Nutrient Retention Modeling in Large Catchments: Mississippi River Basin Case Study

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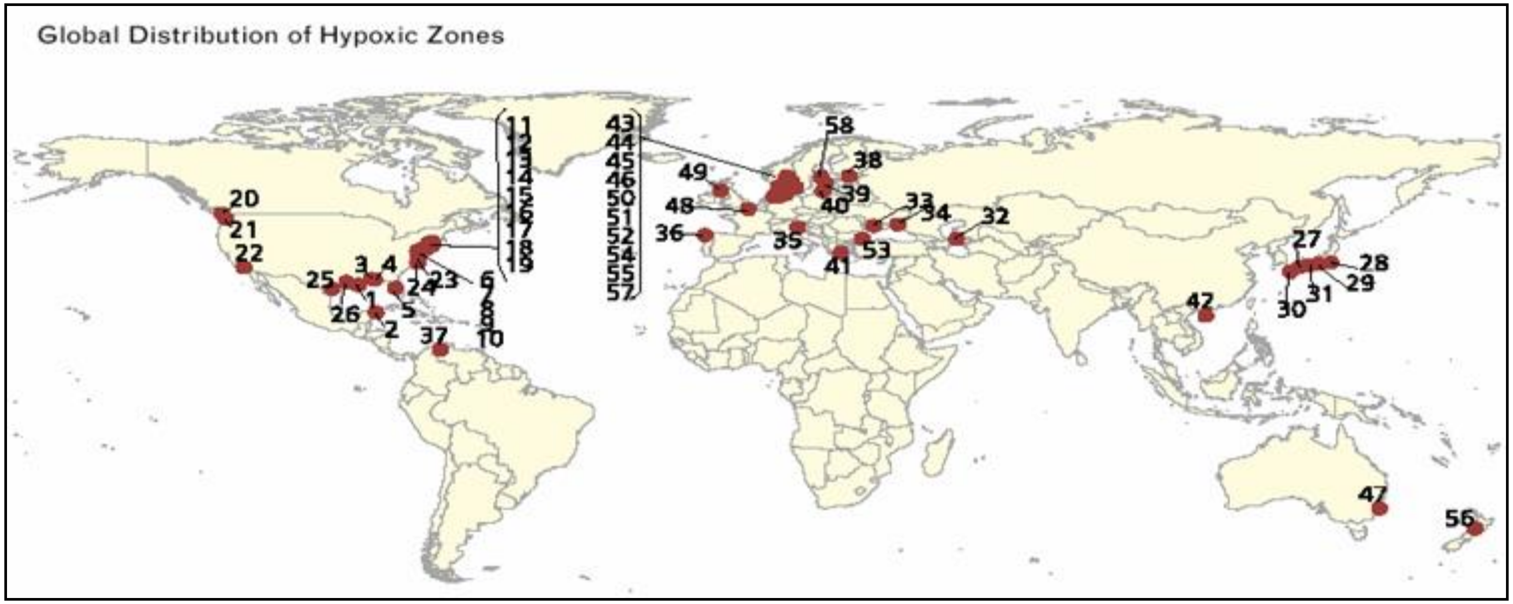
Presentation Topics

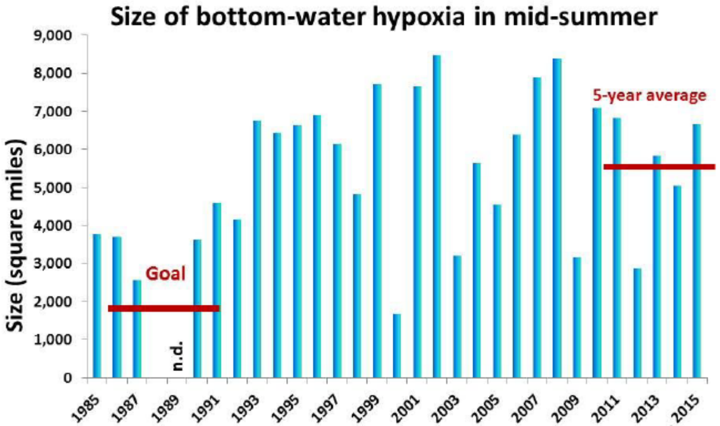
- Motivations for Mississippi modeling
- Progress on modeling nutrient sources and transport/retention in Mississippi Basin
- Regional effects of crop management practices (Upper Mississippi Basin)
- Conclusions and on-going next steps in modeling

