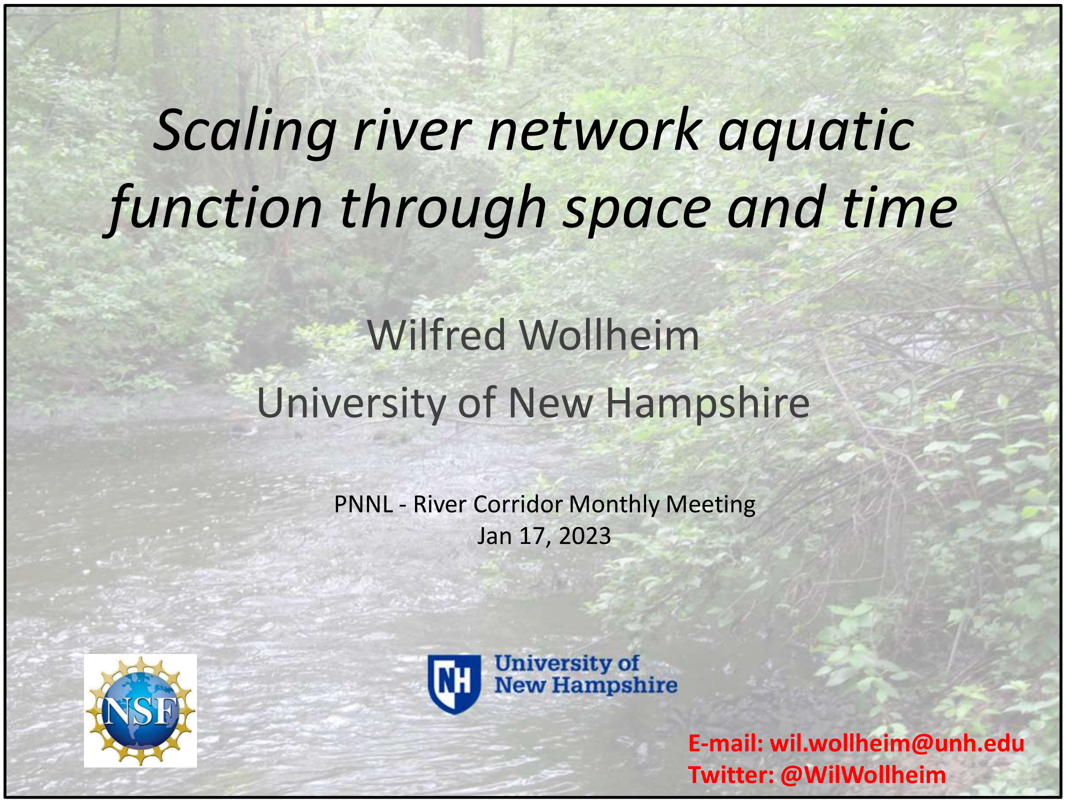


ABOUT AQUATIC FUNCTION. Role of streams and rivers in
First half of talk will be about some potential theories, approaches for generalization of function
Second half about sensor networks. What kind of network is needed to identify the role of aquatic function

nature COMMUNICATIONS

ARTICLE

Check for updates

https://doi.org/10.1038/s41467-022-28630-z OPEN

Superlinear scaling of riverine biogeochemical function with watershed size

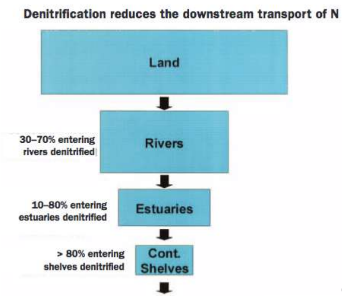
Wilfred M. Wollheim[1✉], Tamara K. Harms[2], Andrew L. Robison[1,7], Lauren E. Koenig[3], Ashley M. Helton[3], Chao Song[4], William B. Bowden[5] & Jacques C. Finlay[6]

River networks regulate carbon and nutrient exchange between continents, atmosphere, and oceans. However, contributions of riverine processing are poorly constrained at continental scales. Scaling relationships of cumulative biogeochemical function with watershed size (allometric scaling) provide an approach for quantifying the contributions of fluvial networks in the Earth system. Here we show that allometric scaling of cumulative riverine function with watershed area ranges from linear to superlinear, with scaling exponents constrained by network shape, hydrological conditions, and biogeochemical process rates. Allometric scaling is superlinear for processes that are largely independent of substrate concentration (e.g., gross primary production) due to superlinear scaling of river network surface area with watershed area. Allometric scaling for typically substrate-limited processes (e.g., denitrification) is linear in river networks with high biogeochemical activity or low river discharge but becomes increasingly superlinear under lower biogeochemical activity or high discharge, conditions that are widely prevalent in river networks. The frequent occurrence of superlinear scaling indicates that biogeochemical activity in large rivers contributes disproportionately to the function of river networks in the Earth system.

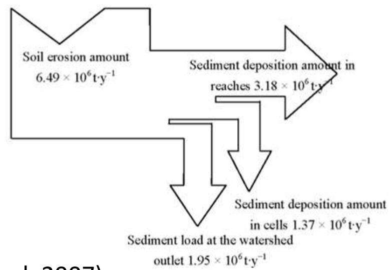
Funded by NSF Macrosystems Biology

Freshwaters influence downstream flux of material inputs from land

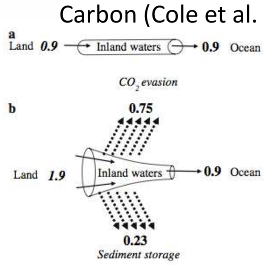
Nitrogen (Galloway et al. 2003)



Sediments (Hua et al. 2012)

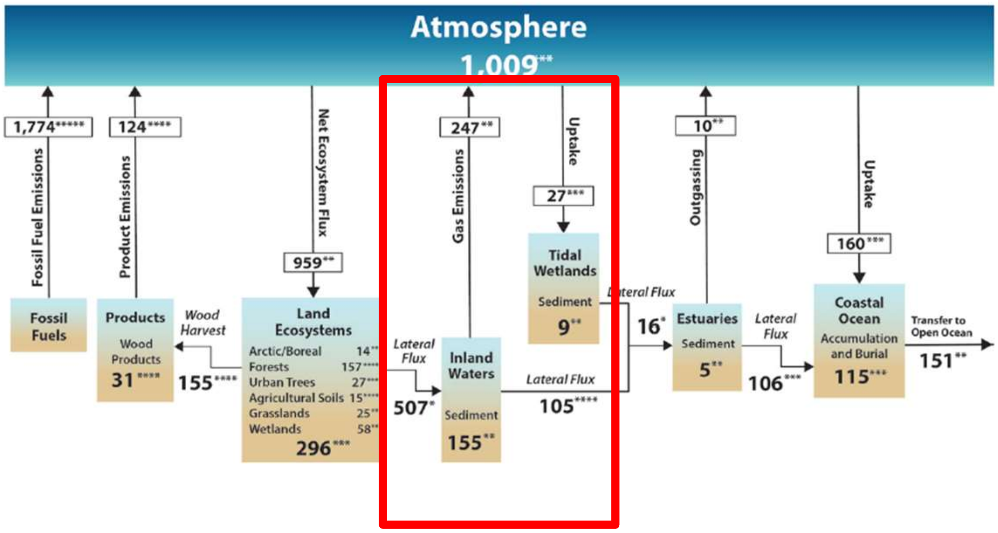


Carbon (Cole et al. 2007)



Aquatic systems are hypothesized to be important transformers of a number of biogeochemical constituents.
Changes in N, Terrestrial Carbon, sediment
Usually this function only emerges at broad spatial scales –need to think about networks.

