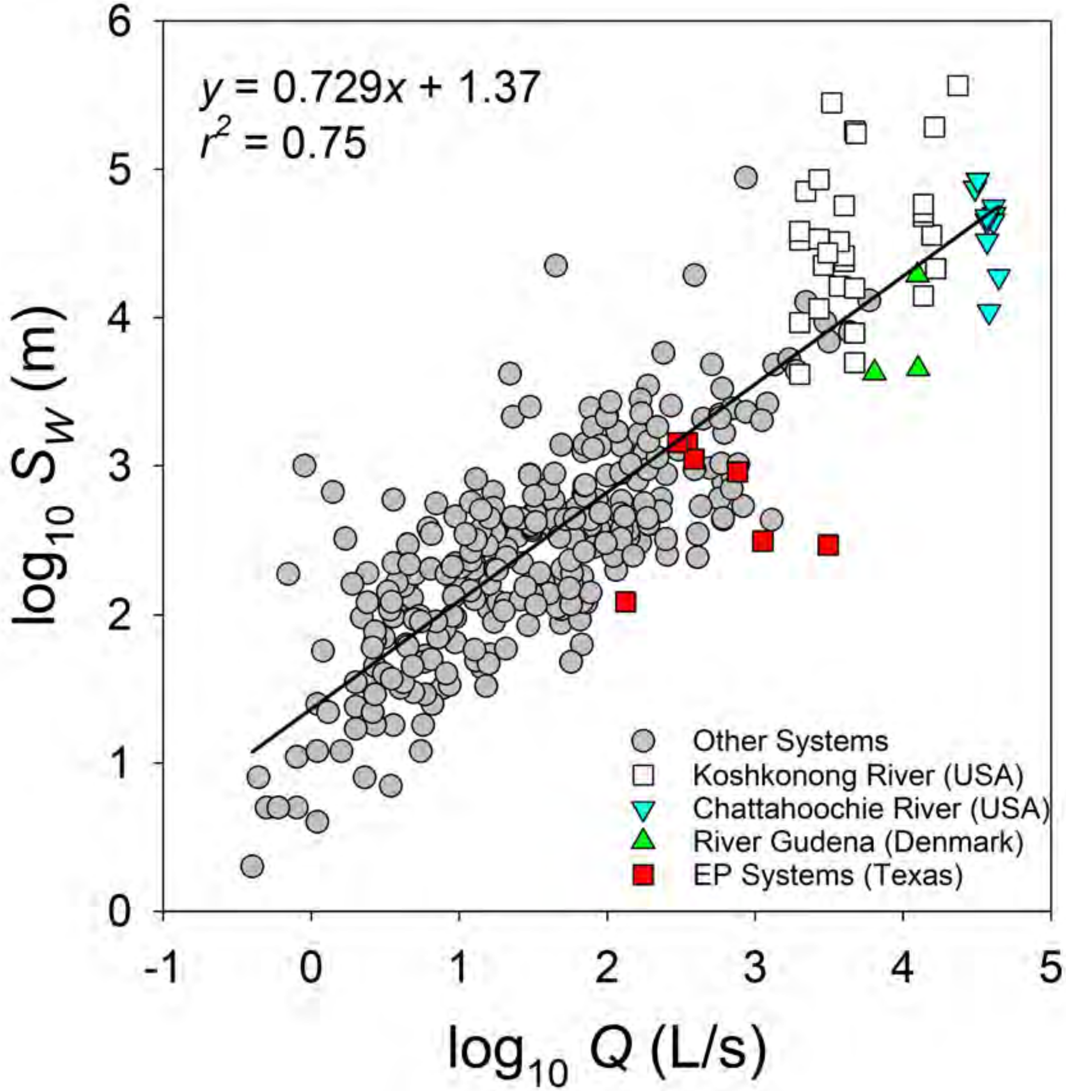
Uptake Velocity in the Edwards



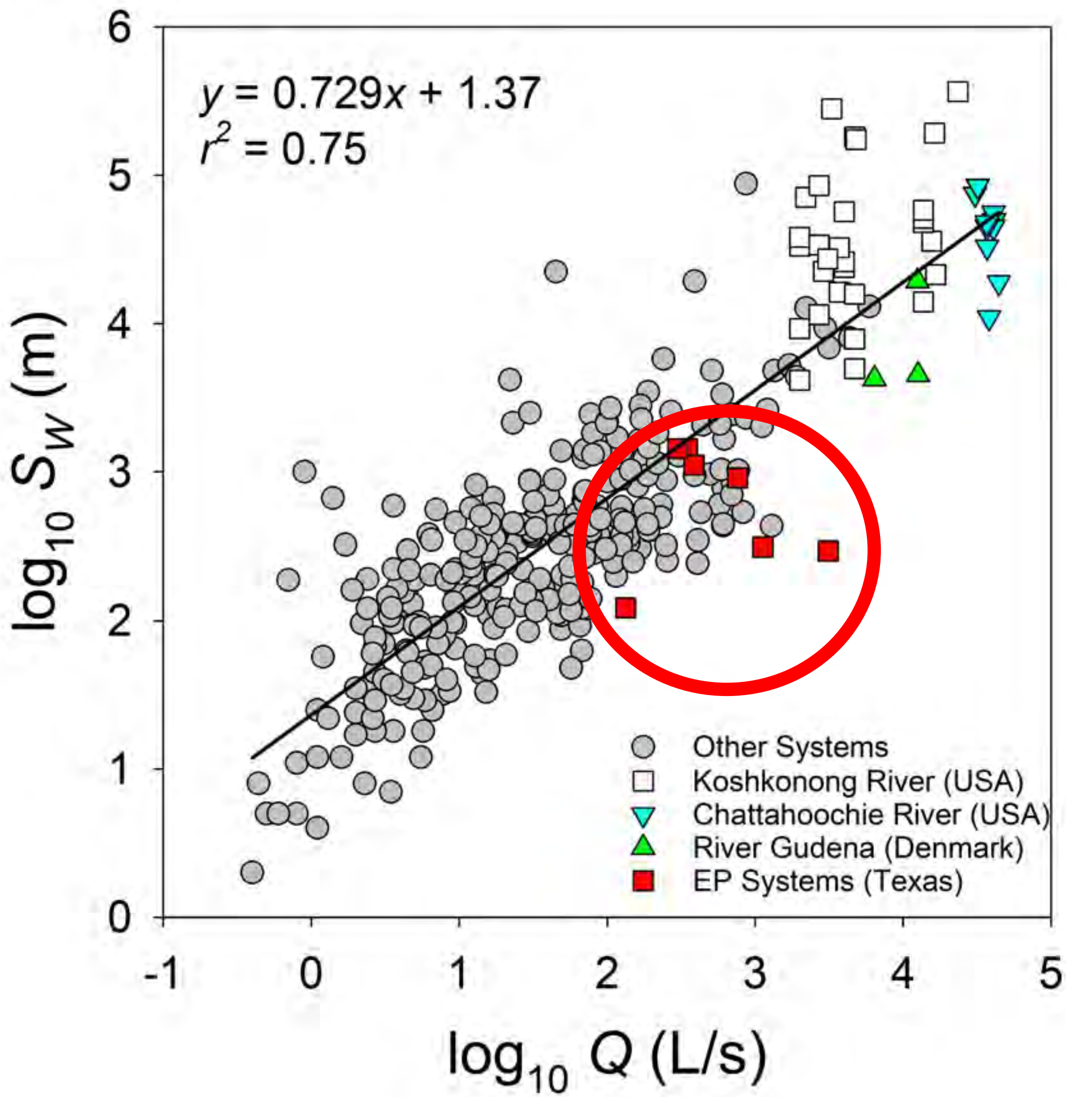
So, why should I care?

- EP systems = high affinity for P
  - 26 mm/min fastest estimated v_f (San Marcos River)
- Biofilms (algal portion) important
- Higher biofilm algal content = higher P content = rapid uptake
  - P-limitation common
  - Sensitive to P loading
- Compared to literature?