Elevated nutrients in riverine loads have contributed to stressed estuarine trophic conditions globally



From Burke et al. 2000

Mississippi River Basin and Gulf Hypoxia



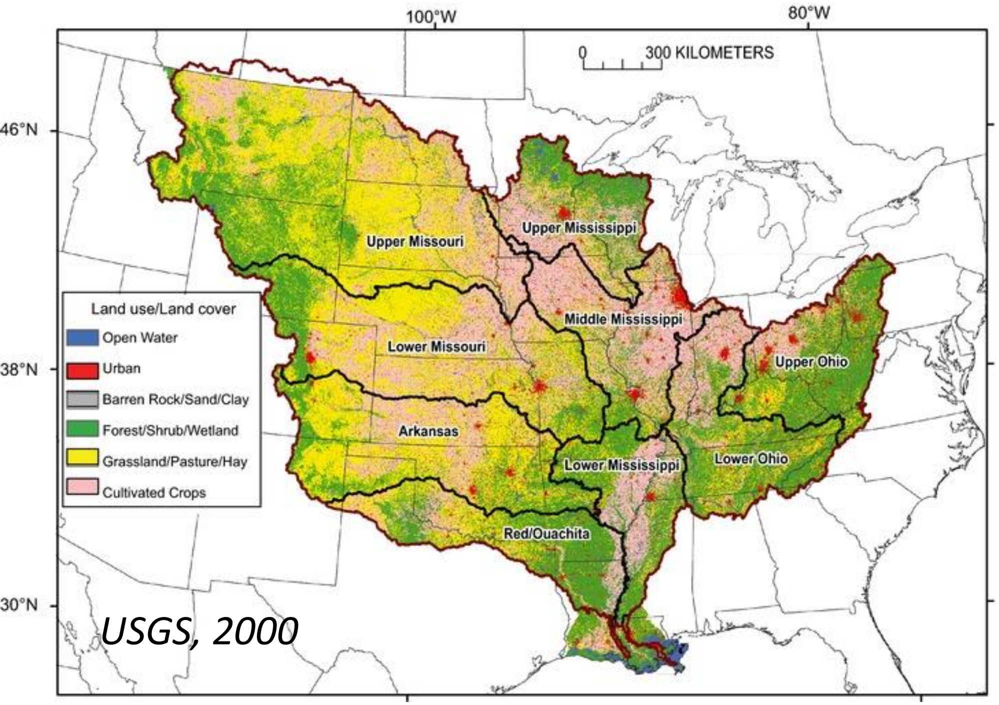
Data source: Nancy N. Rabalais, LUMCON, and R. Eugene Turner, LSU
Funding sources: NOAA Center for Sponsored Coastal Ocean Research and
U.S. EPA Gulf of Mexico Program

Area of bottom water hypoxia (< 2mg/l of dissolved oxygen) for mid-summer cruises, 1985-2015. Hypoxia Action Plan goal for reduced size is shown on the histogram along with the 5 year running average.

Source: US EPA

- **World's second largest drainage area = 3.2x10^{6} km^{2}**
- **~40% of contiguous area of USA**