North American Carbon Cycle

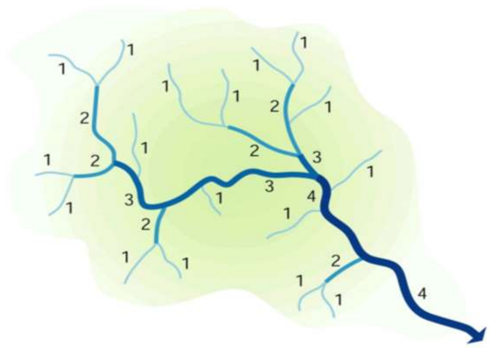


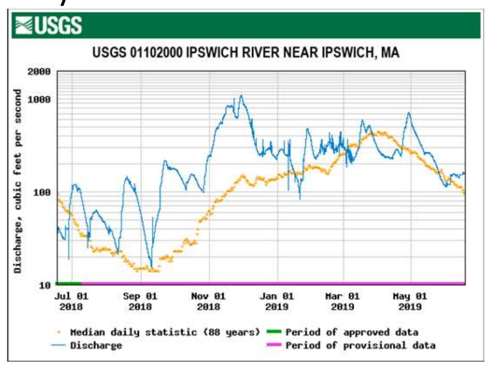
Hayes et al. 2018. Ch. 2 North American Carbon Budget. **In** Second State of the Carbon Cycle Report.

Second State of the CC just released
Net ecosystem exchange on land = 959
Lateral flux = > 50% of this. Half of this is then evaded (either from direct pCO2 or OM respiration)
Fluvial networks (including streams, rivers, lakes, etc) are clearly important!

What Kind of Scaling for River Network Function?

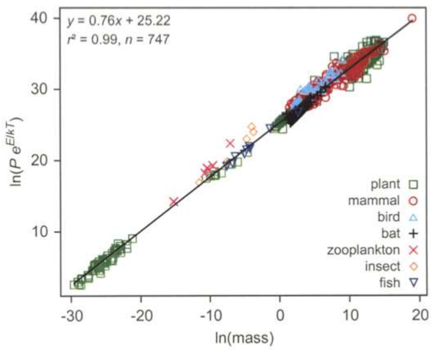
- Cumulative function over all streams/rivers (ponded waters) in entire network
  - NO3 loss (assimilation or denitrification), DOC oxidation, gas evasion, sediment deposition, pathogen mortality, etc.
- Space – increasing watershed area
- Time – accounting for flow variability

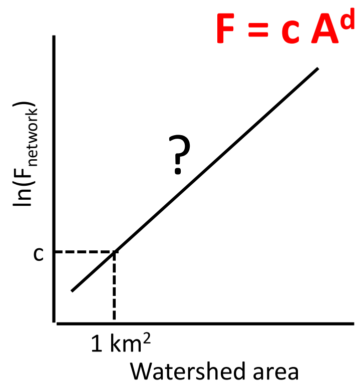


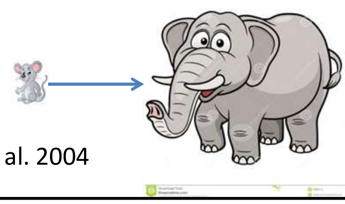


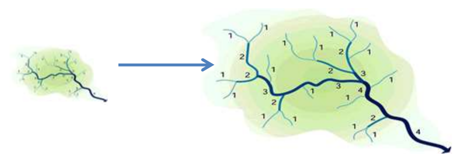
ALSO ponded waters
All functions there in theory could be measured with sensors.

Space: Inspired by Metabolic Theory of Ecology





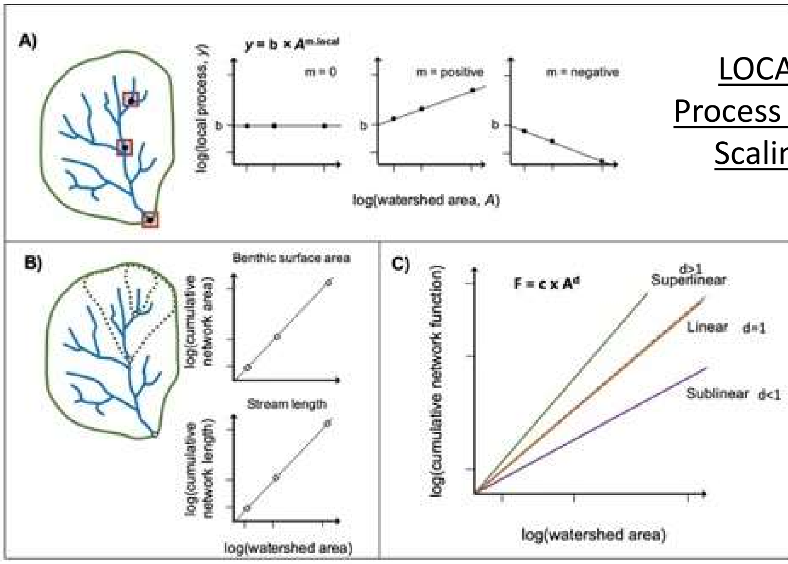




Brown et al. 2004

The slope (log-log scale) is 0.75.   What about watershed area and metabolism

Space:
Allometric Scaling of Cumulative Aquatic Function vs. Drainage Area



<u>LOCAL Process Rate Scaling</u>

<u>CUMULATIVE Process Scaling</u>

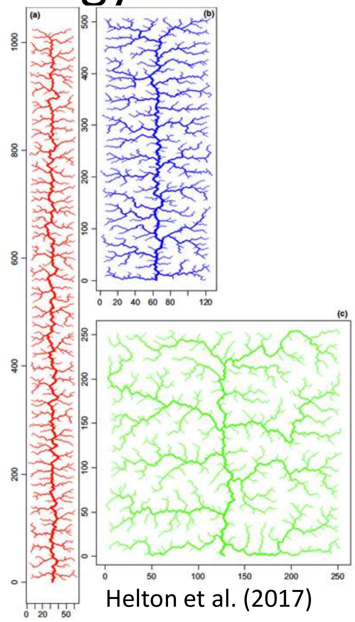
Key point: need to consider large watershed scale