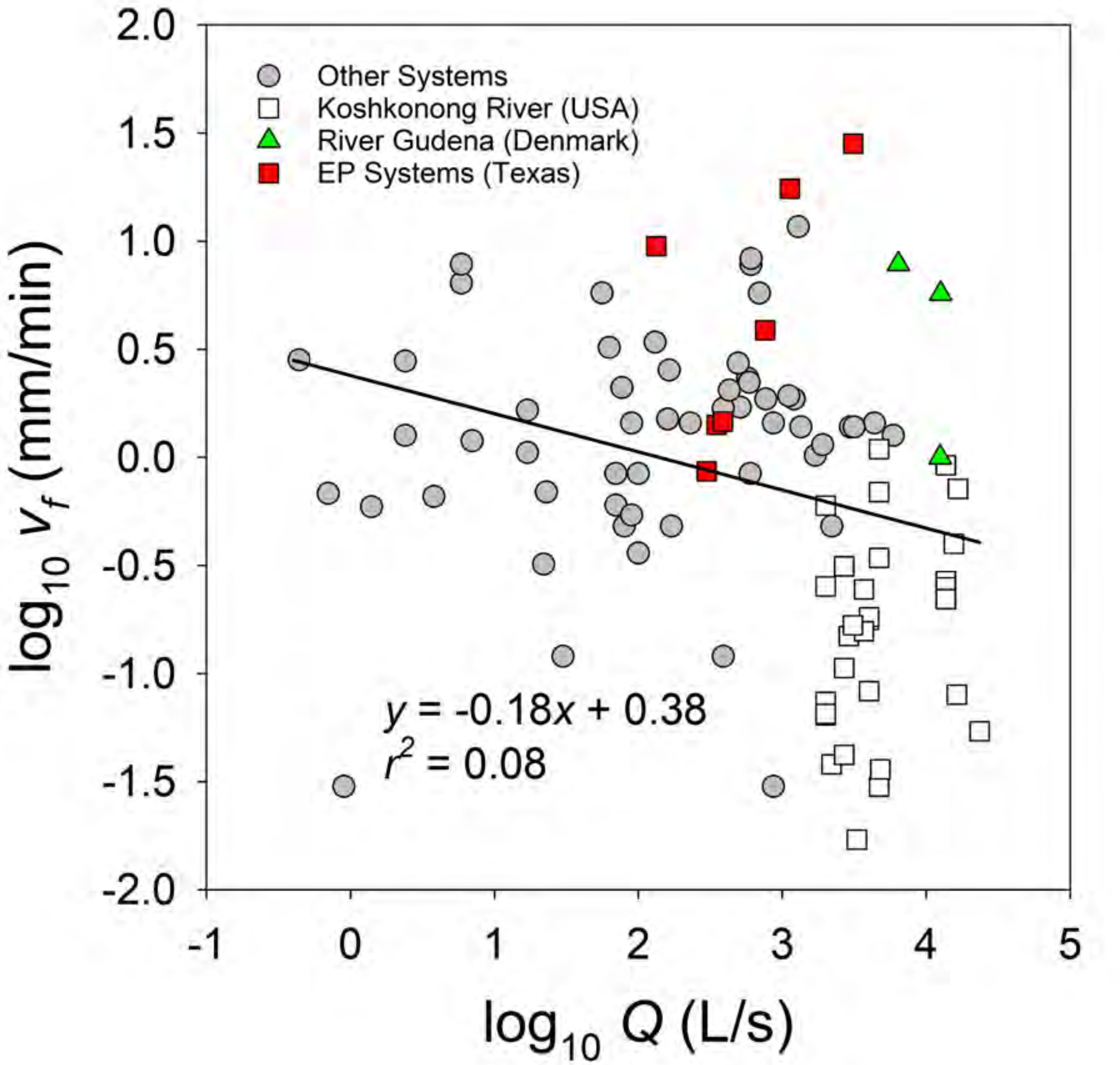
Global $Q - S_W$ Relationship



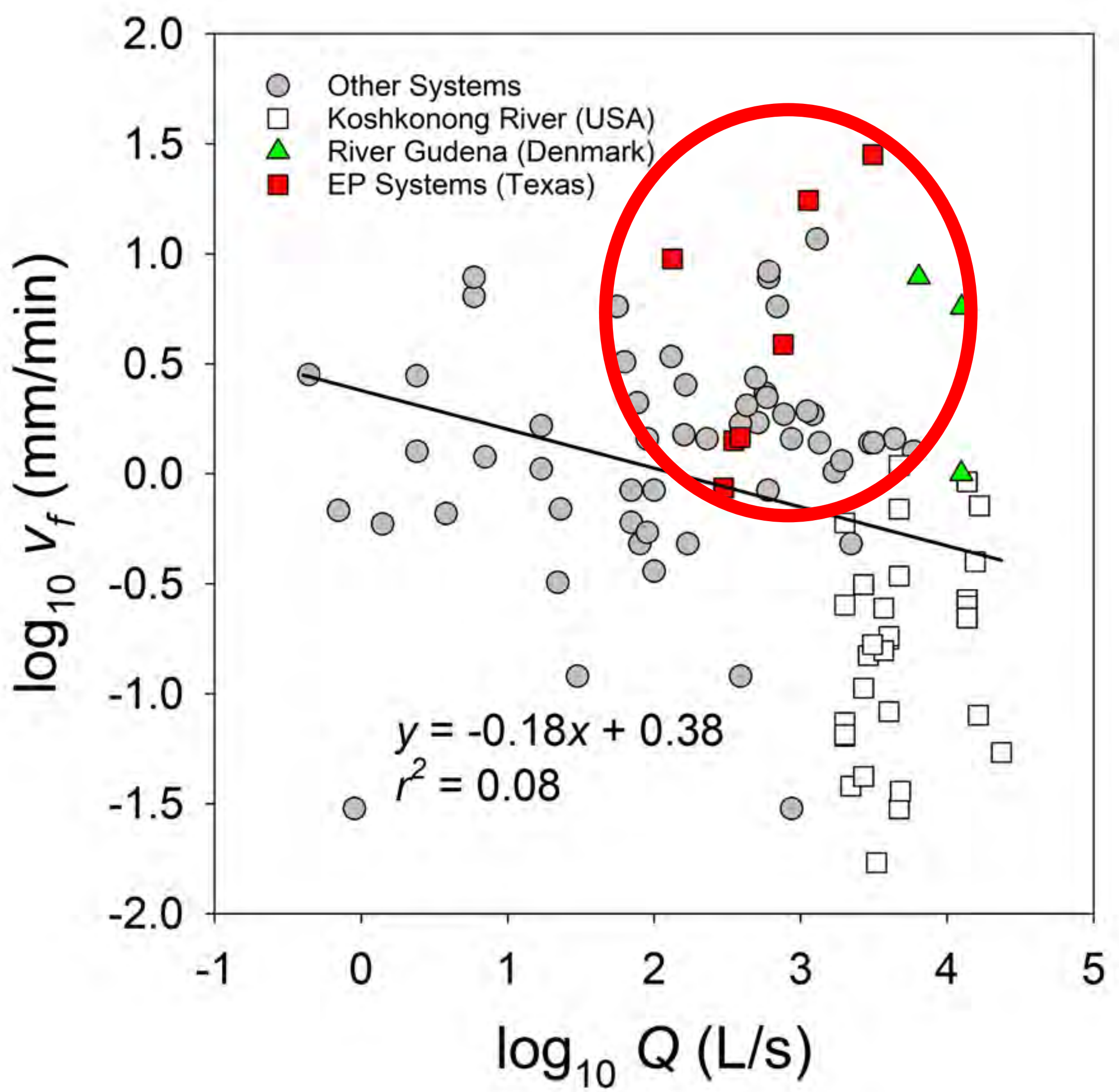
Global $Q - S_W$ Relationship



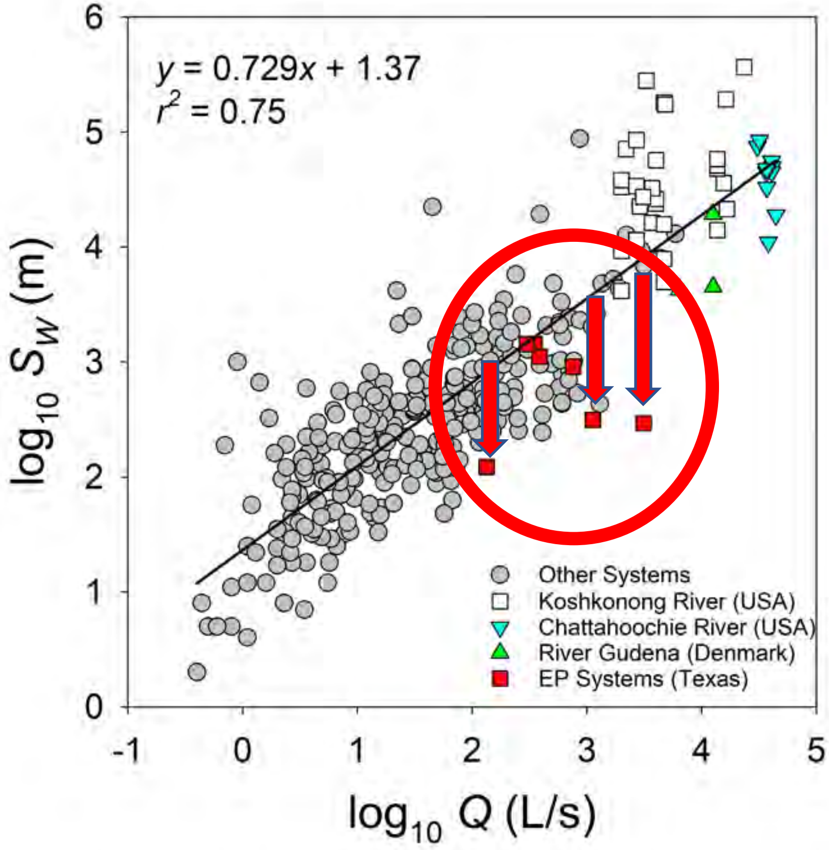
Global $Q - v_f$ Relationship

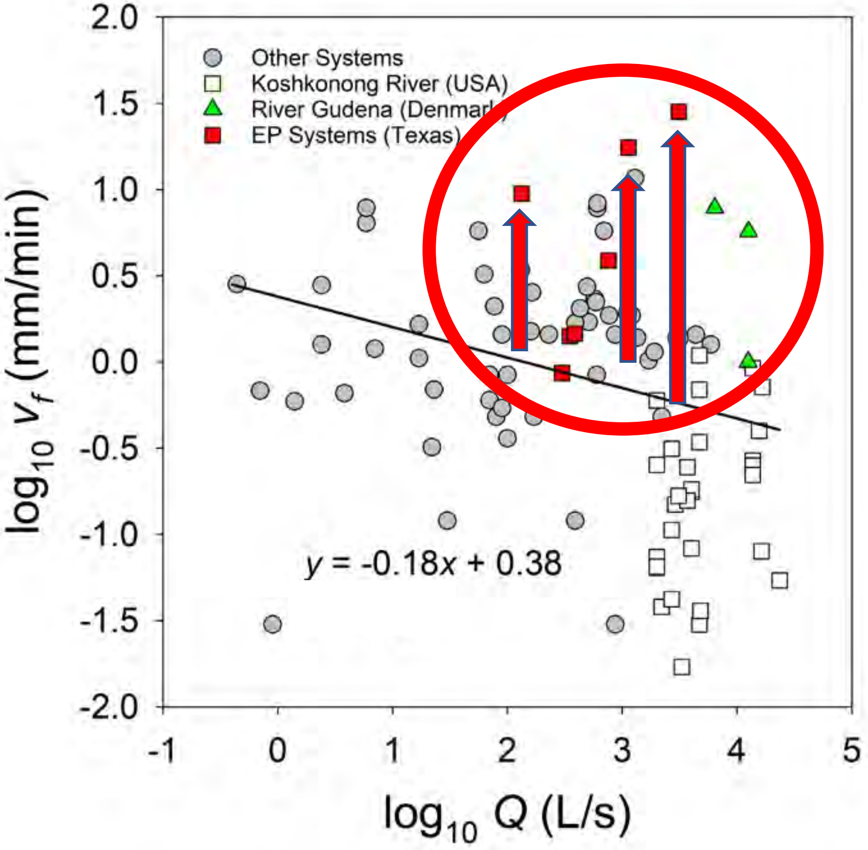


Global $Q - v_f$ Relationship

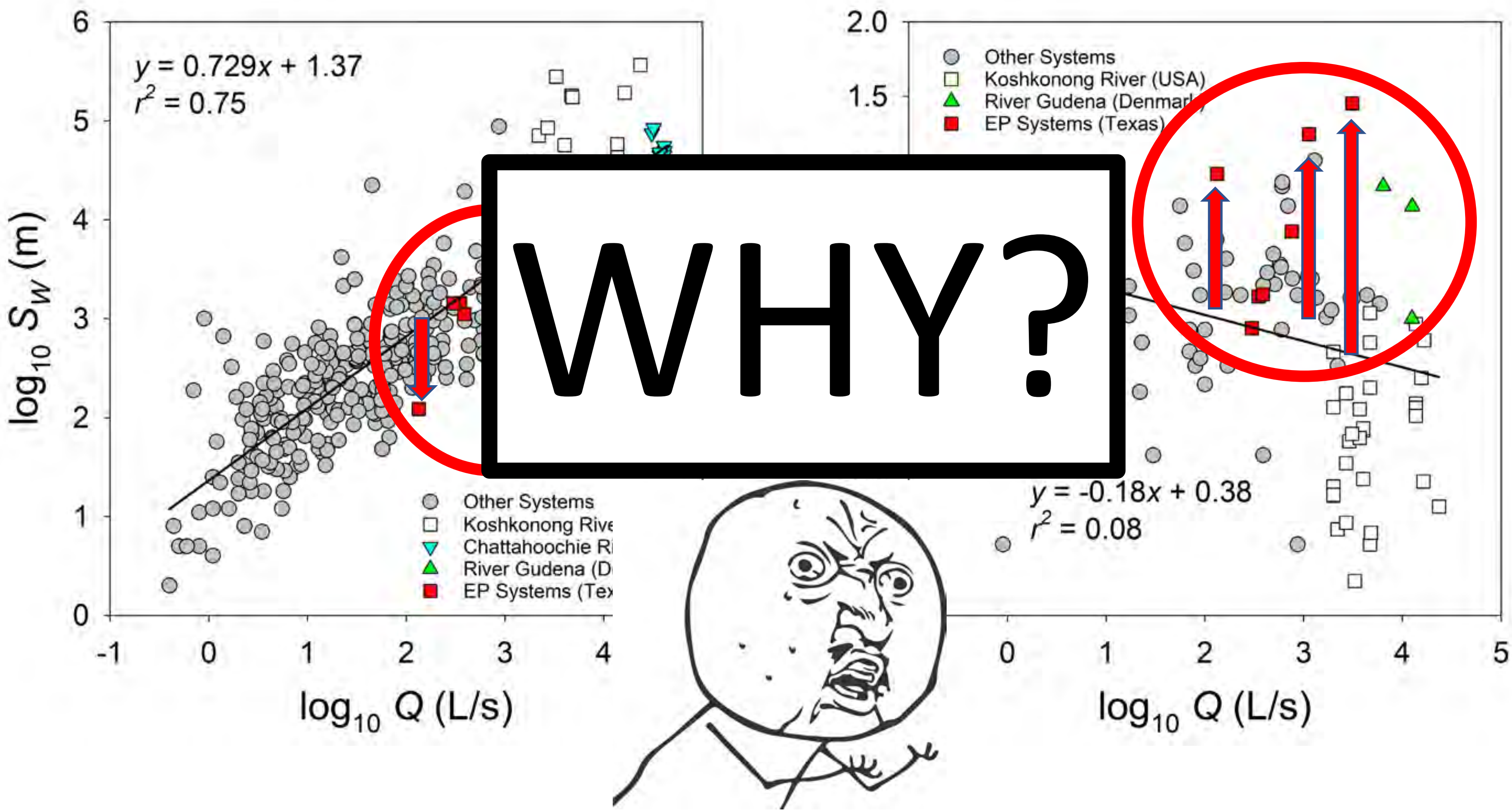


Each point is a "snowflake"...