Mississippi River Basin Land Use



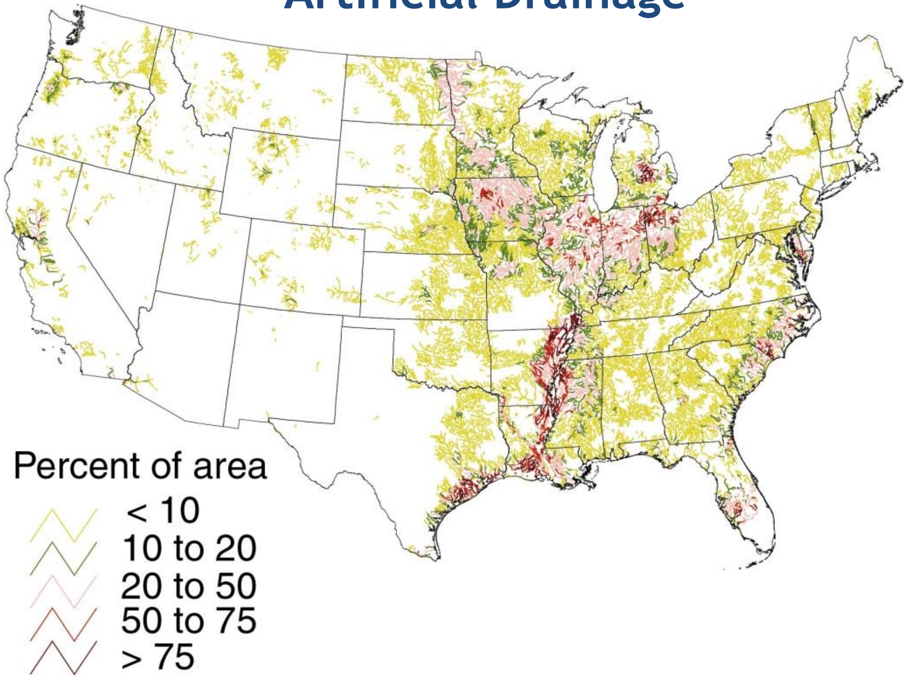
USGS, 2000

Land use

Cropland: 58%
Urban: 6%
Range: 21%
Woodland: 18%

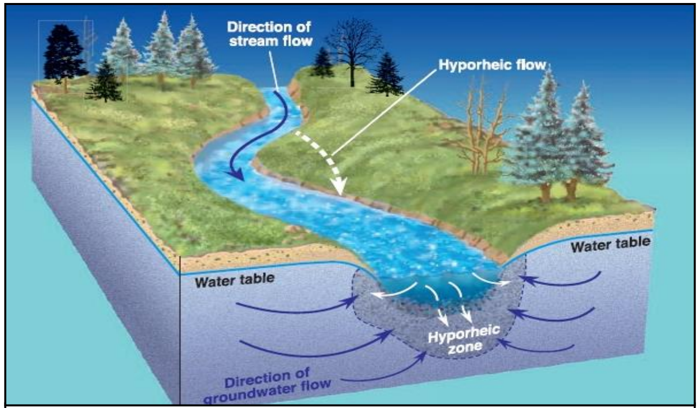
- 92% of agricultural exports in USA
- 78% of the world's exports in feed grains and soybeans
- **Nitrate** ~2.8 increase 1905-1996 (most of increase 1960s-80s)

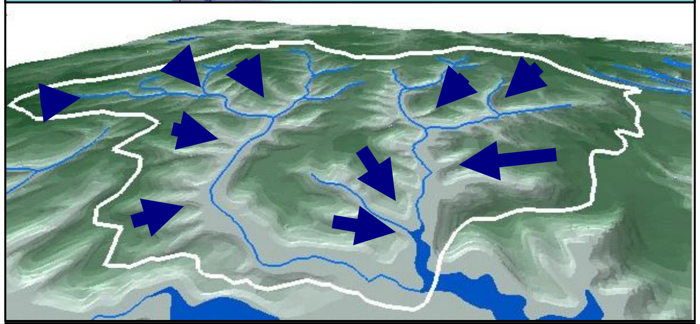
Surface and Subsurface Artificial Drainage

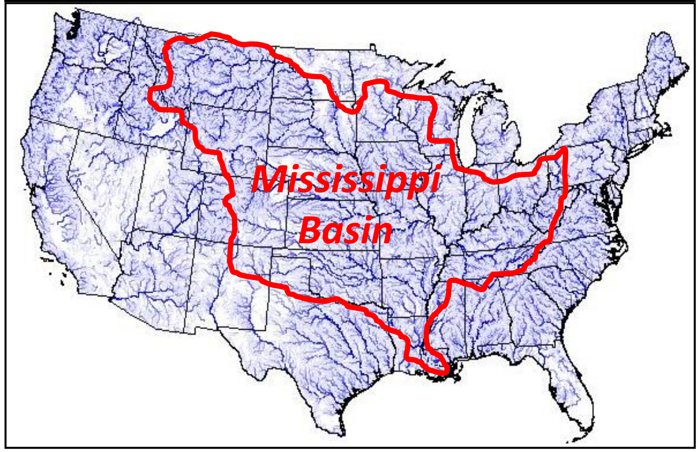


U.S. Department of Commerce, *1978 Census of Agriculture*, Bureau of the Census: Washington, DC

Mississippi Modeling Challenges & Solutions







Prediction challenges and questions:

Appreciable heterogeneity: diverse sources, nonlinear processes, coupled processes, and cumulative effects over large space-time scales

- What are the types and geography of nutrient sources (covering 32 state jurisdictions)?
- What are key landscape controls on transport?
- What are effects of in-stream and reservoir processes?
- What are downstream effects of crop management practices (tile drains, conservation tillage, structural), and timing of the stream response?