The fractal basis: Metabolic networks vs. River networks

Attribute	*Organism*	*River Network*
Fractal Distribution Network	Yes (circulatory)	Yes (flow)
Energy driving transport	Heart	Gravity
Fueled by External Energy	Yes (food)	Yes (terrestrial inputs)
Material Redistribution	Concentrated to distributed (e.g., stomach to cells)	Distributed to concentrated (many small to one large)
Scale of Terminal Unit	Cell (constant)	Headwater Catchment (size varies among watersheds)
Transport Dimensions	3-d	2-d (predominantly)
Processing in Transport	No	Yes
Unit of Comparison	Individual organism	Nested within watershed
Scaling Exponent	0.75	This Study

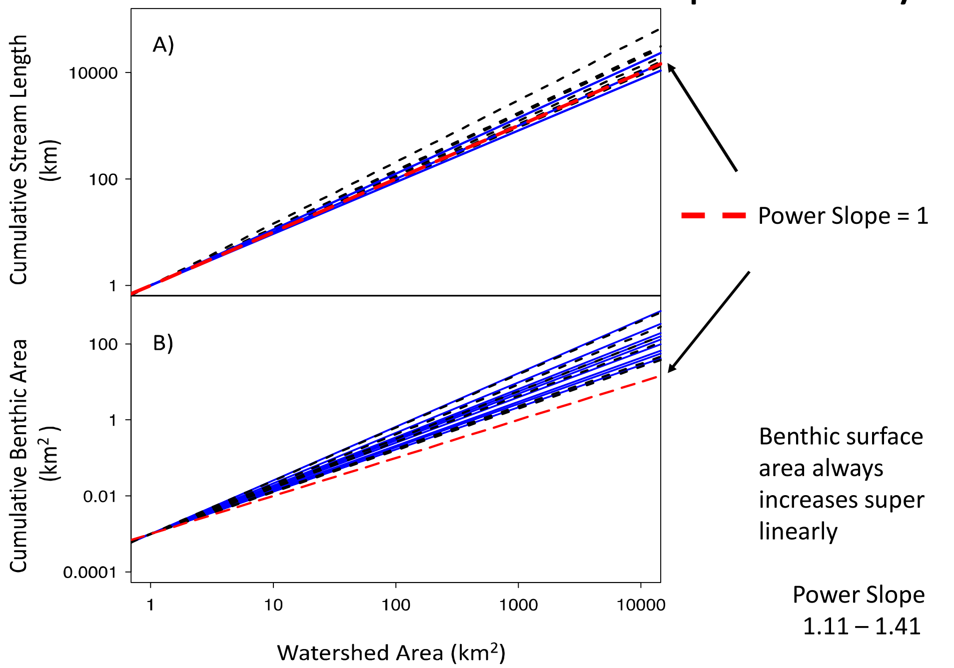
Integration of Geomorphology, Hydrology, and Biology

Variable	Abbreviation	Value	Source
Network Geomorphology	Rb	4.6 (4.1 - 6.9)	Helton et al. (2017)
	Rl	2.5 (2.2 - 4.4)	
	Ra	5.1 (4.7 - 7.4)	
Channel Hydraulics	a	3.5 (1.9 – 5.2)	Knighton (1998)
	a	9.0 (5.8 – 12.2)	Ruegg et al. (2015)
width=aQ^b	b	0.5 (0.45-0.56)	Knighton (1998)
	b	0.41 (0.26 – 0.51)	Ruegg et al. (2015)
	d	0.1 (0.05-0.2)	Knighton (1998)
Biology	Slope	- 0.5 0 0.5	Assumption



Helton et al. (2017)

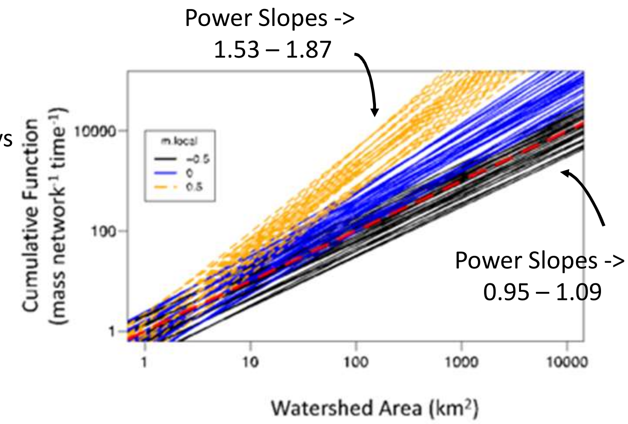
Cumulative Length Scales Linearly. Cumulative Surface Area Scales Superlinearly.

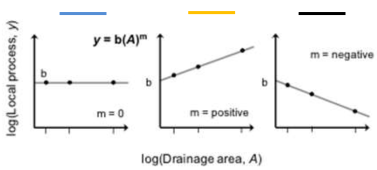


Constants are normalized to compare slopes

Function tends to scale superlinearly (Zero-order processes like GPP or ER)

- Cumulative function always linear to super linear
- Biological activity scaling has greater influence than geomorphology or hydraulics on slopes





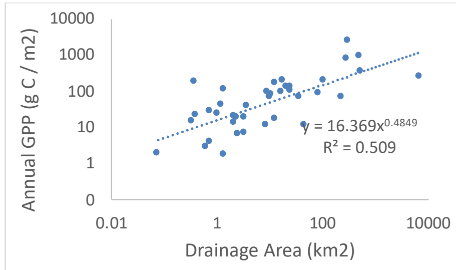
Biological Activity Slope
- 0.5 (increasing with river size)
- 0 (constant)
- -0.5 (decreasing)

We can look at different scenarions of how biology changes with river size. Does it increase with stream size (e.g GPP), does it decrease with stream size (e.g. ER if OM inputs are upstream), or does it remain constant?
Blue, then Green, then Red.

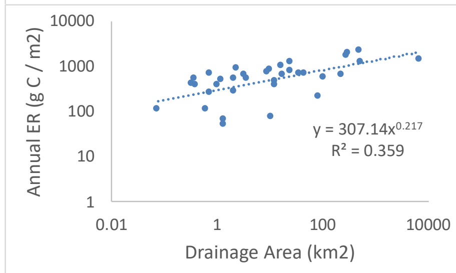
Real World Application

How does carbon produced by entire river network scale with D.A.?

Observed Local Gross Primary Production (**GPP**) vs. River Size (as characterized by D.A.)



Observed Local Ecosystem Respiration (**ER**) vs. River Size



Finlay 2010

NOT NESTED!!!!!