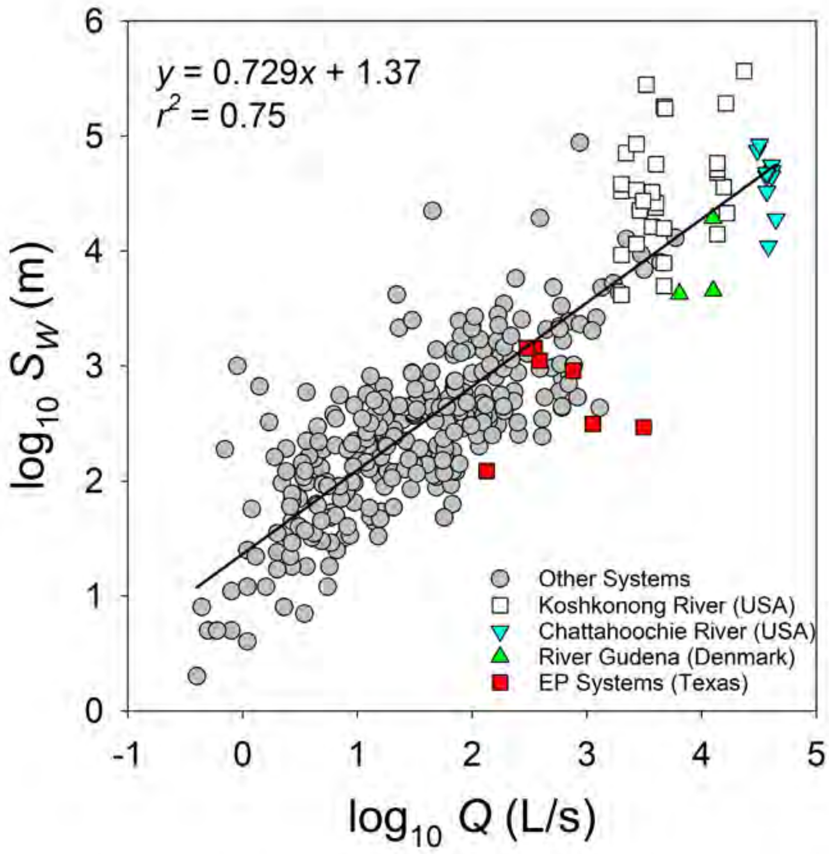


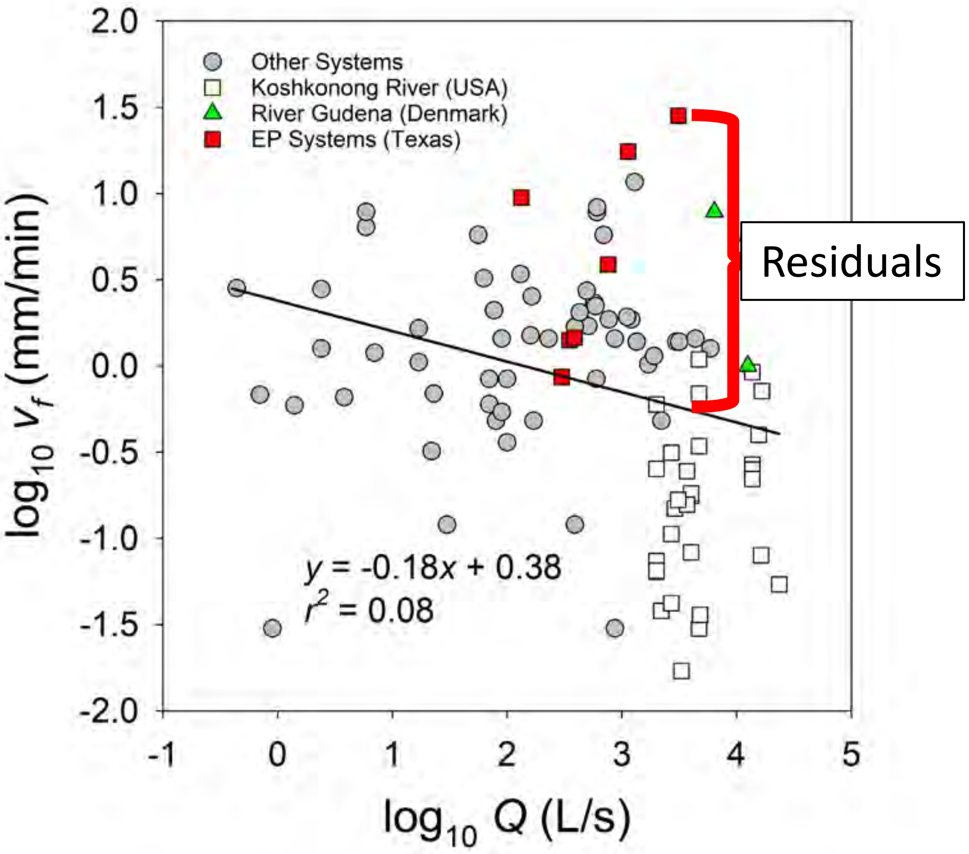


Each point is a "snowflake"…

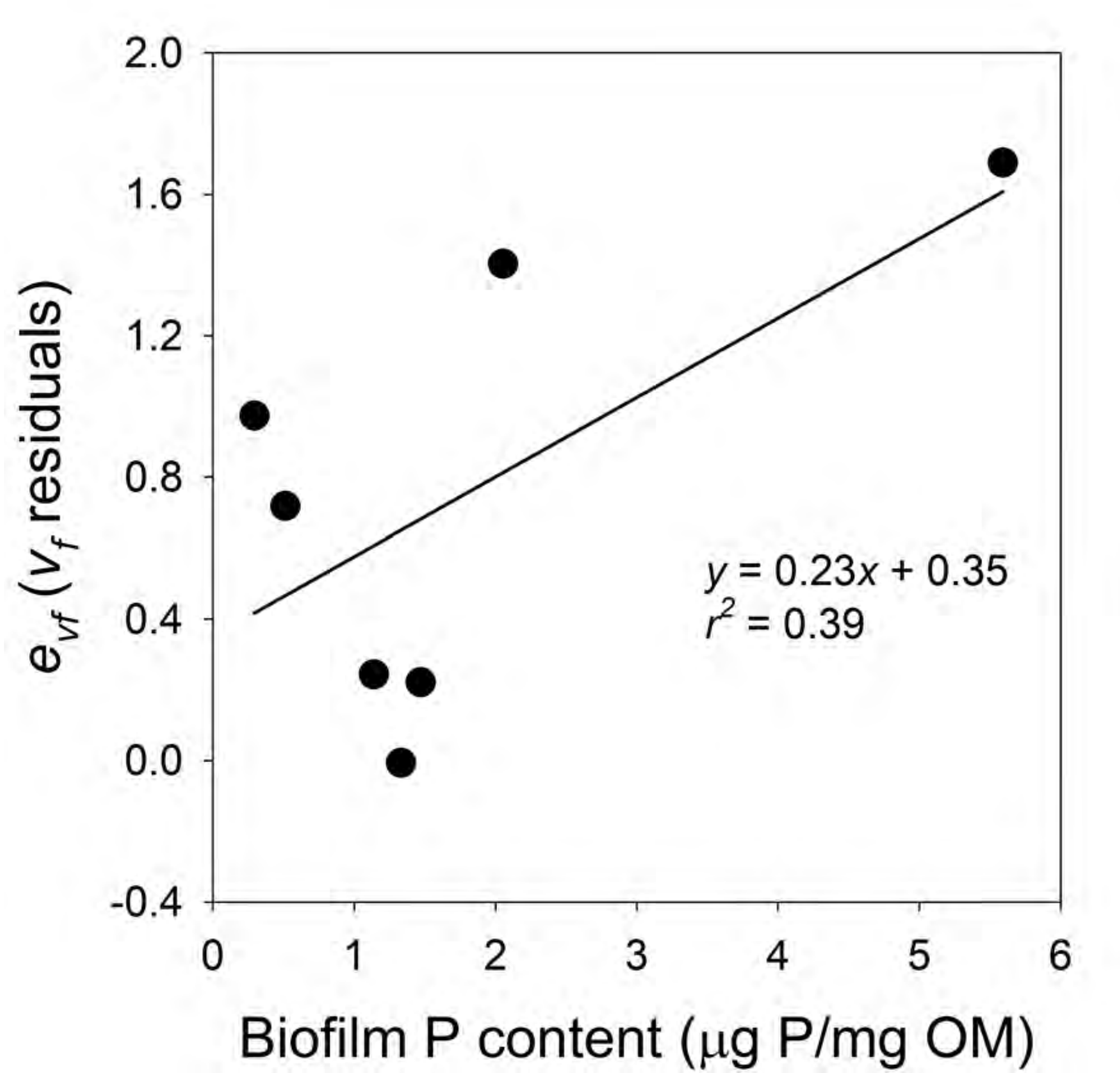


Each point is a "snowflake"…





EP System Residuals and Biofilms

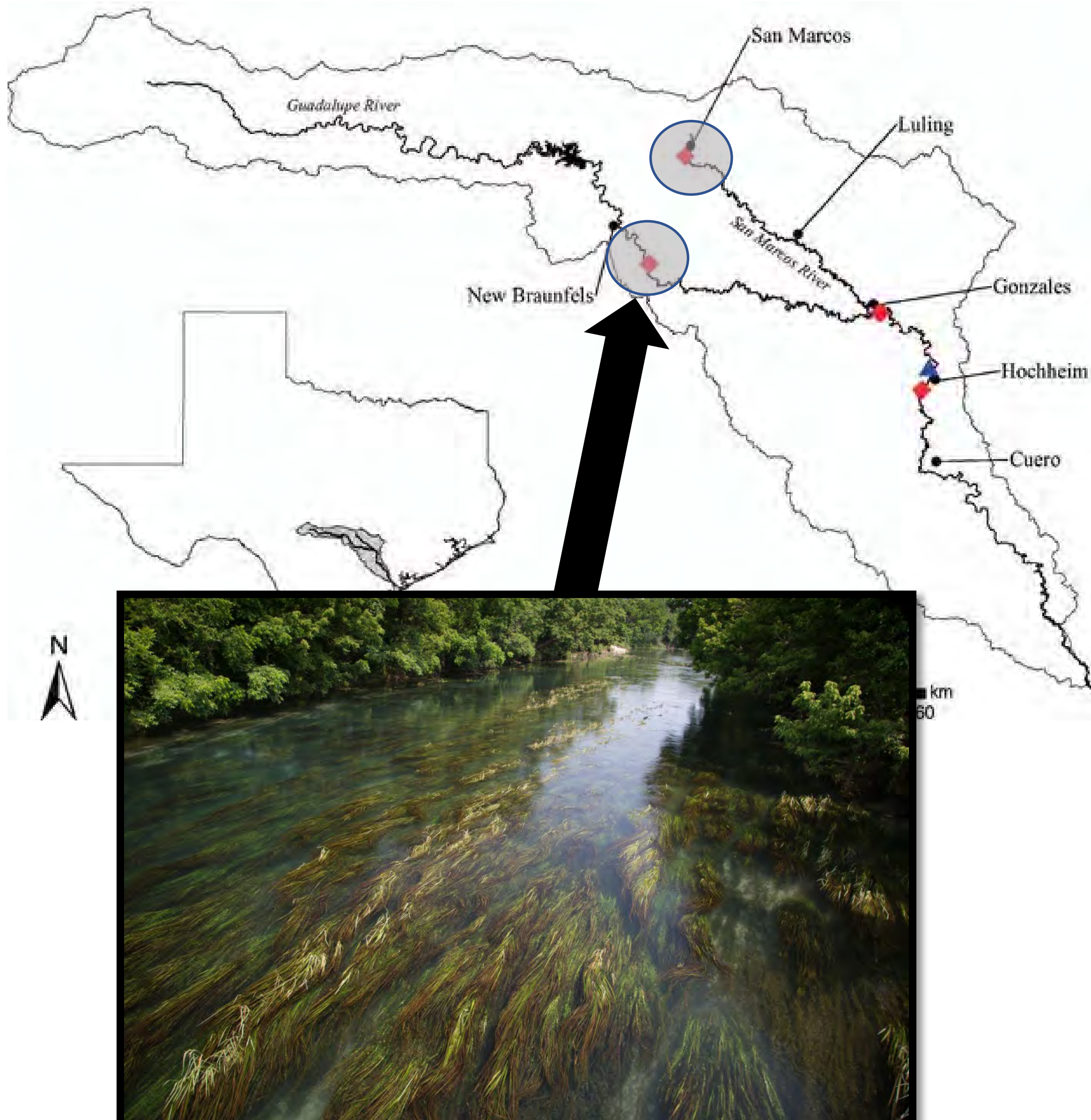


Putting it together (Part 1)

- Groundwater dominated rivers in the Edwards Plateau
  - Rapid nutrient uptake (P)
  - Algal portion of biofilms important
- Scaling up?
  - Increased Q = longer S_W
  - Headwaters = important sites of P retention
  - Downstream = increased turbidity, longer S_W, decreased retention, more downstream export

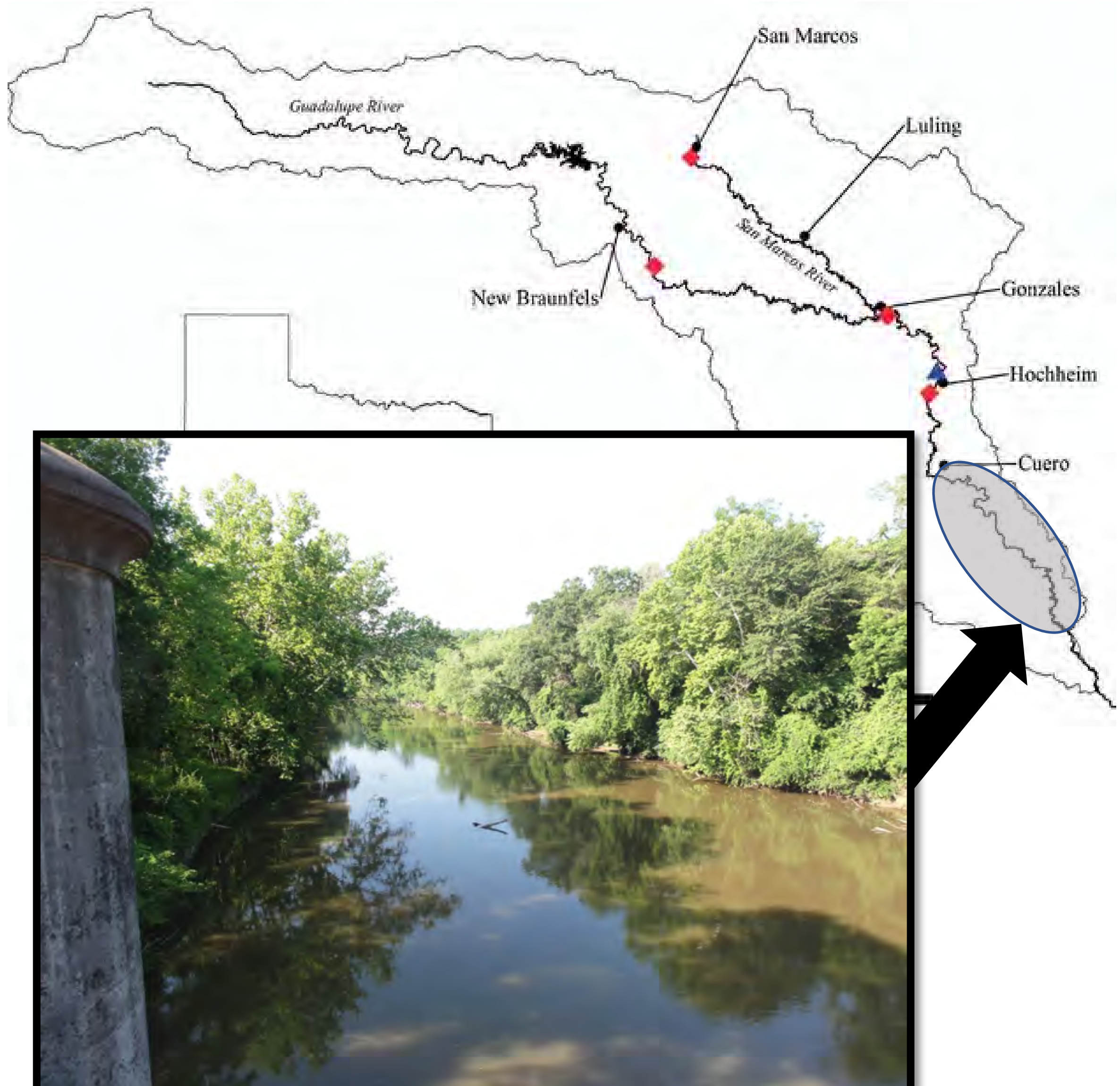
Putting it together (Part 1)

- Groundwater dominated rivers in the Edwards Plateau
  - Rapid nutrient uptake (P)
  - Algal portion of biofilms important
- Scaling up?
  - Increased Q = longer S_W
  - Headwaters = important sites of P retention
  - Downstream = increased turbidity, longer S_W, decreased retention, more downstream export



Putting it together (Part 1)

- Groundwater dominated rivers in the Edwards Plateau
  - Rapid nutrient uptake (P)
  - Algal portion of biofilms important
- Scaling up?
  - Increased Q = longer S_W
  - Headwaters = important sites of P retention
  - Downstream = increased turbidity, longer S_W, decreased retention, more downstream export



Today's Talk

- Phosphorus uptake in groundwater dominated rivers
  - Retention of P in rivers and how does this scale across systems?
  - How do groundwater dominated rivers relate to a "global" river dataset?

- Metabolism of groundwater dominated rivers
  - Seasonal variation in production and respiration in a groundwater dominated river?
  - Role of macrophytes and epiphytes?
  - How do groundwater dominated rivers relate to a "global" dataset?

Groundwater Dominated Rivers

- Seasonal and interannual "stable" flows
- High water clarity
- Physicochemical consistency
- Higher *Q* than predicted by stream order

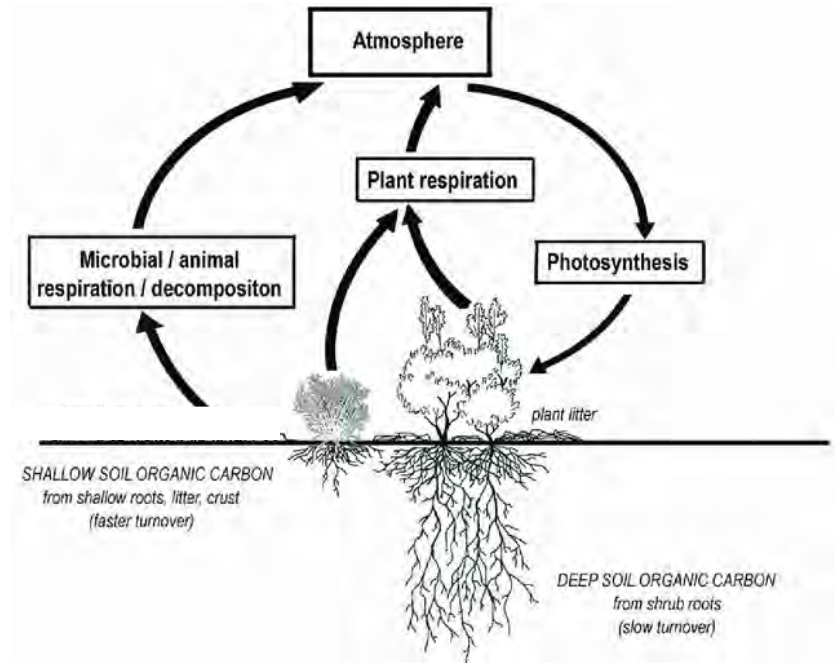
- Can GW rivers be used to understand scaling ecosystem processes?
- Are they "unique" ecosystems and can they inform us of processes in rivers, in general?