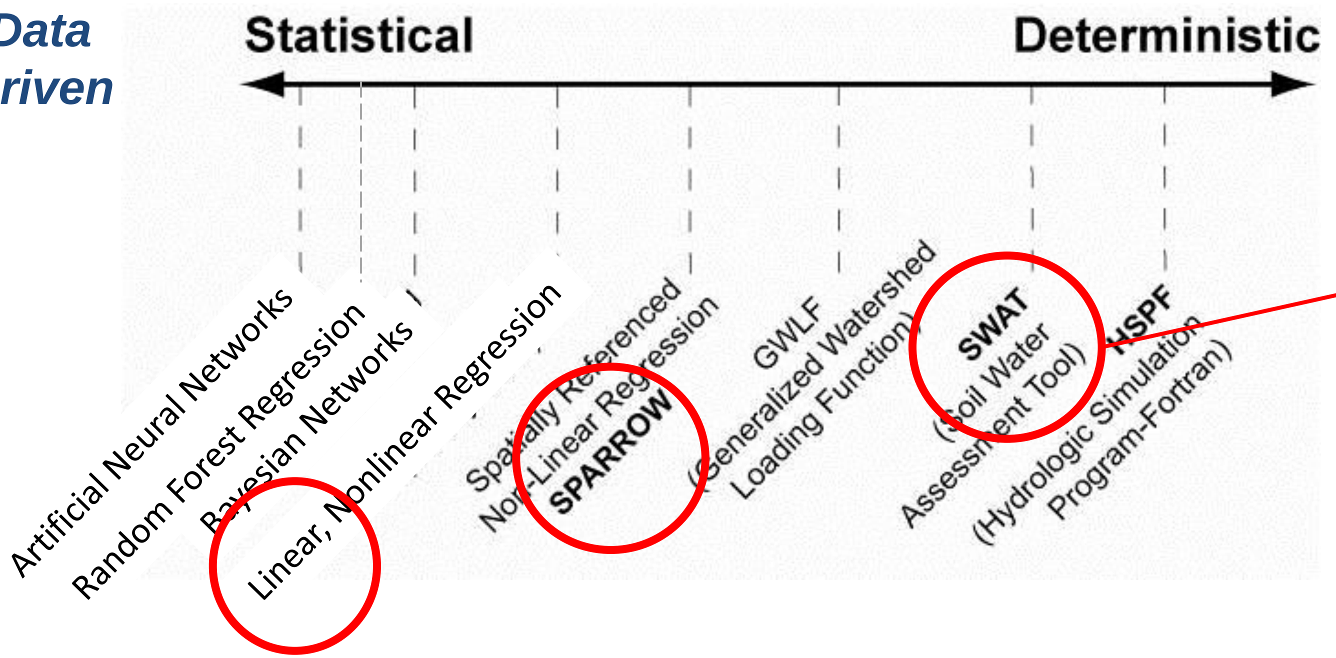
Solutions:

- Process- and statistically-based models, with variable complexity and scale
- Spatially explicit models
- Identification of key scaling variables
- Parameter and uncertainty estimation to identify parsimonious model specifications