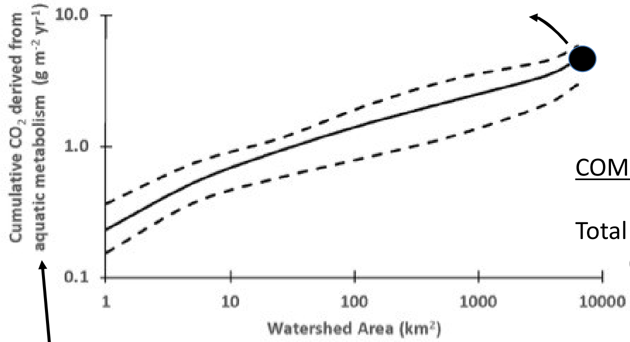
LOCAL Scaling (Not Cumulative). Earlier scenario of increasing

Power slope of 0.49 for GPP, 0.25 for ER.

Cumulative aquatic carbon production is superlinear

(rectangular network, mean r.o. = 500mm yr^{-1})

4.7 gC m^{-2} yr^{-1}



Aquatic (ER –GPP) per unit <u>watershed</u> area

<u>COMPARISON WITH LITERATURE</u>

Total aquatic CO_2 emissions = 24 gC m^{-2} yr^{-1}
(Butman et al. 2018)

Aquatic Metabolism Contribution to C emissions = 28%.
(Hotchkiss et al. 2015)

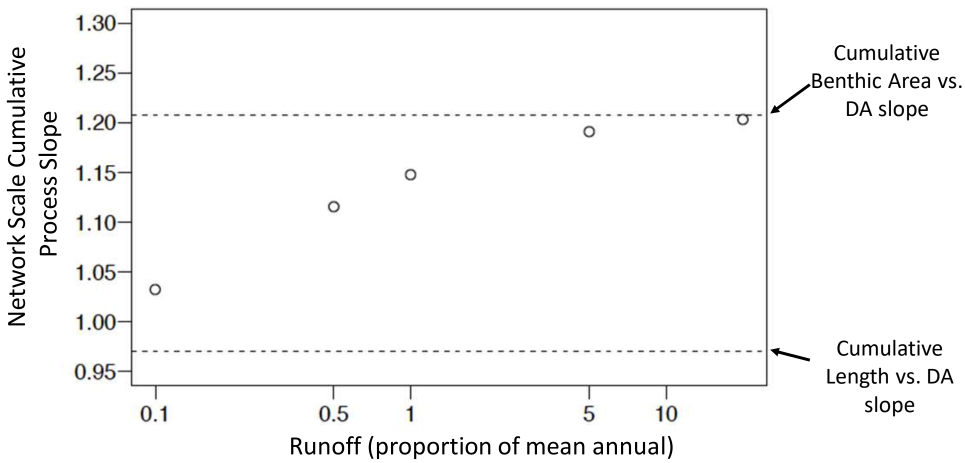
Aquatic metabolism CO2 emissions = 24 * 0.28 = 6.7 gC m^{-2} yr^{-1}

Headwater catchments contribute little. Despite having higher per unit area NEP, because not enough benthic surface area. Steepest increase is towards intermediate watersheds. Slow increase in larger rivers because NEP per area declines as GPP increases faster with river size than

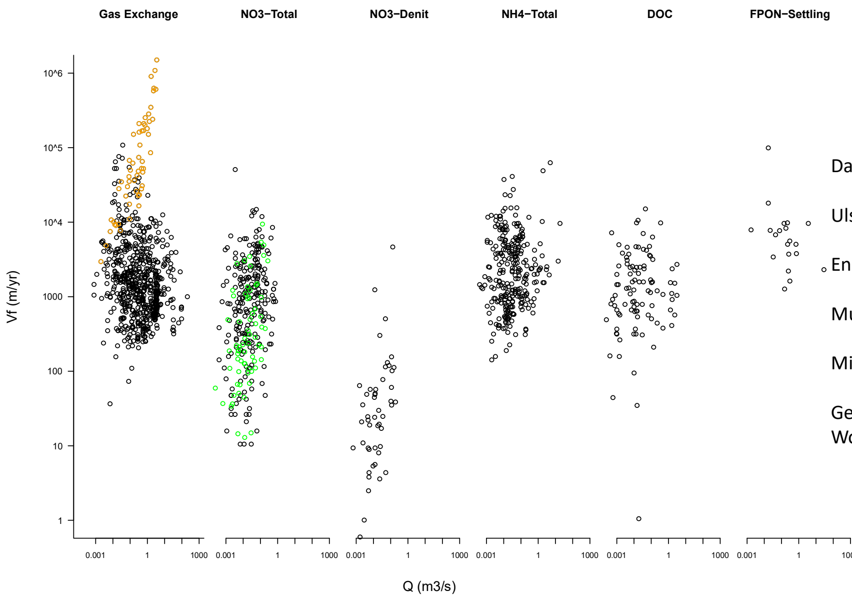
More realistic model: concentration-dependent (1st order) processes

- Representative of most biogeochemical processes across interfaces
  - Nutrient uptake
  - Denitrification
  - Gas exchange
  - Particle settling
- Uptake velocity (υ_f)
  - AREAL UPTAKE / CONCENTRATION
- Allows nutrient concentration to limit function, especially downstream
- Upstream removal proportions depend on flow, accounts for flow impacts.

As flow increases, allometric scaling shifts from linear (loading scaling), to super linear (reactive area scaling).



Model Can Be Used to Understand Scaling for Different Processes



Data from:

Ulseth et al. 2019

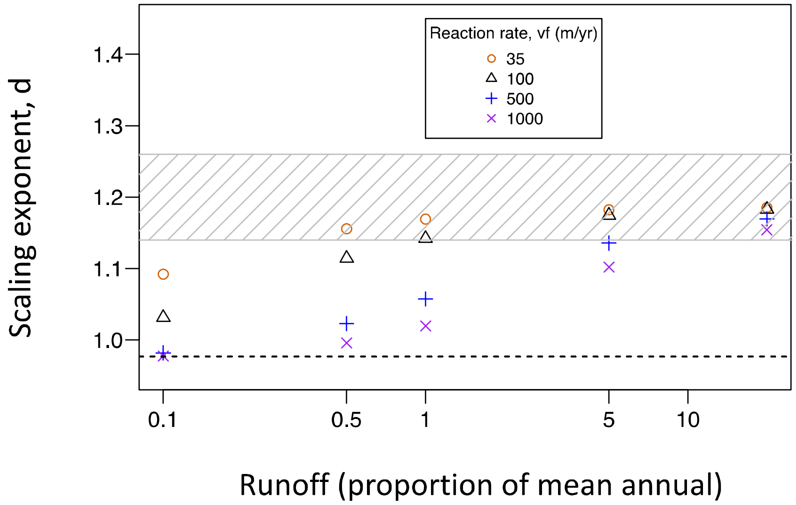
Ensign and Doyle 2005

Mulholland et al. 2009

Mineau et al. 2016

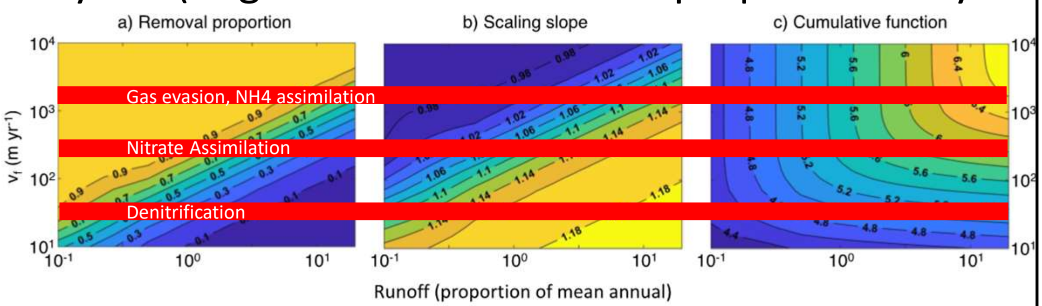
Georgian et al. 2003
Wollheim et al. 2001

As reaction rate (vf) declines, scaling becomes superlinear: for same reason as with flow.



Implications

- Nitrate uptake vs. Denitrification vs. Degassing of terrestrial CO2
- When superlinear, watershed size matters for global cycles (large rivers contribute disproportionately



Opportunities

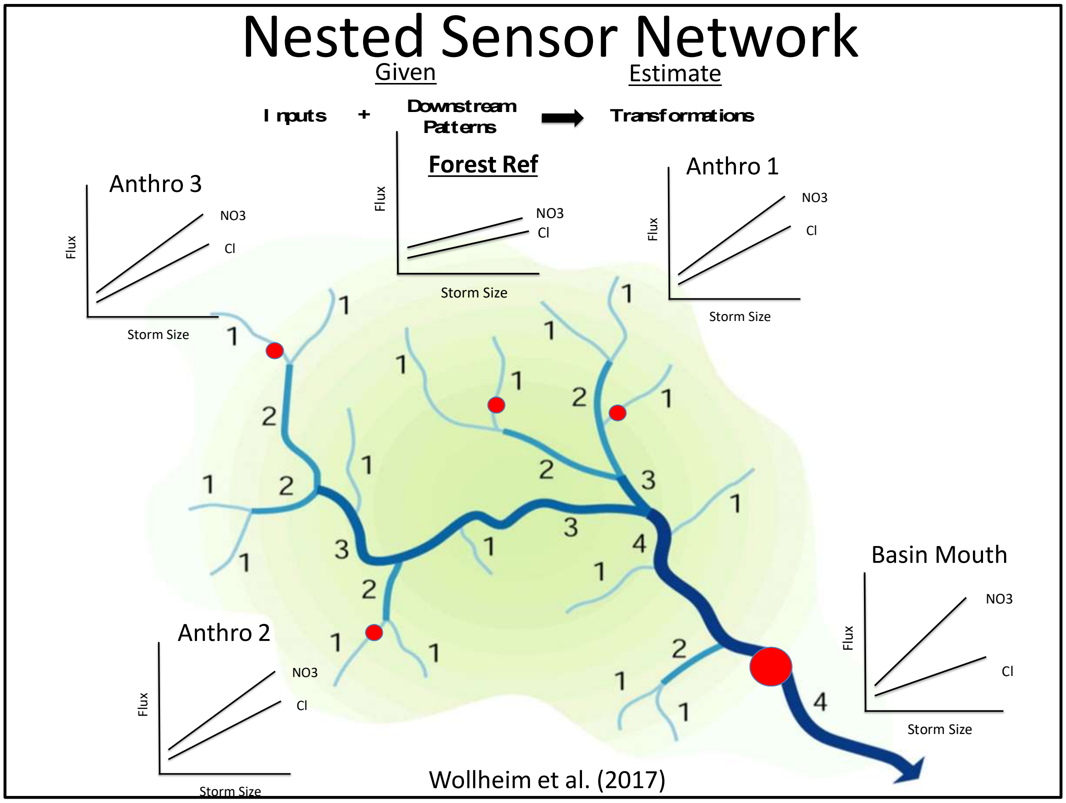
- Relative importance of HTS
- Role of heterogeneity
- Role of anthropogenic activity

- Nested sensor networks will improve testing of model results.
  – Deploy in multiple watershed types to generalize
  – Accurately capture loading (small headwater streams)
  – Conservative vs. reactive solutes
  – Account for storm events, flow variability

Design of sensor networks for river network scale function

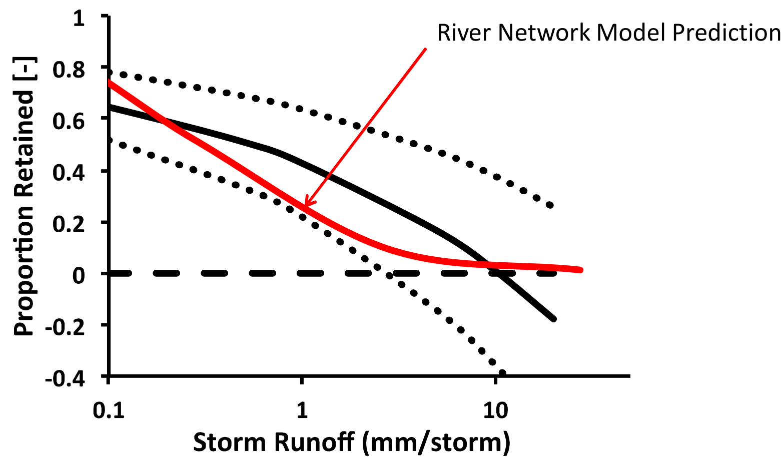
- Nested within single network
- What comes in (**inputs**)
- What goes out (**patterns**)

- Plus
  - Synoptic measurements (**patterns**)
  - Spatially distributed process rates (**transformations**)
- <u>Include Both</u>: Reactive and conservative tracers



Depicted graphically here.

Dynamic River Network Model Predictions Within Empirical Error



Data from Wollheim et al. 2017. WRR.
Model based on Wollheim et al. (2006, 2018). Includes only net removal.