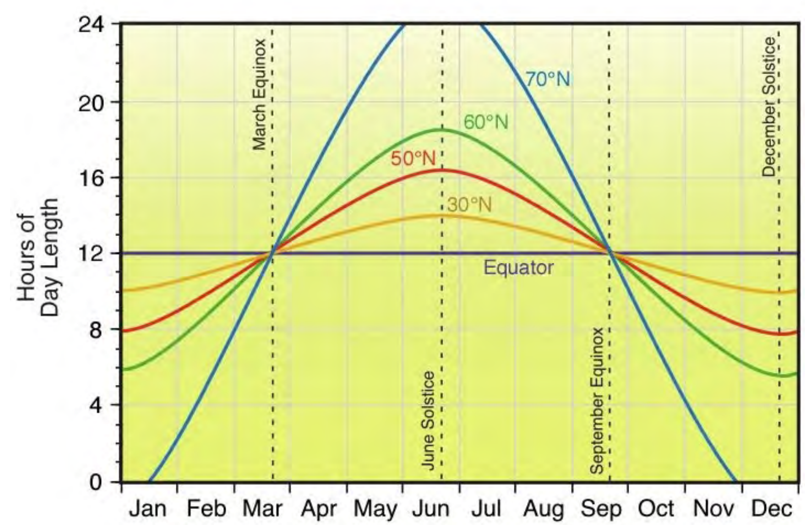
Ecosystem Metabolism?

- Much like metabolism at the "individual" level…
- Primary production (PP)
  - Amount of C fixed by primary producers
  - Some respiratory loss (R_{plant})
  - Gross primary production (GPP) versus net primary production (NPP)
- Ecosystem respiration (ER)
  - Respiration losses via heterotrophs (R_{hetero})
  - Respiration losses via plants (R_{plant})

Ecosystem Metabolism

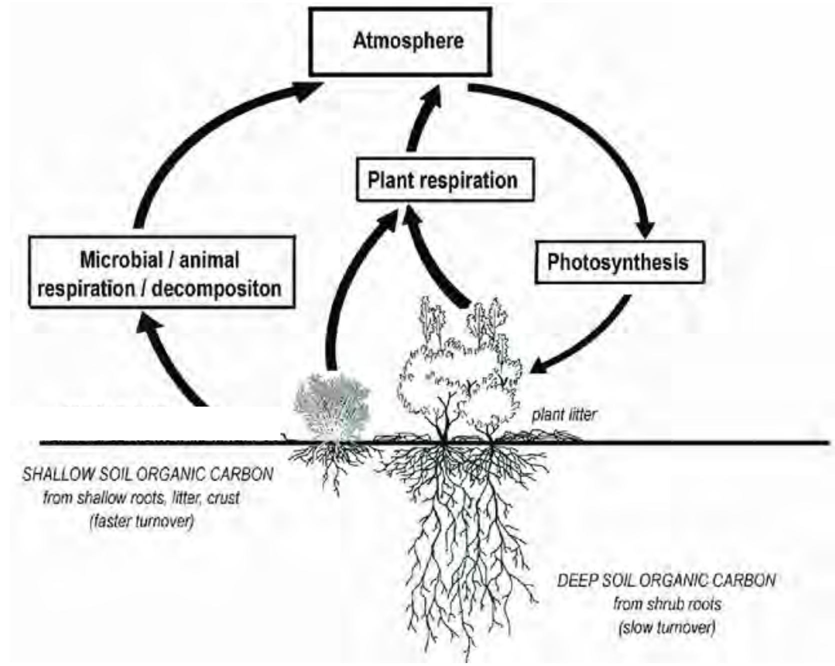
- Drivers of metabolism
- <u>Primary Production</u>
  - <u>Light</u> – day length, intensity, seasonal variation
  - <u>Nutrients</u> – N and P
  - <u>Temperature</u> – secondary role



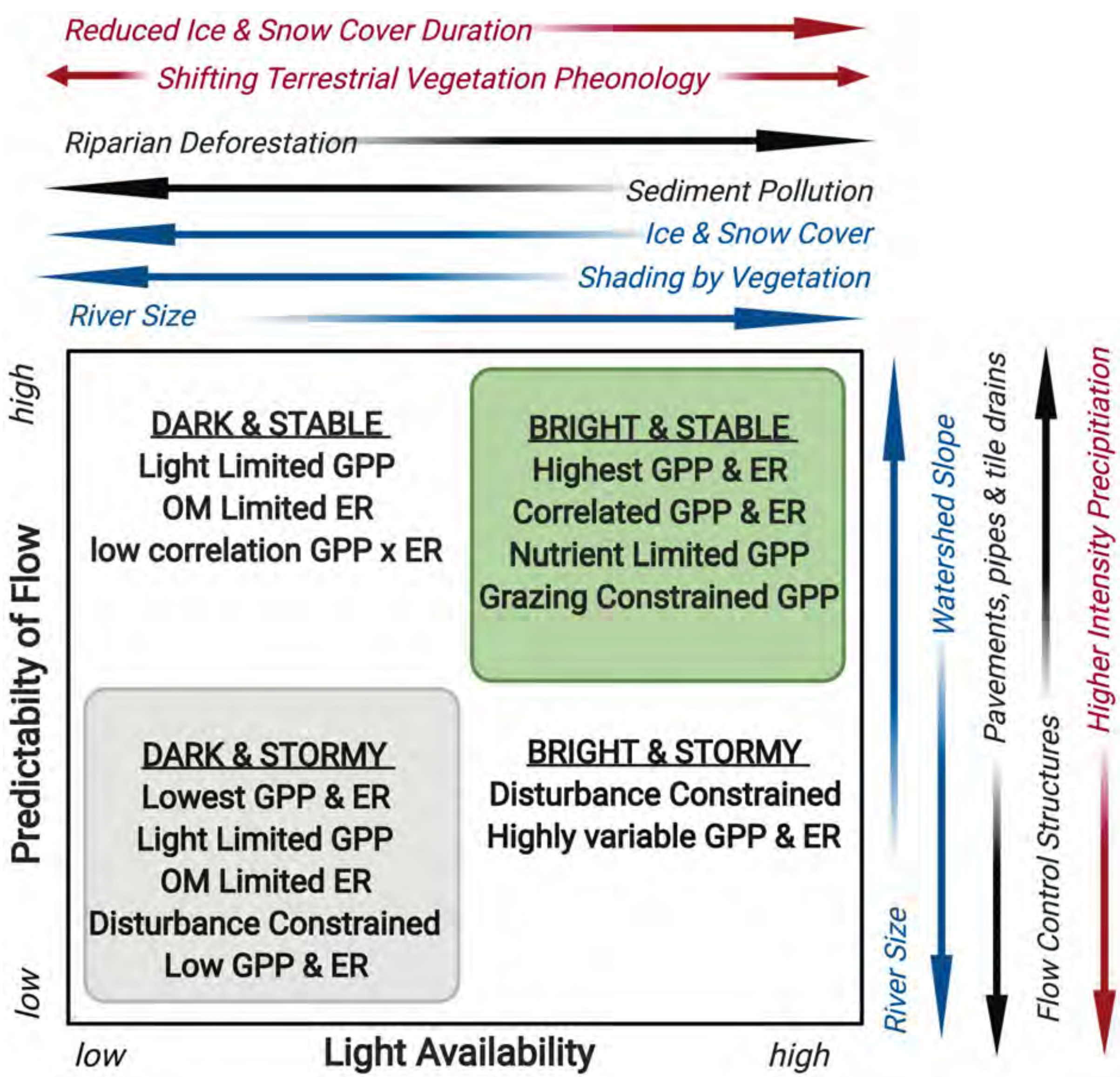


Ecosystem Metabolism

- Drivers of metabolism
- <u>Ecosystem Respiration</u>
  - <u>Temperature</u>
  - <u>Supply of OM</u>
    - Light and nutrients