Water-Quality Modeling Continuum

Data Driven

Physically Based



Three leading models used in Mississippi Basin

SPARROW and SWAT offer complementary methods

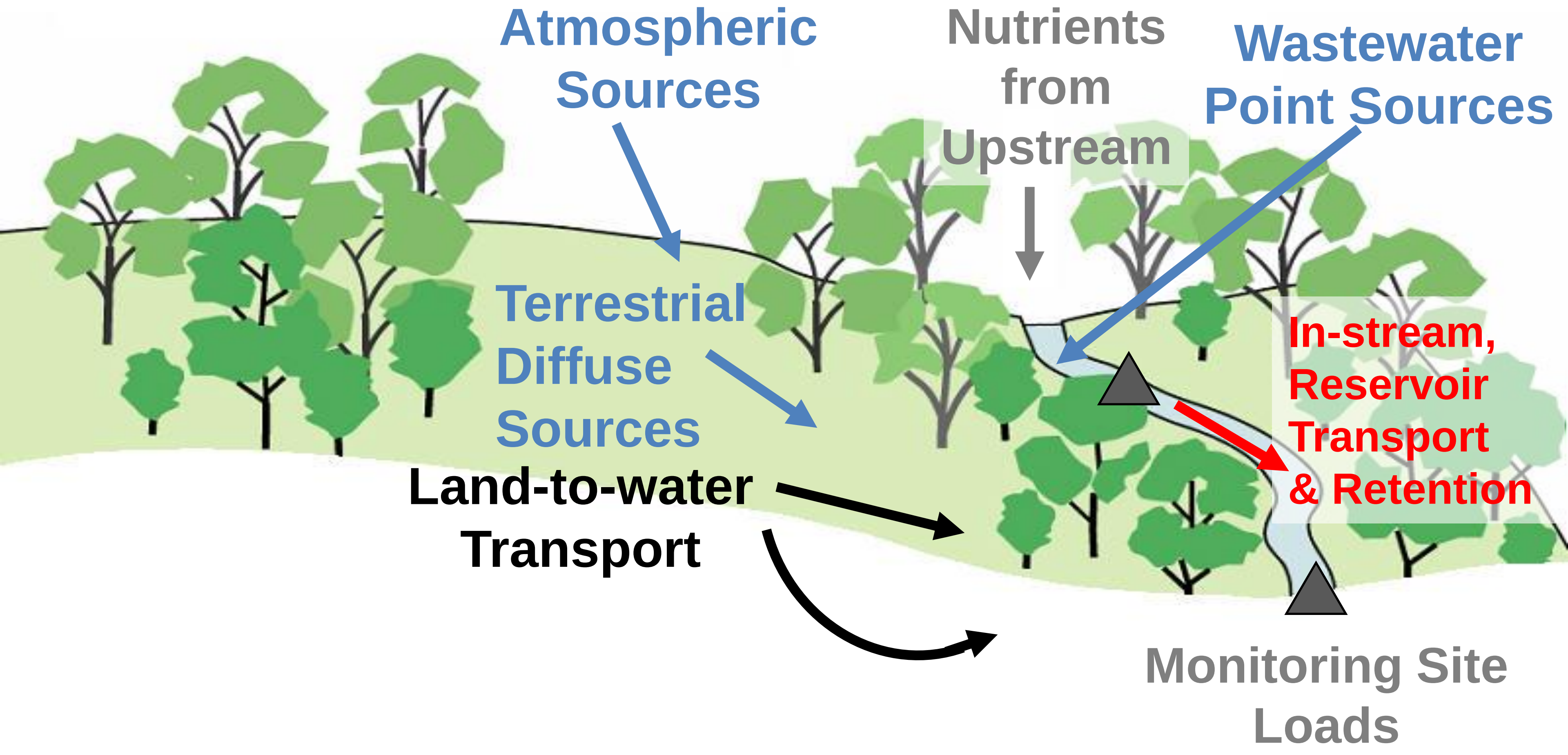
← *Optimal fit to data, but limited process understanding*

Increasing process complexity and interpretability, but possible over-specification and parameter non-uniqueness (i.e., most dynamics driven by relatively few parameters)

Complexity ≠ Accuracy

USGS SPARROW Conceptual Framework

SPAtially Referenced Regression on Watershed Attributes (Smith et al., *WRR*, 1997)