When we apply a simple river network model, using parameters based on literature for denitrification, we get this pattern.
Shows similar response to increasing flow. High retention for small storms, declining, but never cross zero, because this simple model only includes net retetnion, not resuspension


Thank You!
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Twitter: @WilWollheim

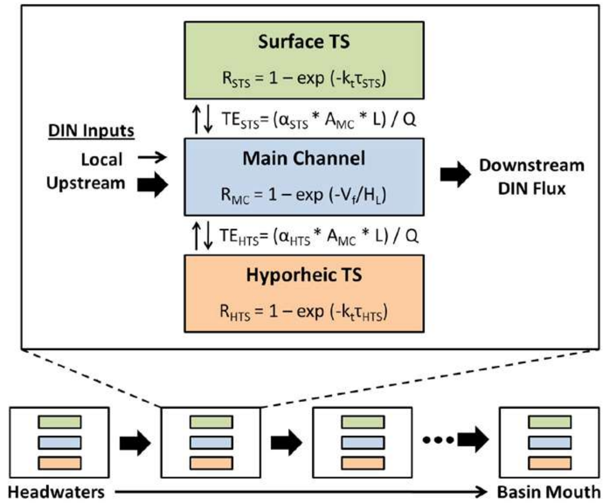
WATER RESOURCES RESEARCH, VOL. 47, W00J10, doi:10.1029/2010WR009896, 2011

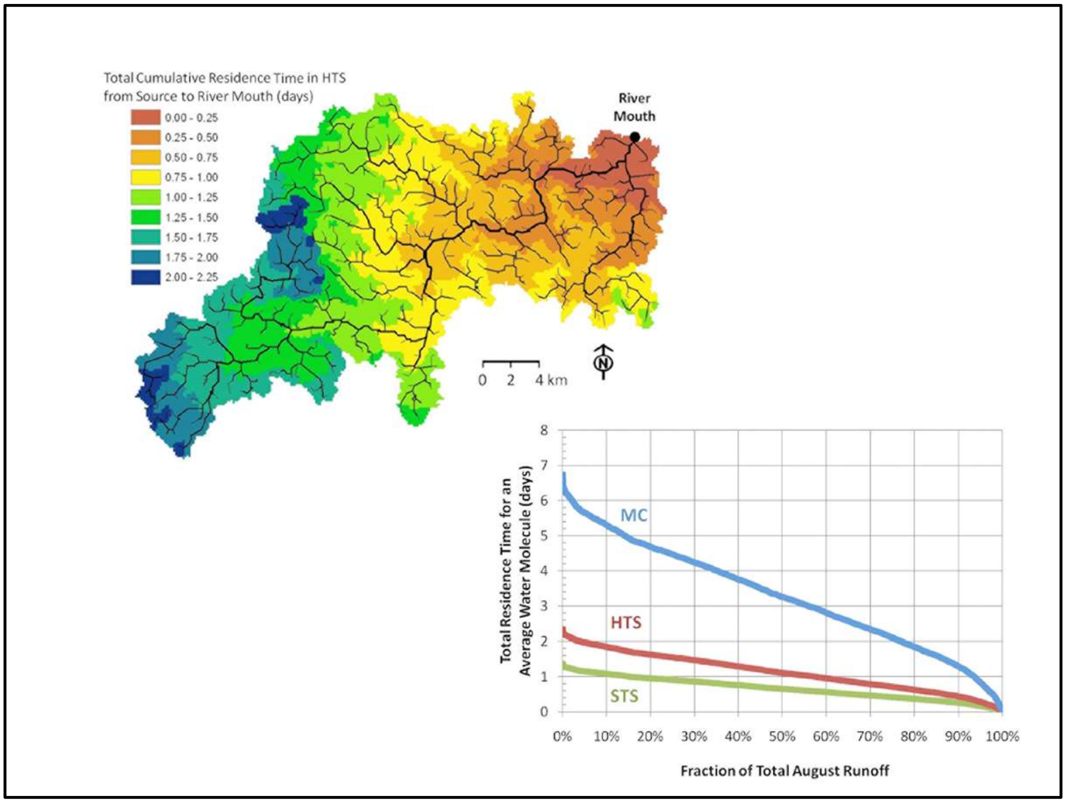
Separation of river network–scale nitrogen removal among the main channel and two transient storage compartments

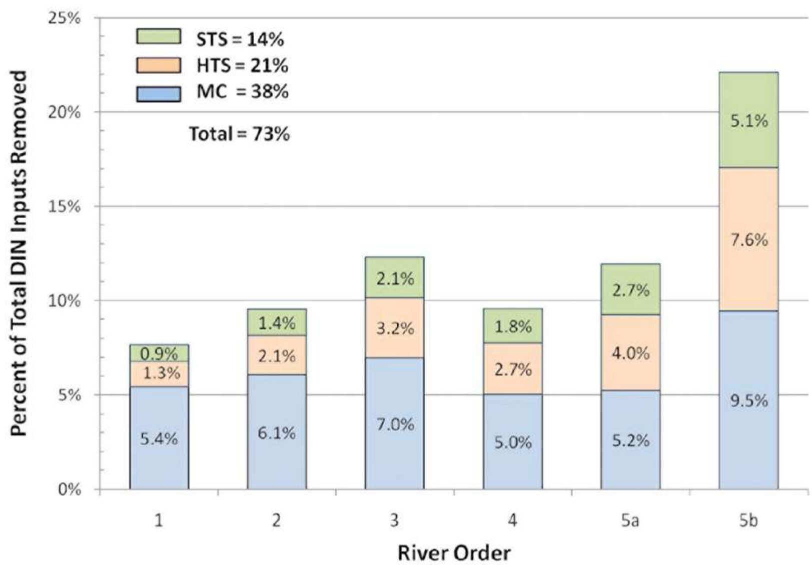
Robert J. Stewart,[1] Wilfred M. Wollheim,[1,7] Michael N. Gooseff,[2] Martin A. Briggs,[3] Jennifer M. Jacobs,[4] Bruce J. Peterson,[5] and Charles S. Hopkinson[6]

Received 17 August 2010; revised 9 June 2011; accepted 15 June 2011; published 30 August 2011.

[1] Transient storage (TS) zones are important areas of dissolved inorganic nitrogen (DIN) processing in rivers. We assessed sensitivities regarding the relative impact that the main channel (MC), surface TS (STS), and hyporheic TS (HTS) have on network denitrification using a model applied to the Ipswich River in Massachusetts, United States. STS and HTS connectivity and size were parameterized using the results of in situ solute tracer studies in first- through fifth-order reaches. DIN removal was simulated in all compartments for every river grid cell using reactivity derived from Lotic Intersite Nitrogen Experiment (LINX2) studies, hydraulic characteristics, and simulated discharge. Model results suggest that although MC-to-STS connectivity is greater than MC-to-HTS connectivity at the reach scale, at basin scales, there is a high probability of water entering the HTS at some point along its flow path through the river network. Assuming our best empirical estimates of hydraulic parameters and reactivity, the MC, HTS, and STS removed approximately 38%, 21%, and 14% of total DIN inputs during a typical base flow period, respectively. There is considerable uncertainty in many of the parameters, particularly the estimates of reaction rates in the different compartments. Using sensitivity analyses, we found that the size of TS is more important for DIN removal processes than its connectivity with the MC when reactivity is low to moderate, whereas TS connectivity is more important when reaction rates are rapid. Our work suggests a network perspective is needed to understand how connectivity, residence times, and reactivity interact to influence DIN processing in hierarchical river systems.