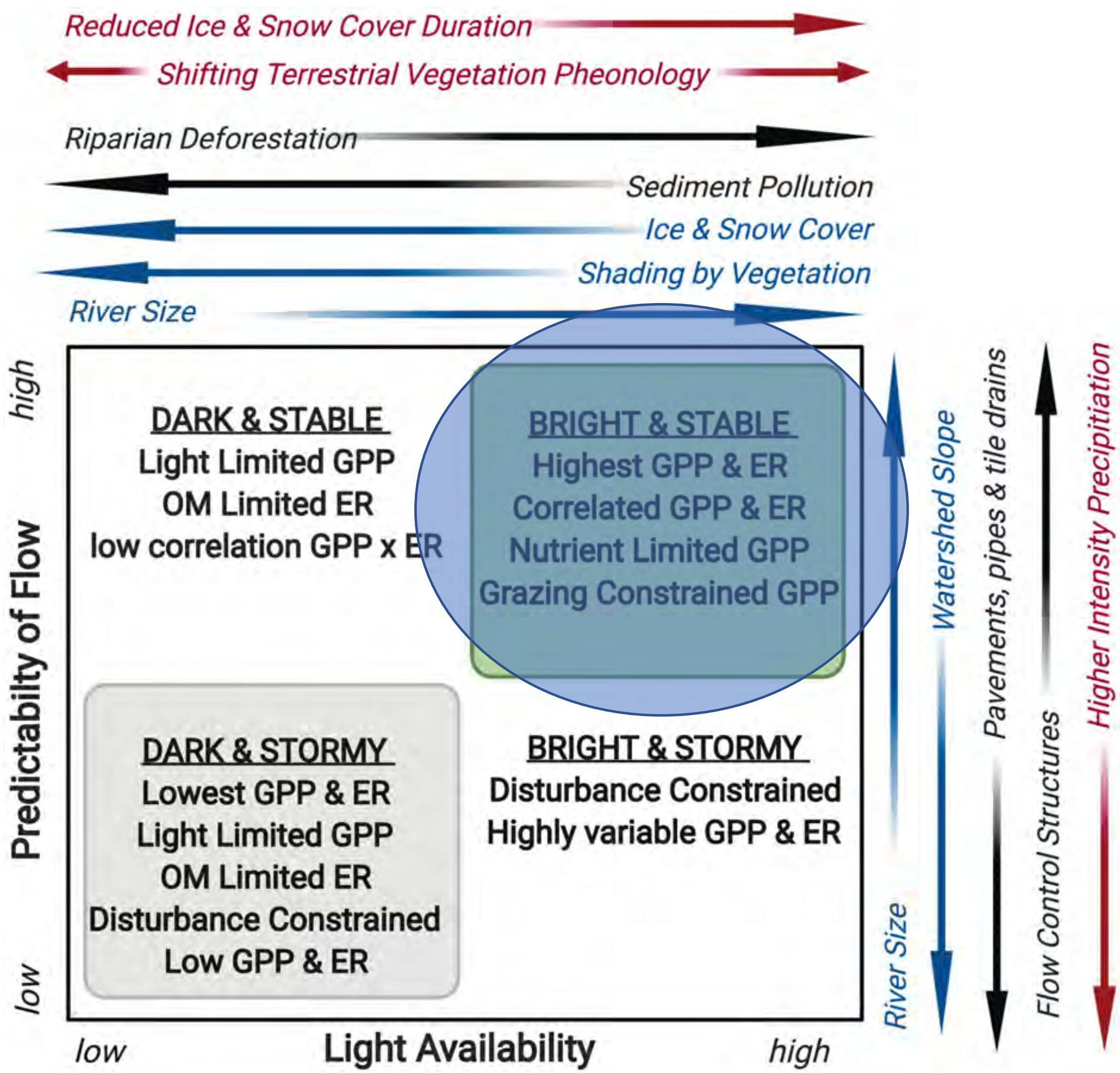


Drivers of River Metabolism



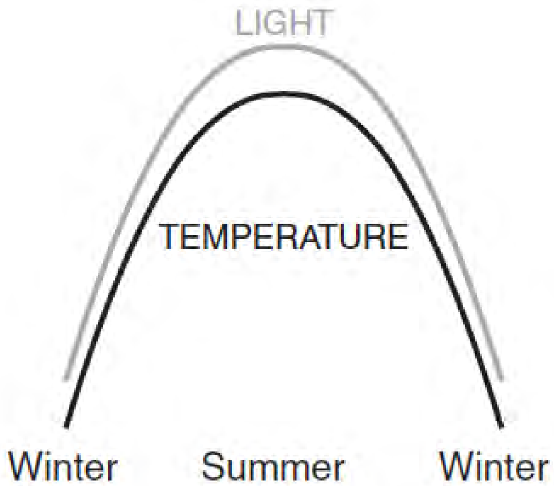
Bernhardt et al. 2022

Drivers of River Metabolism



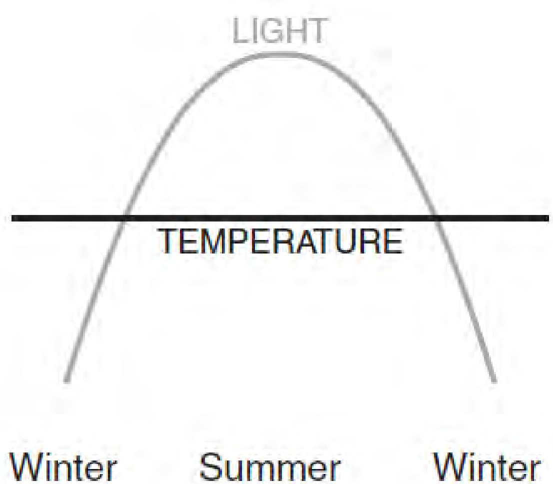
Bernhardt et al. 2022

“Typical” Rivers

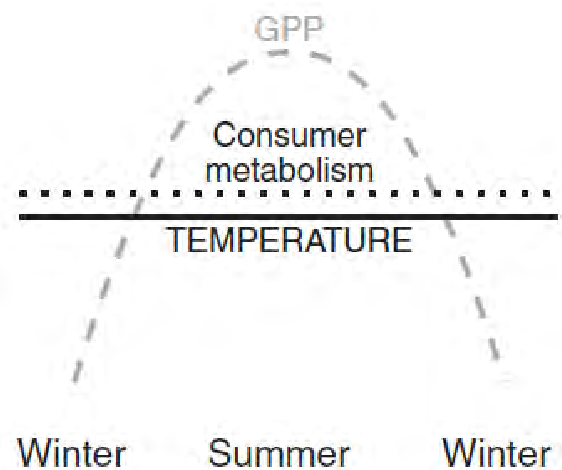


GPP and ER Coupled

Groundwater Dominated Rivers

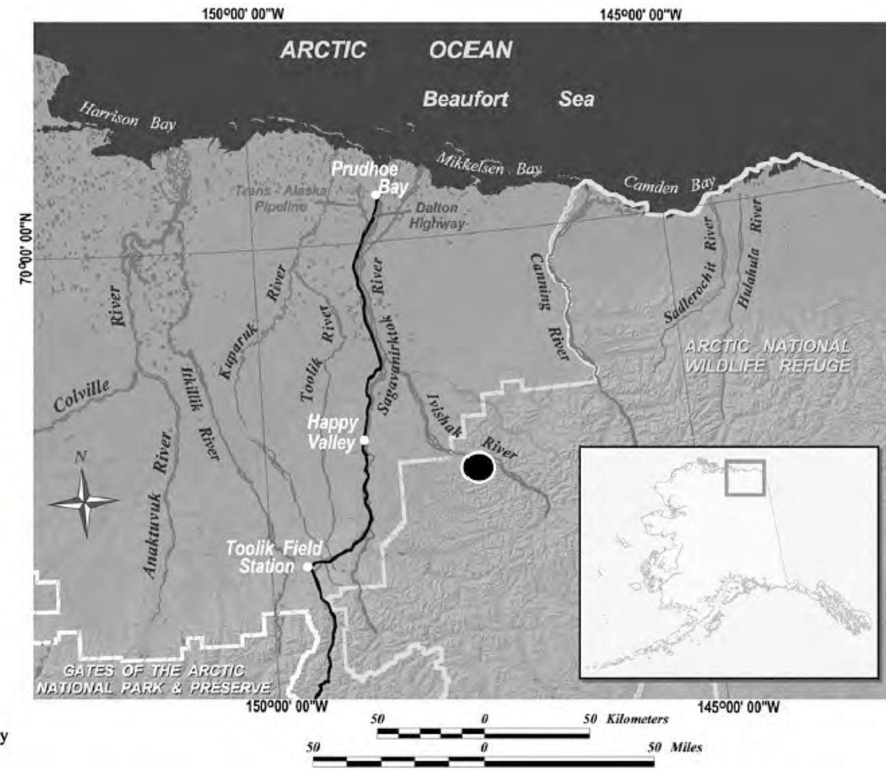


GPP and ER Decoupled

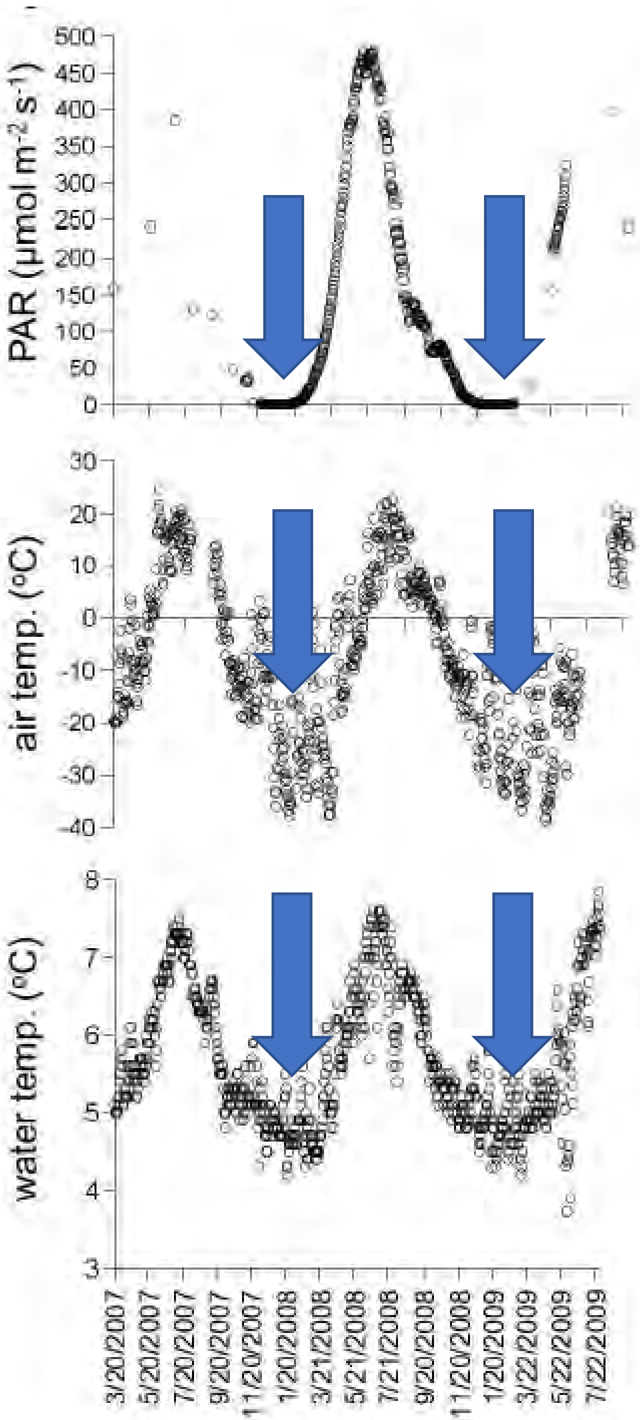


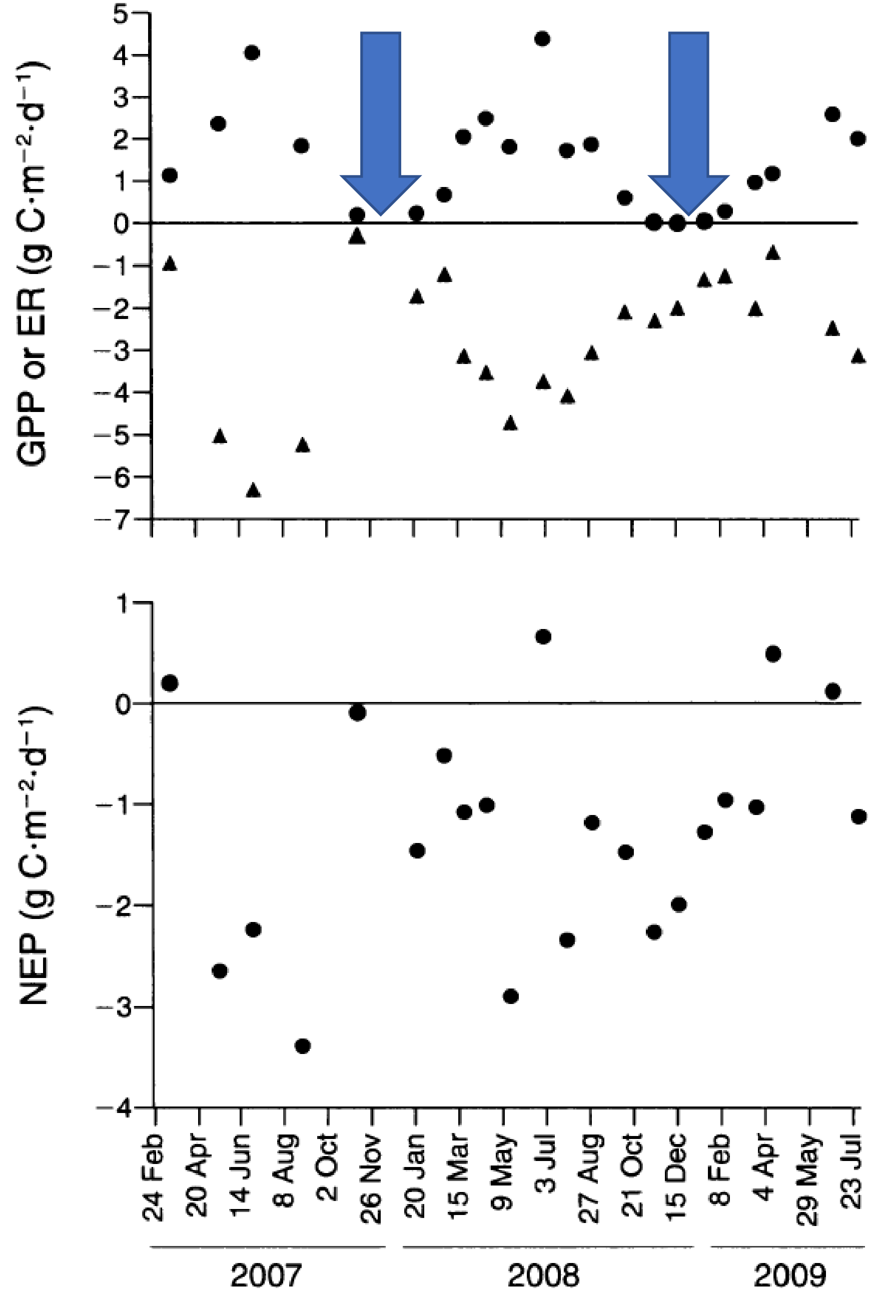
Huryn and Benstead 2019

PLATE 1. Photo of the study reach of Ivishak Spring stream (69.023814° N, 147.721335° W, Alaska, USA) taken on 25 January 2008. The air temperature at the time this photo was taken was −40.0°C; the water temperature was ~5°C.



Huryn and Benstead 2019





Huryn and Benstead 2019

Questions and Predictions

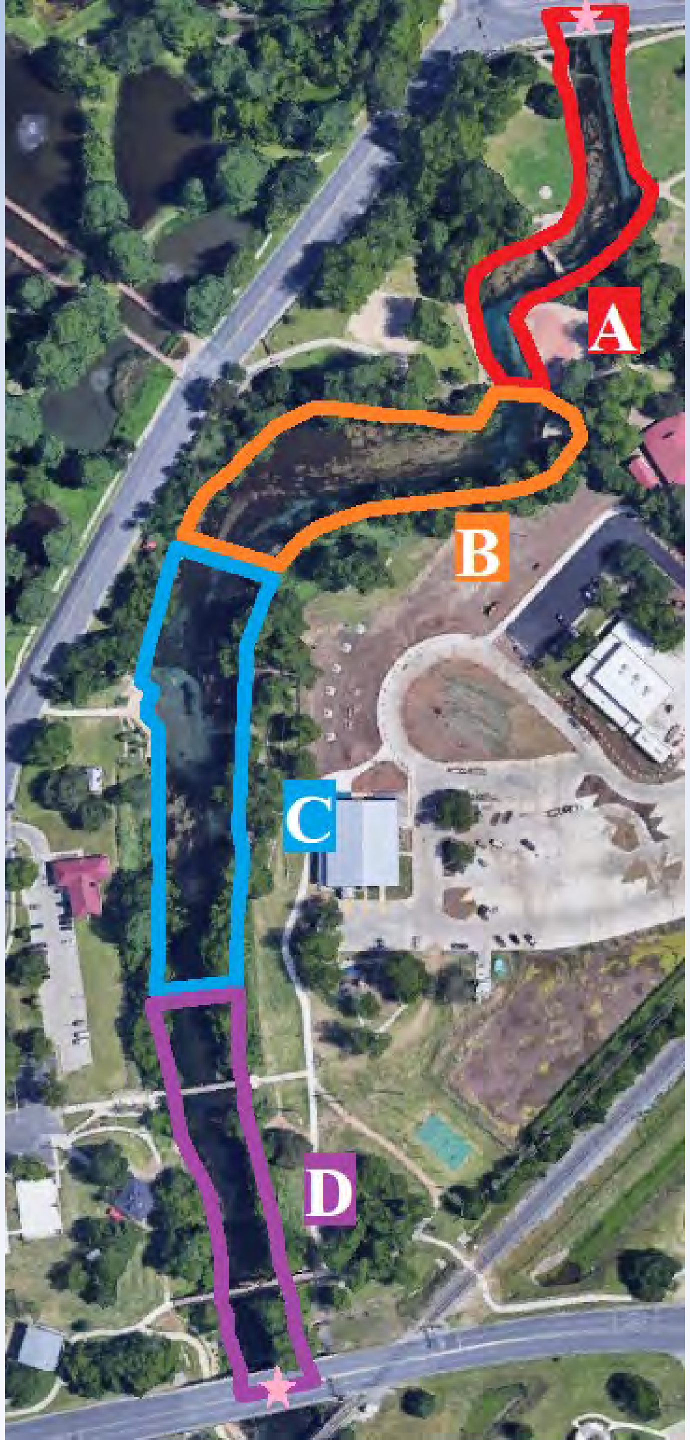
- Does metabolism in a sub-tropical, groundwater dominated river change with season?
  - Metabolism is positively correlated with seasonal light availability; GPP & ER highest in summer, lowest in winter

- Does seasonal variation in macrophyte biomass affect metabolism?
  - Macrophyte biomass is positively correlated with seasonal light availability and influences GPP & ER.

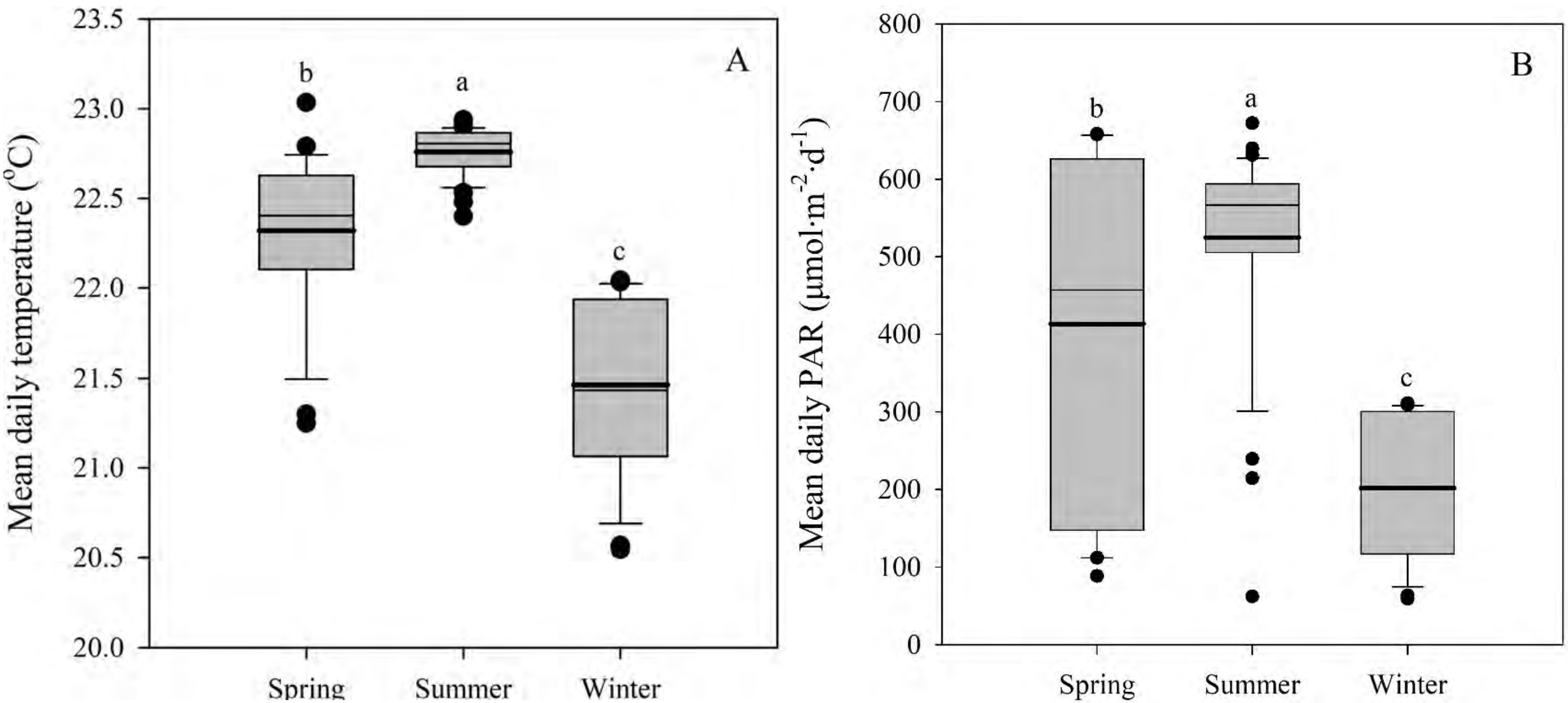
- Does metabolism of a sub-tropical, groundwater dominated river with abundant macrophytes differ from surface water dominated rivers?
  - Due to abundant macrophyte biomass, GPP & ER will be relatively high compared to the literature

Methods

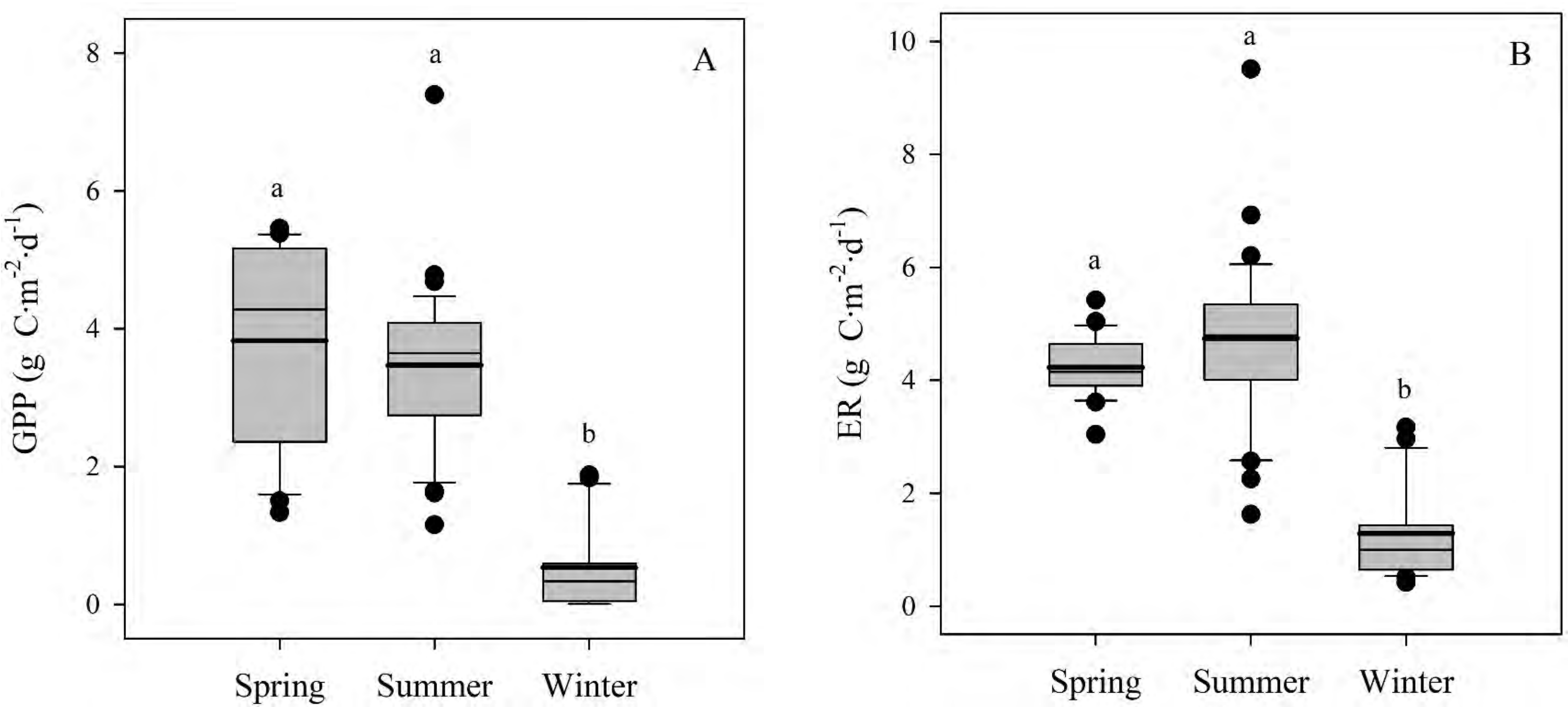
- Performed in the upper San Marcos River (Texas)
- DO, Temp, Depth, PAR
  - Spring (4/20/2021 – 5/12/2021; *n* = 23)
  - Summer (7/17/2021 – 8/23/2021; *n* = 38)
  - Winter (12/20/2021 – 1/10/2022; *n* = 25)
- streamMetabolizer (Appling et al. 2018)
  - GPP + ER = NEP
  - Arrhenius plots
  - ANOVA: Metabolism ~ Season



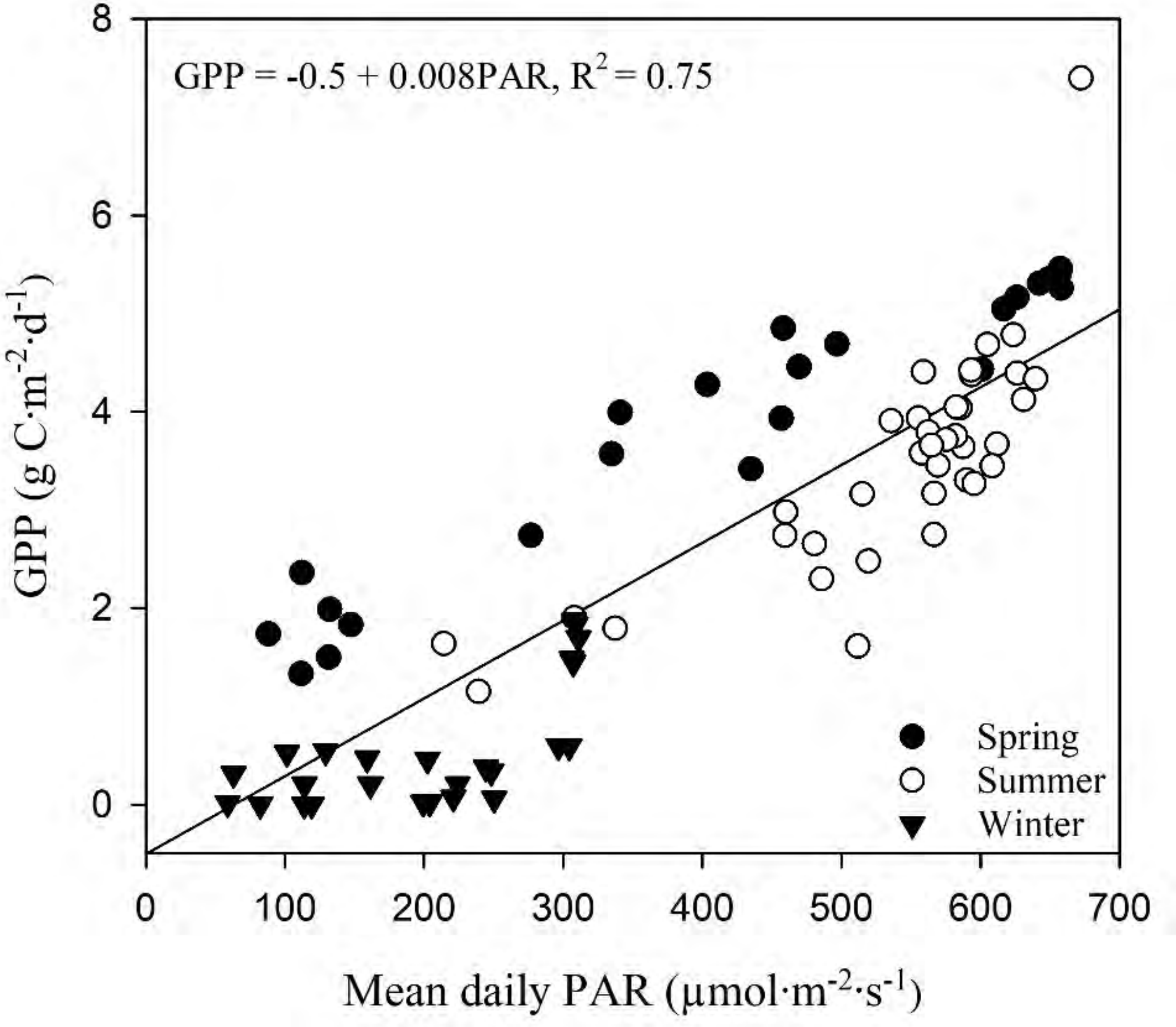
Seasonal Variation in Light and Temperature