Surface TS
$R_{STS} = 1 - \exp(-k_t \tau_{STS})$
$TE_{STS} = (\alpha_{STS} * A_{MC} * L) / Q$
DIN Inputs
Local
Upstream
Main Channel
$R_{MC} = 1 - \exp(-V_f/H_L)$
Downstream
DIN Flux
$TE_{HTS} = (\alpha_{HTS} * A_{MC} * L) / Q$
Hyporheic TS
$R_{HTS} = 1 - \exp(-k_t \tau_{HTS})$
Headwaters
Basin Mouth


Total Cumulative Residence Time in HTS
from Source to River Mouth (days)
0.00 - 0.25
0.25 - 0.50
0.50 - 0.75
0.75 - 1.00
1.00 - 1.25
1.25 - 1.50
1.50 - 1.75
1.75 - 2.00
2.00 - 2.25
River
Mouth
0 2 4 km
N
Total Residence Time for an Average Water Molecule (days)
MC
HTS
STS
Fraction of Total August Runoff
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
0 1 2 3 4 5 6 7 8


STS = 14%
HTS = 21%
MC = 38%
Total = 73%
Percent of Total DIN Inputs Removed
25%
20%
15%
10%
5%
0%
0.9%
1.3%
5.4%
1.4%
2.1%
6.1%
2.1%
3.2%
7.0%
1.8%
2.7%
5.0%
2.7%
4.0%
5.2%
5.1%
7.6%
9.5%
1
2
3
4
5a
5b
River Order

Statistical Model (Wollheim et al. 2006, 2018)

Model based on river flowpath probabilities
(Geomorphic Unit Hydrograph, Rodriguez-Iturbe et al. 1979)

Flux from all streams of order ω in a watershed:

$$F_{\omega-1} * P(\omega-1, \omega_{up}) * \exp(-\upsilon_f / H_{Lup(\omega)}) + \left[\sum_{k=1}^{\omega-1} F_k * P(k, \omega_{mid}) + I_\omega \right] * \exp(-\upsilon_f / H_{Lmid(\omega)})$$

Order	Direct	Length	Area	Number	Q	Qmid	Depth	Width	Velocity
-	-	km	km2	-	m3/s	m3/s	m	m	m/s
1	0.33	1.5	1.0	1838.3	0.016	0.012	0.056	0.82	0.26
2	0.25	3.5	4.2	525.2	0.067	0.049	0.095	1.7	0.30
3	0.16	7.9	17.6	150.1	0.280	0.206	0.16	3.7	0.35
4	0.11	18.3	74.1	42.9	1.18	0.867	0.28	7.7	0.41
5	0.07	42.0	311.2	12.3	4.93	3.64	0.47	16.3	0.48
6	0.05	96.5	1306.9	3.5	20.7	15.3	0.80	34.3	0.56
7	0.03	222.1	5489.0	1.0	87.0	64.2	1.35	72.3	0.66

	ReceivingOrder						
SourceOrder	1	2	3	4	5	6	7
1	-	0.786	0.107	0.054	0.027	0.015	0.011
2	-	-	0.786	0.108	0.055	0.029	0.021
3	-	-	-	0.788	0.110	0.059	0.042
4	-	-	-	-	0.795	0.120	0.085
5	-	-	-	-	-	0.821	0.179
6	-	-	-	-	-	-	1
7	-	-	-	-	-	-	-

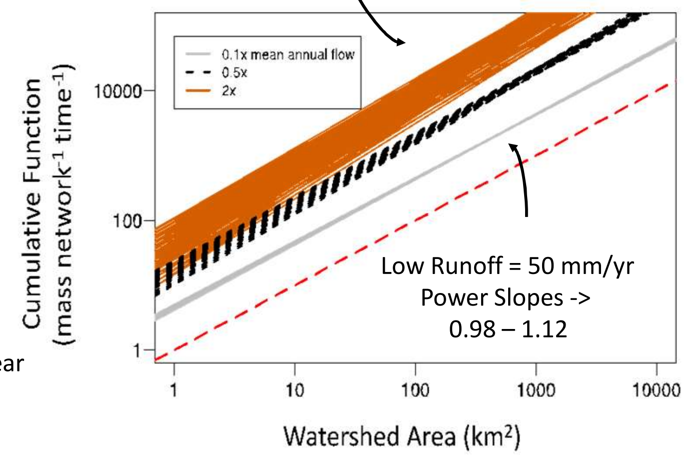
Assumptions

- Spatially uniform runoff (500 mm yr^{-1}) and loading concentration
- Distribution of loading does not change with increasing runoff
- Chemostatic
- Homogeneity (except gradients with river size)
- Linear uptake kinetics
- A variety of river network shapes and hydraulic assumptions of width vs. Q

- ESTIMATE CUMULATIVE UPSTREAM BIOGEOCHEMICAL FUNCTION WITH INCREASING WATERSHED SIZE

Flow affects allometric scaling: Low flow = linear, high flow = superlinear

High Runoff = 2500 mm/yr
Power Slope ->
1.07 – 1.33

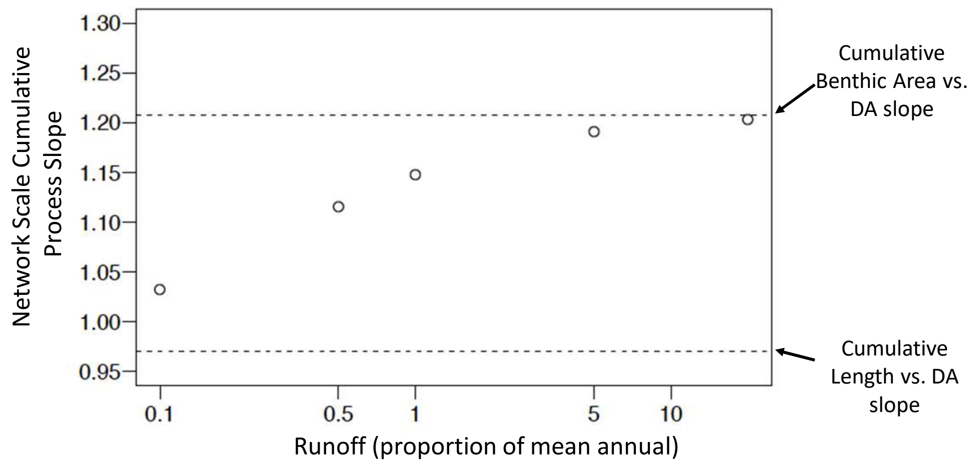


Low Runoff = 50 mm/yr
Power Slopes ->
0.98 – 1.12

- Low flow has linear scaling
  - Approaches cumulative length scaling
- High flow shifts to super-linear scaling
  - Approaches cumulative benthic area scaling

Vf = 100 m/yr
At low flow, slopes are nearly linear (approaching length scaling)
At high flow, slopes are superlinear (near BSA scaling

As flow increases, allometric scaling shifts from linear (loading scaling), to super linear (reactive area scaling).