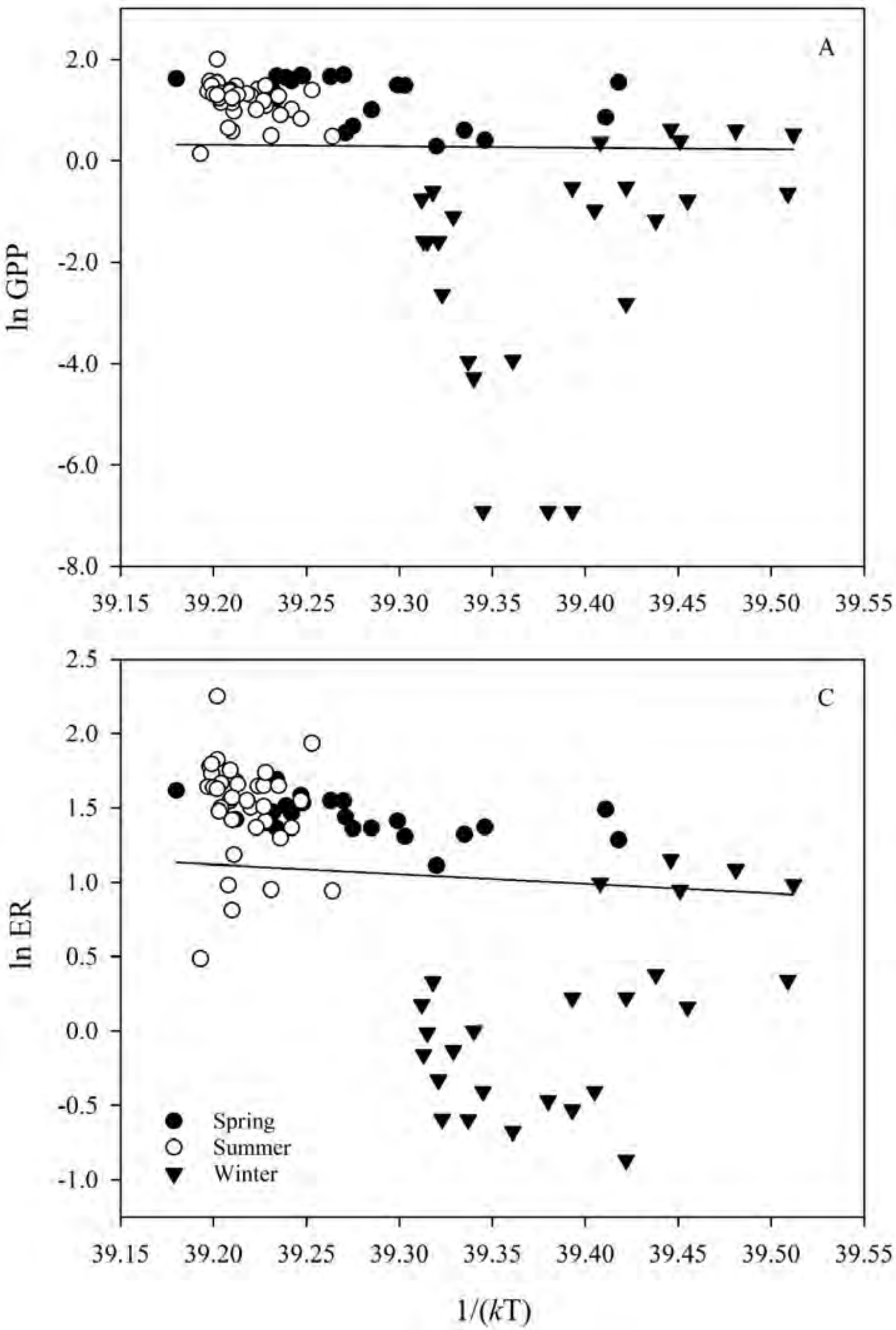


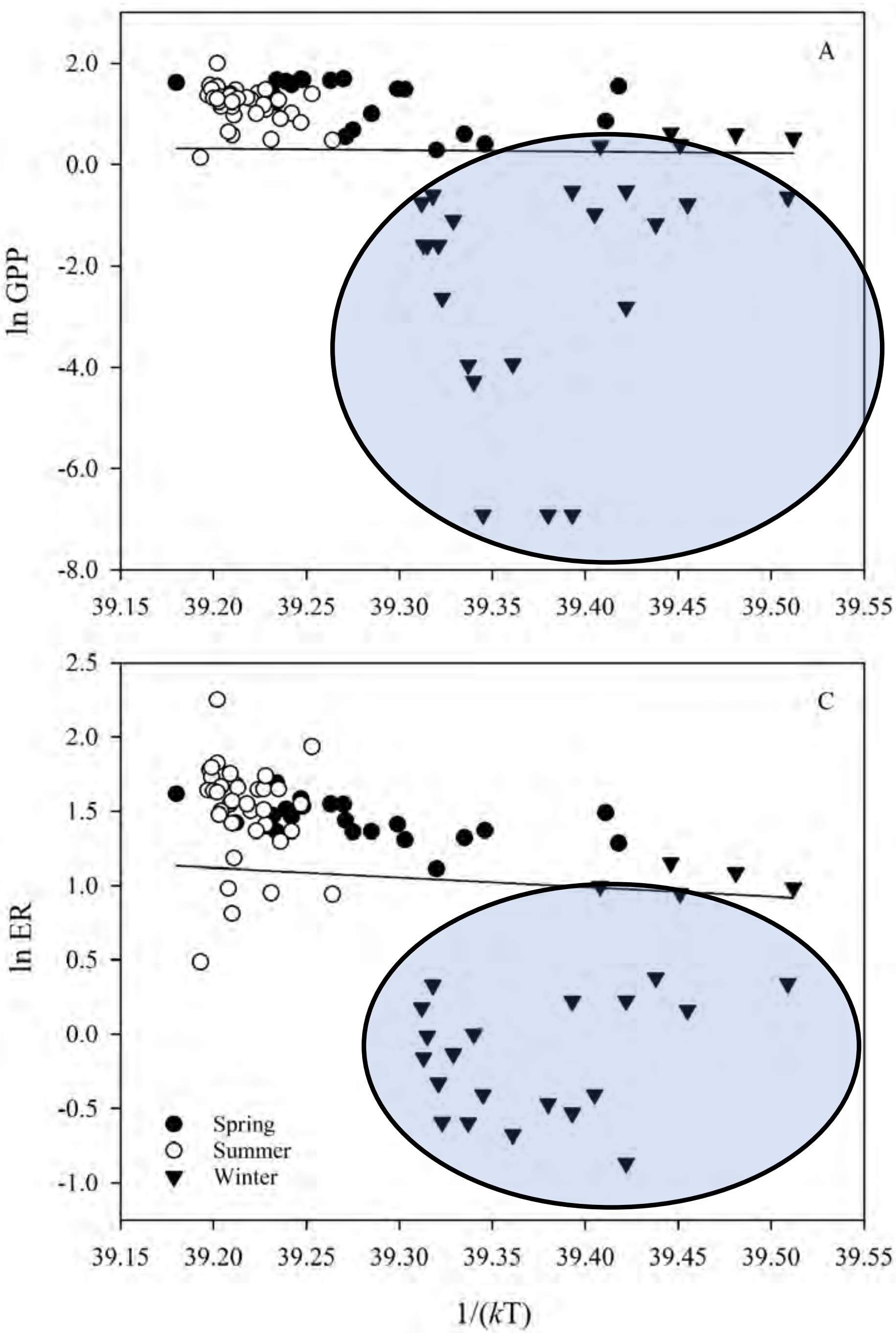
San Marcos River Metabolism

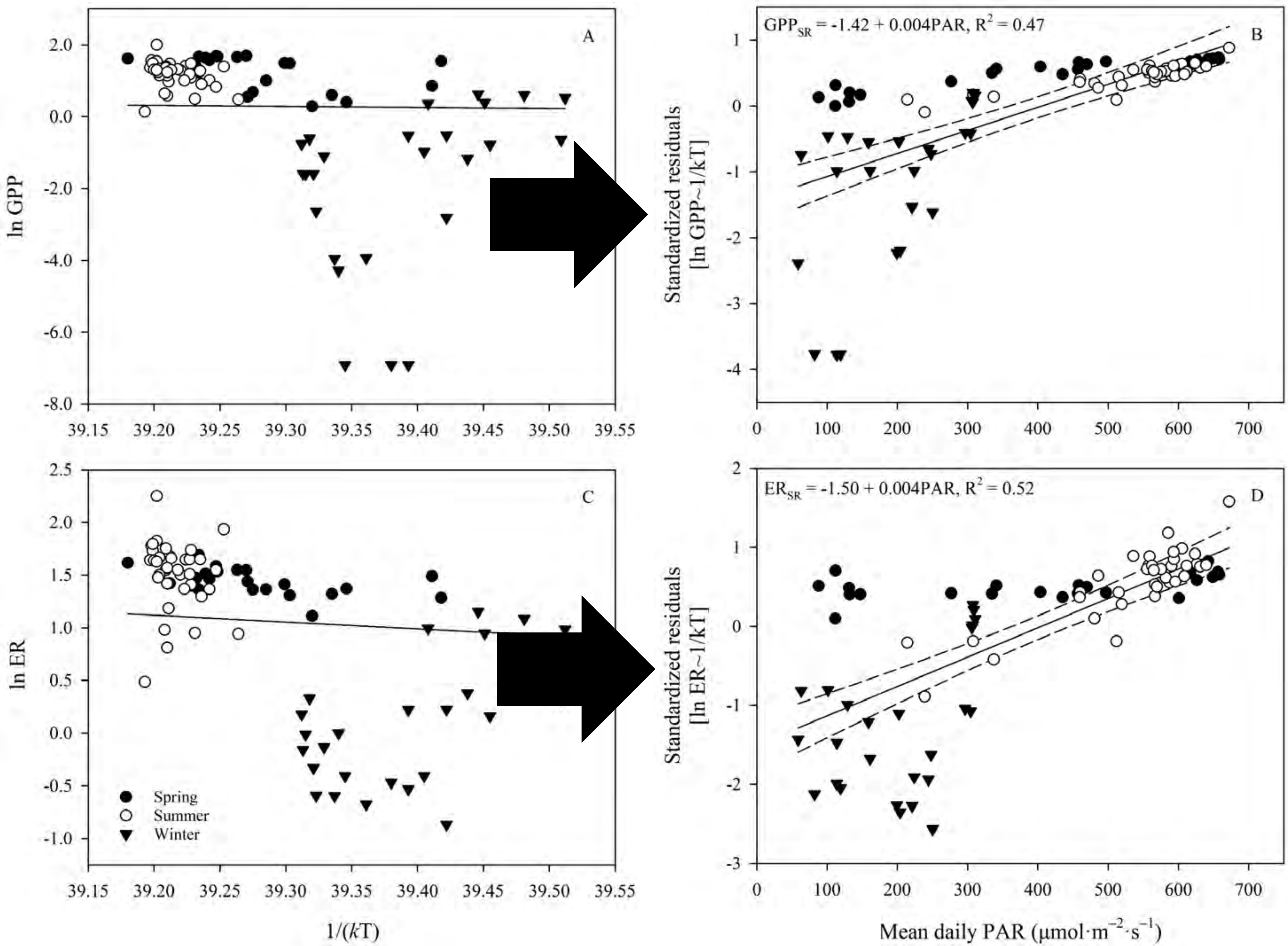


San Marcos River Metabolism




A
ln GPP
2.0
0.0
-2.0
-4.0
-6.0
-8.0
39.15
39.20
39.25
39.30
39.35
39.40
39.45
39.50
39.55
C
ln ER
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
Spring
Summer
Winter
1/(kT)


A
ln GPP
2.0
0.0
-2.0
-4.0
-6.0
-8.0
39.15
39.20
39.25
39.30
39.35
39.40
39.45
39.50
39.55
C
ln ER
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
Spring
Summer
Winter
1/(kT)



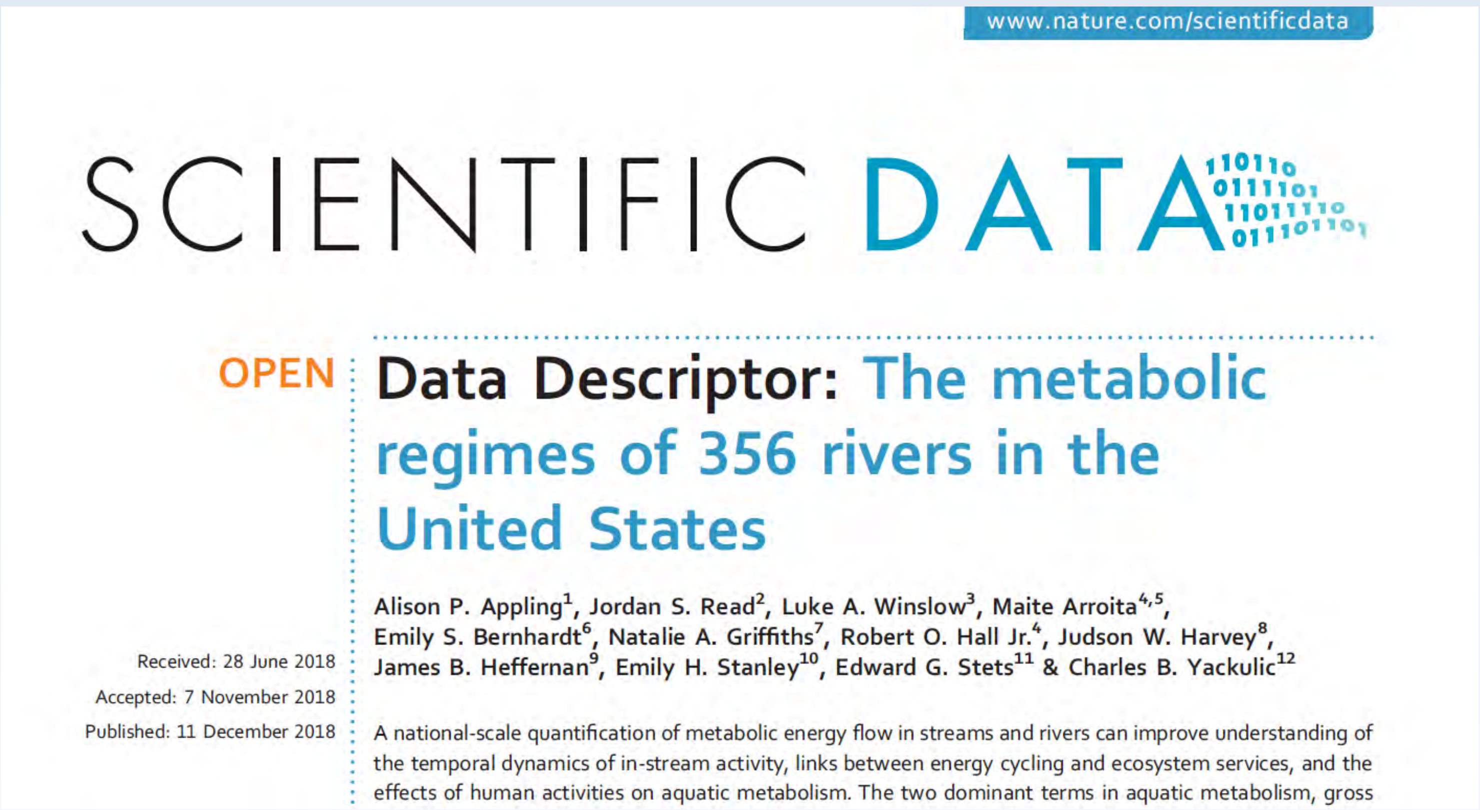
A
B
C
D
GPP_SR = -1.42 + 0.004PAR, R^2 = 0.47
ER_SR = -1.50 + 0.004PAR, R^2 = 0.52
ln GPP
ln ER
Standardized residuals [ln GPP~1/kT]
Standardized residuals [ln ER~1/kT]
1/(kT)
Mean daily PAR (μmol·m^-2·s^-1)
Spring
Summer
Winter

Seasonal Macrophyte Biomass

Seasonal Macrophyte Biomass

Comparison to the Literature?

- Obtained estimates of daily GPP and ER
  - Randomly selected n = 847 daily estimates


www.nature.com/scientificdata

SCIENTIFIC DATA

OPEN

Data Descriptor: The metabolic regimes of 356 rivers in the United States

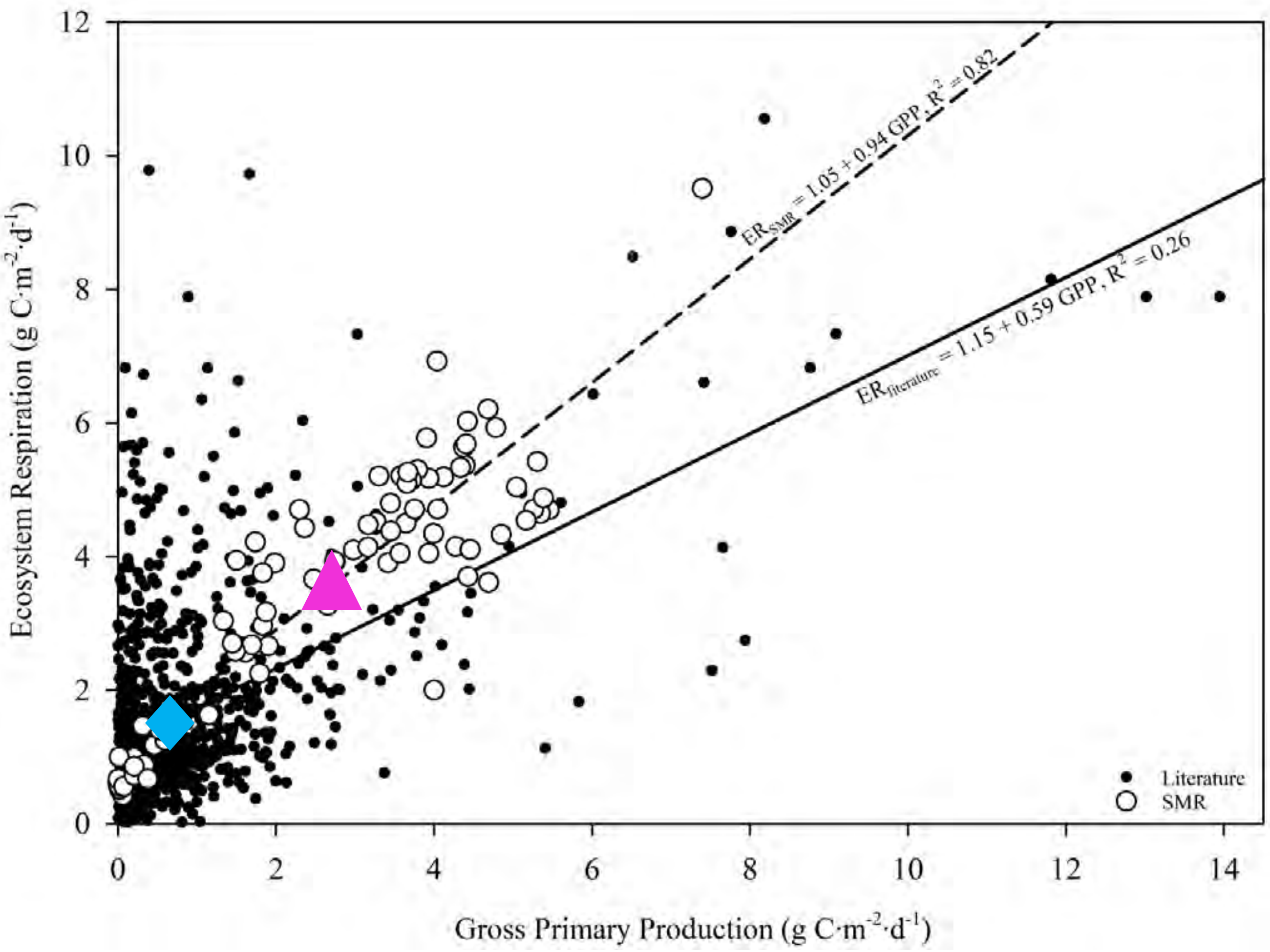
Alison P. Appling[1], Jordan S. Read[2], Luke A. Winslow[3], Maite Arroita[4,5], Emily S. Bernhardt[6], Natalie A. Griffiths[7], Robert O. Hall Jr.[4], Judson W. Harvey[8], James B. Heffernan[9], Emily H. Stanley[10], Edward G. Stets[11] & Charles B. Yackulic[12]

Received: 28 June 2018
Accepted: 7 November 2018
Published: 11 December 2018

A national-scale quantification of metabolic energy flow in streams and rivers can improve understanding of the temporal dynamics of in-stream activity, links between energy cycling and ecosystem services, and the effects of human activities on aquatic metabolism. The two dominant terms in aquatic metabolism, gross