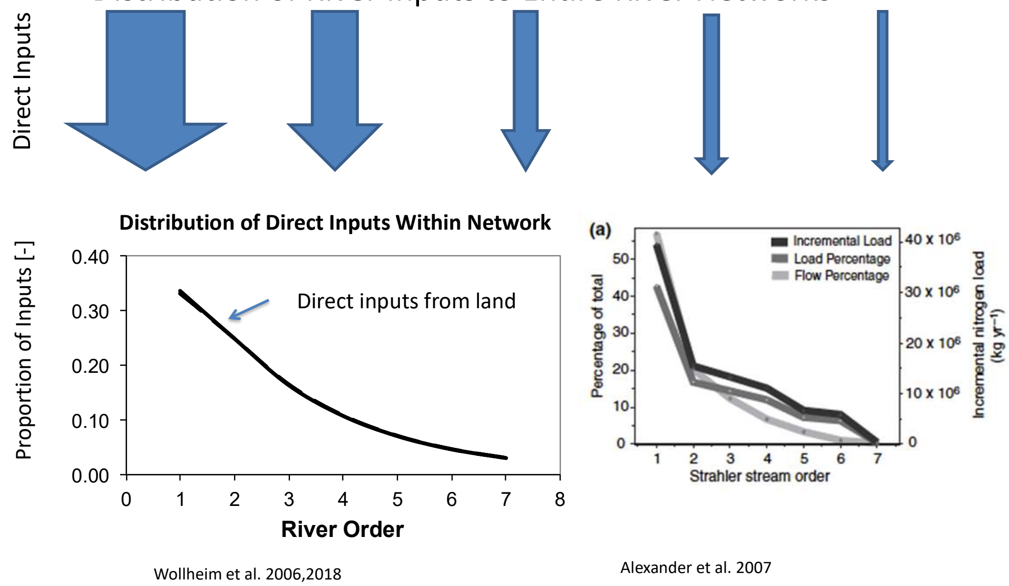
Why does scaling parameter shift from linear to super linear when flow increases?

Distribution of Loading (constant)

RELATIVE TO

Distribution of Processes (Source Limitation)

MOST INPUTS TO HEADWATER STREAM: Distribution of River Inputs to Entire River Networks



Most inputs enter in low order streams.

Distribution of Processes

- Under low flow, all inputs removed quickly upon entry to loading
  – Downstream rivers receive no material, so U small
  – RESULT: Linear scaling (scales with loading)

- Under high flow, most inputs flux downstream
  – Downstream rivers receive a lot of material, U high
  – RESULT: Superlinear scaling (scales with reactive area)

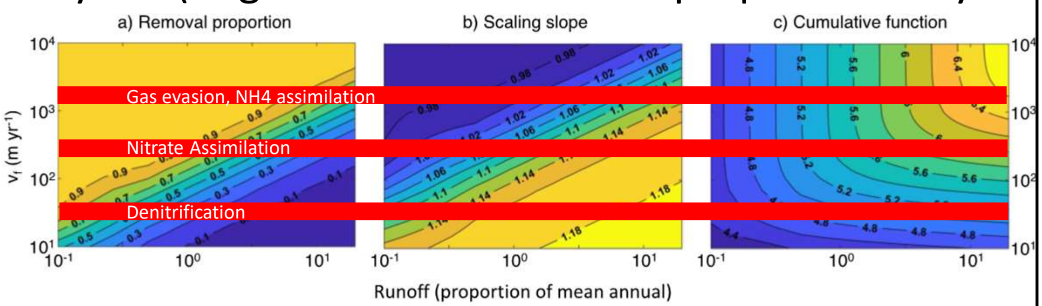
Implications

- Large rivers in large watersheds important at global scales.

- River networks may regulate substantial amount of downstream fluxes, even if not evident in watershed size comparisons (i.e. no watershed size effect on exports)
  - Examples of no watershed size effect
    - Caraco et al. 1999 (NO3)

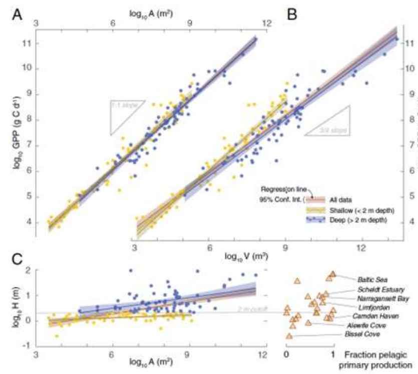
Implications

- Nitrate uptake vs. Denitrification vs. Degassing of terrestrial CO2
- When superlinear, watershed size matters for global cycles (large rivers contribute disproportionately



Contrast with organisms and individual ecosystems

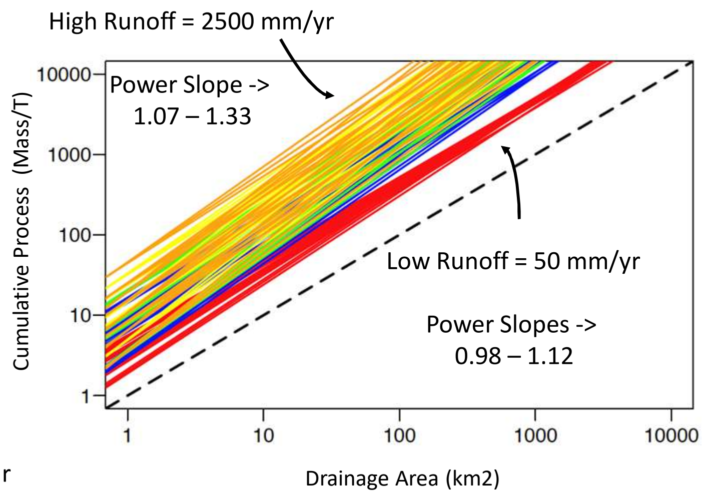
- MTE – sublinear scaling
  - 0.66 or 0.75 (Brown, West, etc)
- Estuaries and Lakes
  - Nidzieko, Glazier, Schramski
  - Shallow – linear
  - Deep – sublinear (0.75)



Nidziko 2017

- River Networks
  - Based on watershed size – linear to superlinear
  - **Based on benthic area –sublinear to linear (similar to individual estuaries or lakes)**
  - Varies with flow, depends on reaction rate.

First-order Processing (Denitrification) variability of flow



Low flow has linear scaling
- Approaches cumulative length scaling

High flow shifts to super-linear scaling
- Approaches cumulative benthic area scaling

At low flow, slopes are nearly linear (approaching length scaling)
At high flow, slopes are superlinear (near BSA scaling