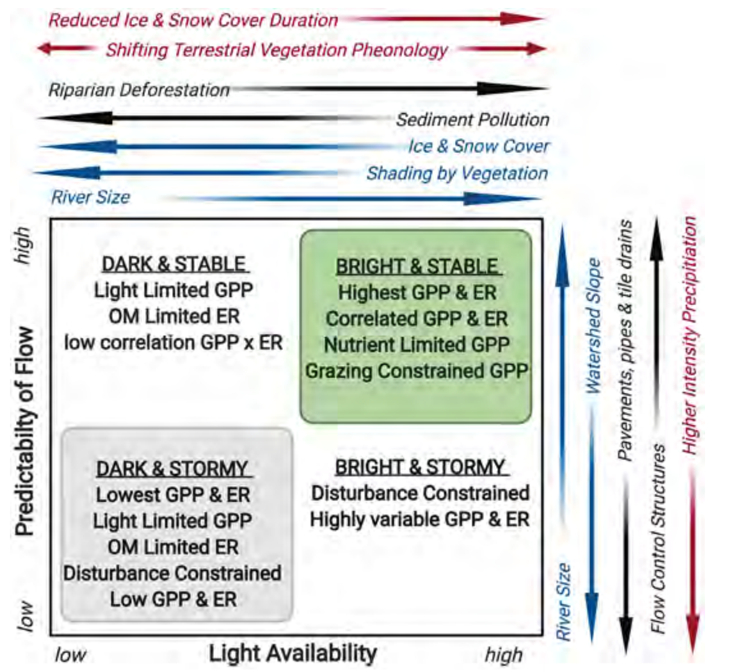
Literature Comparison

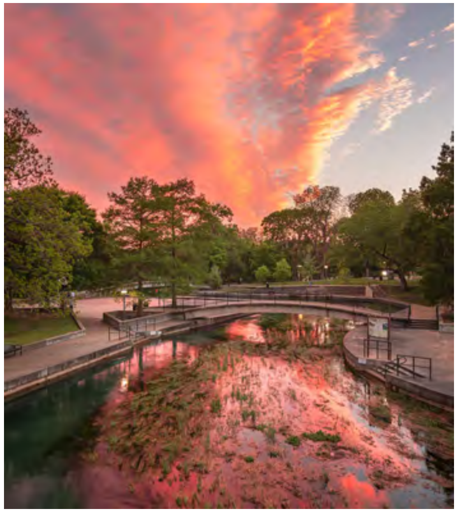
- GPP ($g\ C \cdot m^{-2} \cdot d^{-1}$)
  - SMR = 2.70 ± 0.19
  - Lit = 0.86 ± 0.05
- ER ($g\ C \cdot m^{-2} \cdot d^{-1}$)
  - SMR = 3.59 ± 0.20
  - Lit = 1.66 ± 0.05
- NEP ($g\ C \cdot m^{-2} \cdot d^{-1}$)
  - SMR = -0.87 ± 0.09
  - Lit = -0.80 ± 0.05



Putting it Together (Part 2)

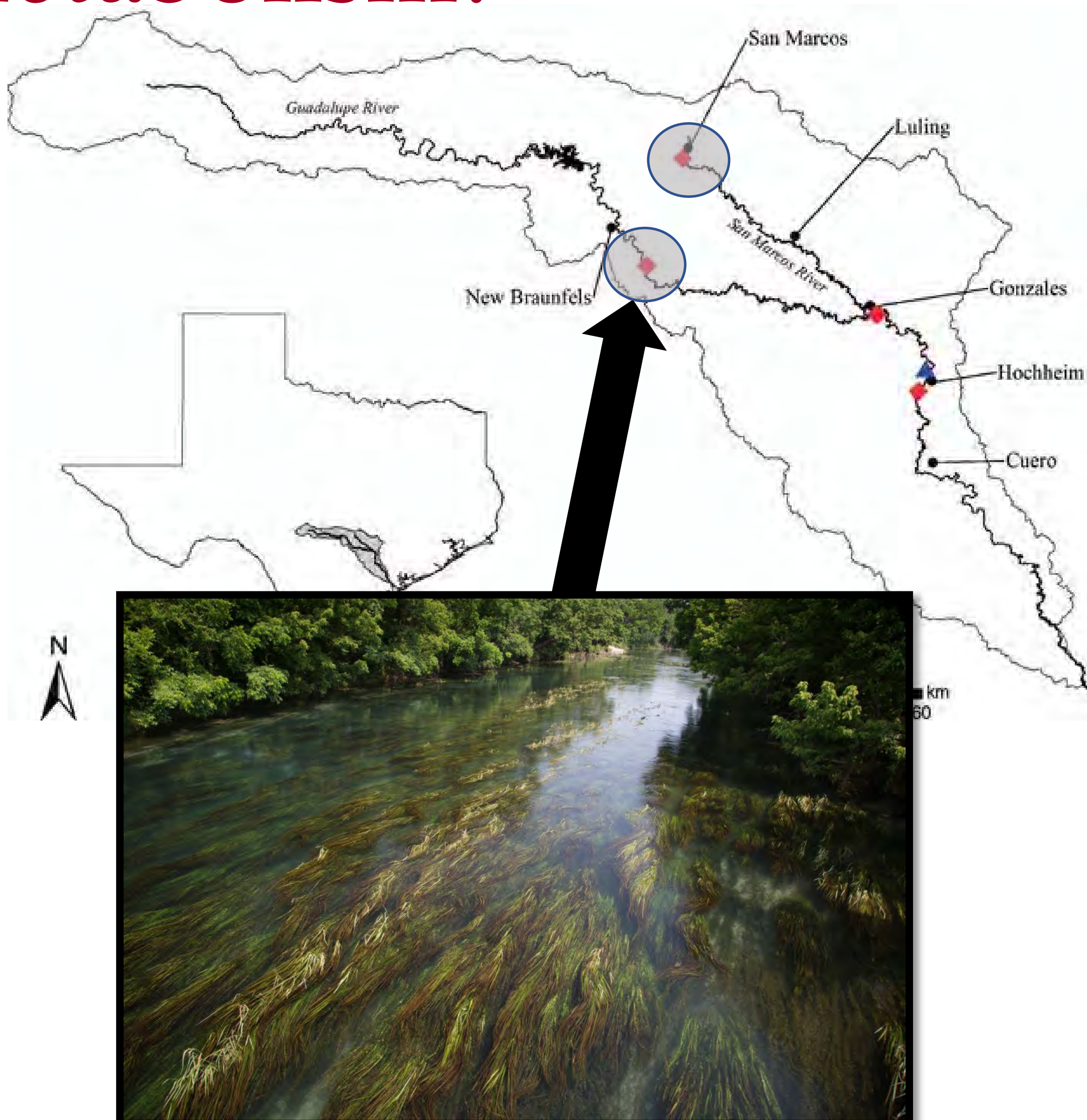
- Subtropical groundwater dominated river
- GPP and ER changed seasonally and were correlated
  - Largely driven by light availability
- Seasonal variation in macrophytes largely driven by human impacts in accessible reaches
  - Recreational activity, not correlated with metabolism
- GPP and ER estimates were higher than literature





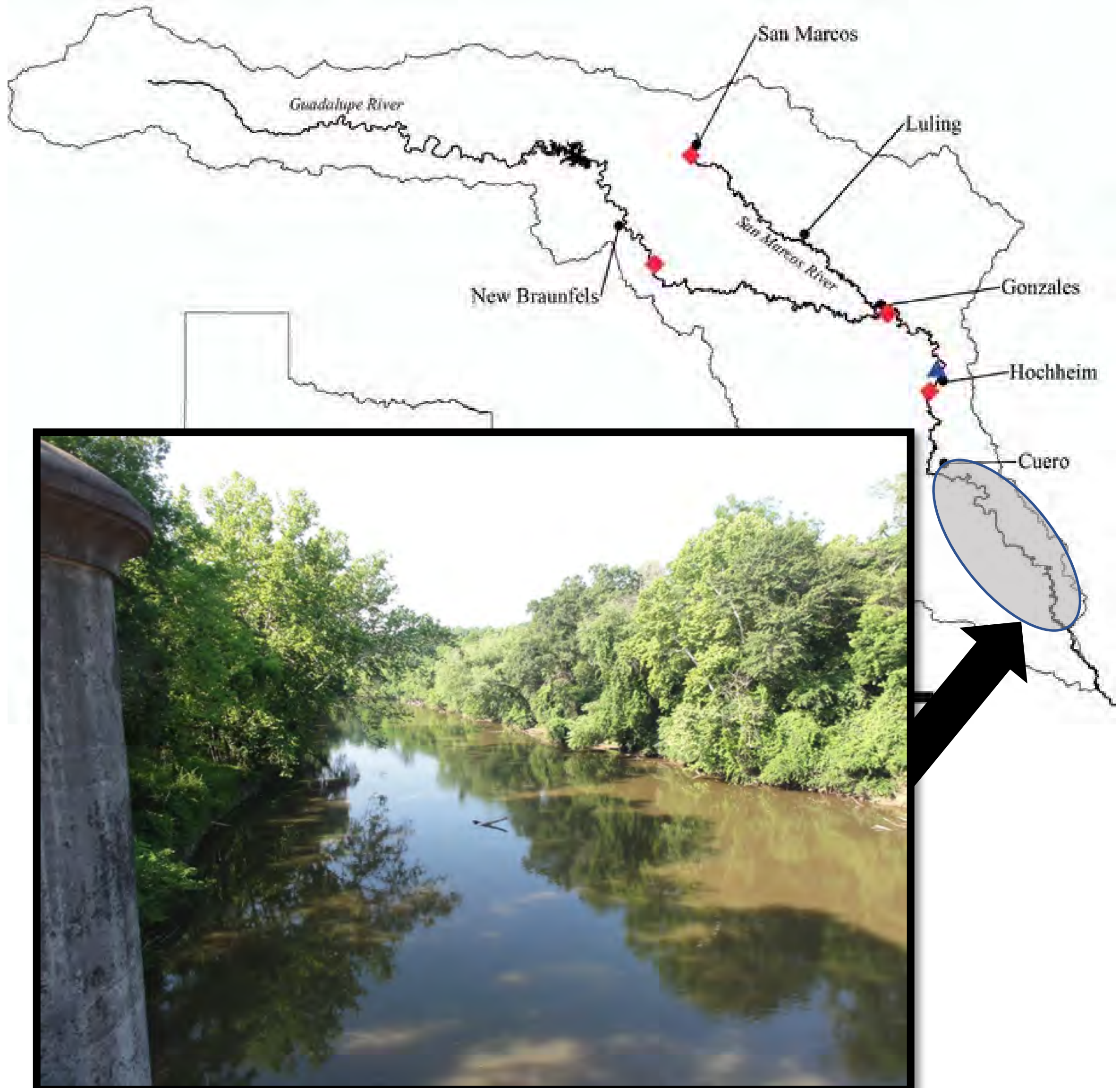
Scaling Up Metabolism?

- Scale up from a reach to a basin?
  - <u>Upper headwaters</u> = high light, stable flows, consistent temperatures metabolism driven by seasonal light availability



Scaling Up Metabolism?

- Scale up from a reach to a basin?
  - Lower reaches = lower light, more or less variable flows, metabolism driven by seasonal light and temperature covariation, larger seasonal variation



What's the Deal with Groundwater Dominated Rivers?

What's the Deal with Groundwater Dominated Rivers?

- Respond to same drivers as surface water rivers
- Light availability and water clarity play critical role
  - Macrophytes and biofilms
  - Nutrient uptake and C metabolism
- They are on end of the spectrum for some ecosystem processes
- Do they tell us something about rivers, in general?
  - Absolutely

Where do we go from here?

- Scaling uptake and metabolism up to basin levels
- Scaling up in Phase II…?

Ecosystems (2021) 24: 1792–1809
https://doi.org/10.1007/s10021-021-00618-8

ECOSYSTEMS

The Metabolic Regimes at the Scale of an Entire Stream Network Unveiled Through Sensor Data and Machine Learning

Pier Luigi Segatto,[1] Tom J. Battin,[1]* and Enrico Bertuzzo[2]*

[1]Stream Biofilm and Ecosystem Research Laboratory, Ecole Polytechinque Fédérale de Lausanne, CH-1015 Lausanne, Switzerland;
[2]Department of Environmental Sciences, Informatics and Statistics, University of Venice Ca' Foscari, 30170 Venice, Italy

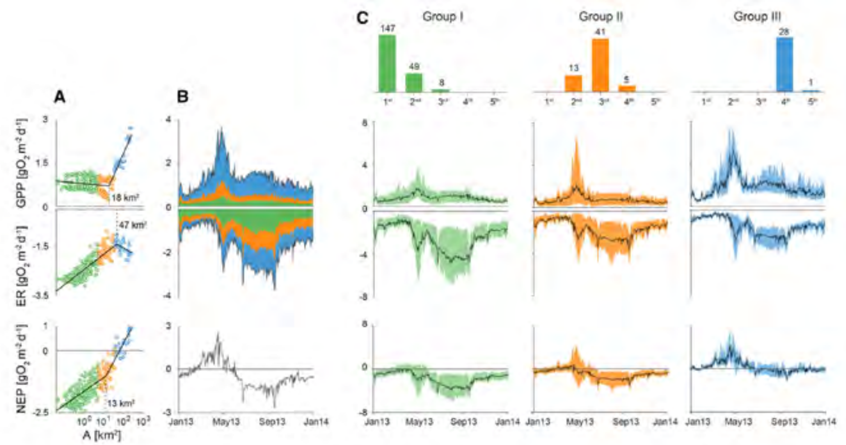


Figure 4. Stream ecosystem metabolic regime at network scale. Stream reaches have been clustered in three major groups according to their Strahler's stream order and catchment size (panel a and c). Group I (green) includes all streams with catchment size smaller than the largest first-order stream (5.6 km^2), group II (orange) those smaller than the largest third-order stream (that is, from 5.6 to 36 km^2) and group III (blue) all the other larger streams. Panel a displays scatter plots of reach-scale mean daily GPP, ER and NEP against drainage area, in logarithmic scale, and their piece-wise regression lines whose equations read as follows (lbp = left side; rbp = right site of the break point): $GPP_{lbp} = 0.779 - 0.027 \log(A)$; $GPP_{rbp} = -1.264 + 0.676 \log(A)$; $ER_{lbp} = -2.43 + 0.270 \log(A)$; $ER_{rbp} = -0.59 - 0.207 \log(A)$; $NEP_{lbp} = -651 + 0.240 \log(A)$; $NEP_{rbp} = -2.712 + 0.649 \log(A)$. Breakpoints have been selected to minimize the overall RMSE among all possible combinations (including no breakpoints). Panel b displays the contribution of the different groups to the total, network-scale GPP and ER, expressed per unit of streambed area of the entire river network. Bottom plot of panel b shows network scale NEP per unit of river network streambed area. Top row of panel c shows the frequency distribution of the Strahler's order of the streams belonging to the three different groups. Bottom plots show the range of variability (colored areas) and the average trend (black lines) of the reach-scale GPP, ER, and NEP of the three different groups.

Where do we go from here?

- Other ecosystem processes…
  - Dr. Tonya Ramey
  - Decomposition
  - Metabolism estimates