Atmospheric Sources

Nutrients from Upstream

Wastewater Point Sources

Terrestrial Diffuse Sources

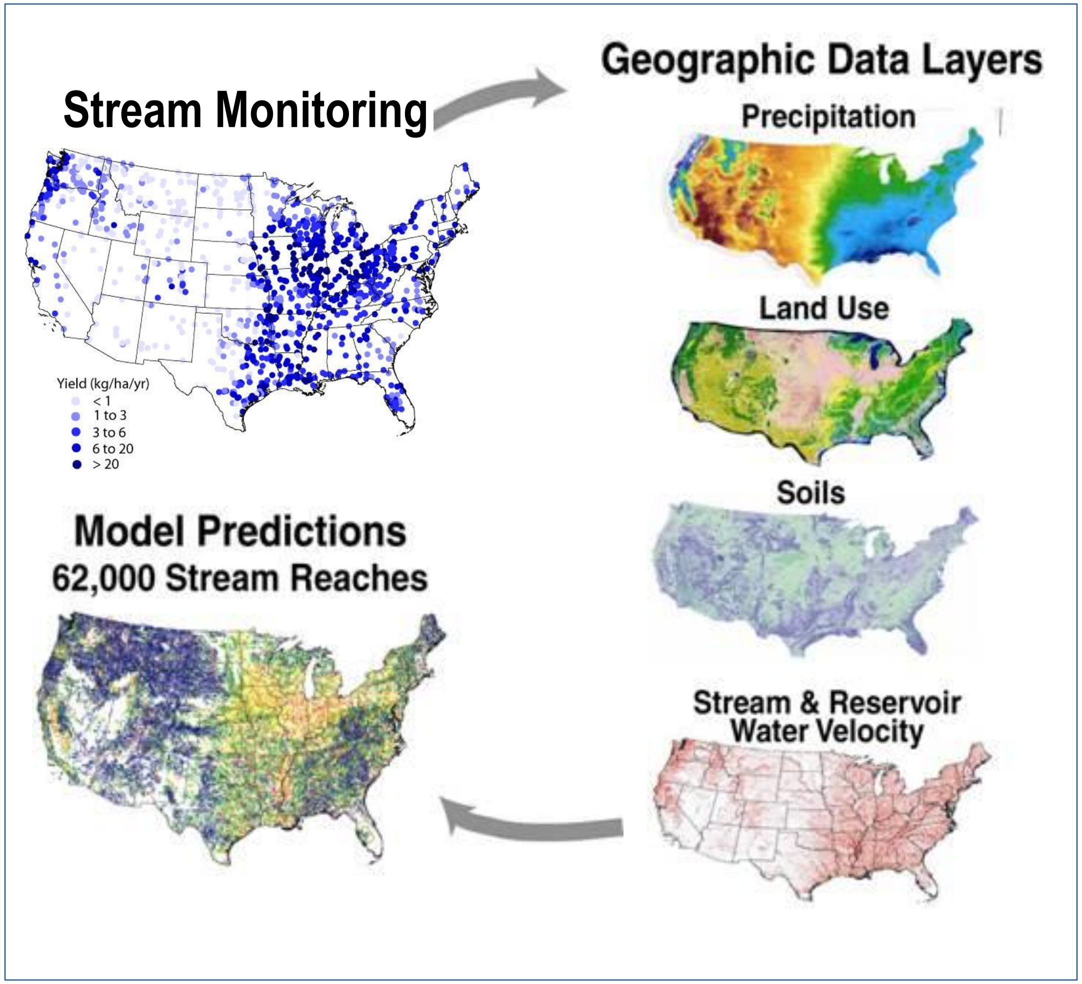
In-stream, Reservoir Transport & Retention

Land-to-water Transport

Monitoring Site Loads

USGS SPARROW Water-Quality Model

SPAtially Referenced Regression on Watershed Attributes (Smith et al., 1997)



SPARROW: http://water.usgs.gov/nawqa/sparrow

Top-down modeling approach

Quantifies major process effects observed over large spatial scales

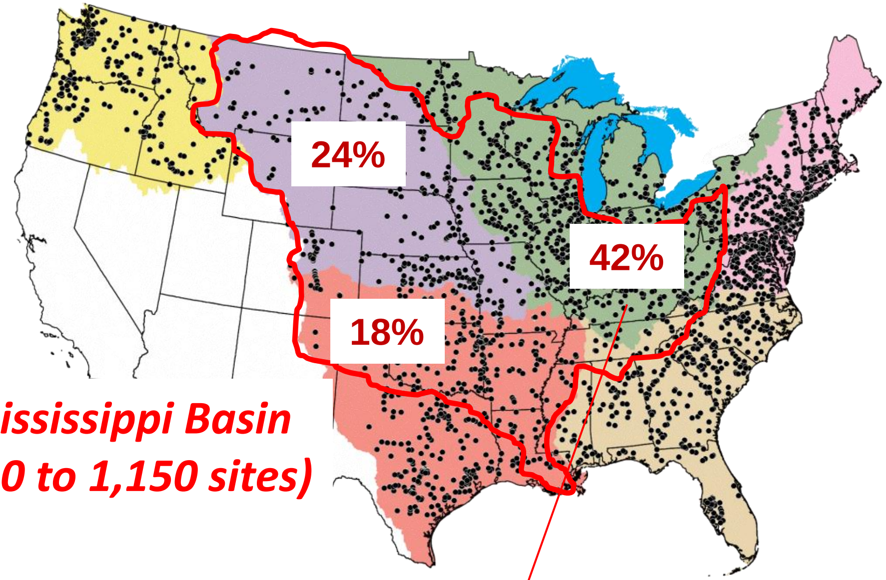
Hybrid framework

- spatially explicit, nonlinear, mass balance structure
- non-conservative transport
- parsimonious complexity; constrained by monitoring data
- Steady state (long-term mean conditions); dynamic version more recent

Monitoring Data Are Critical for SPARROW

Load Estimation (Response Variable), Process Identification, Model and Prediction Uncertainties

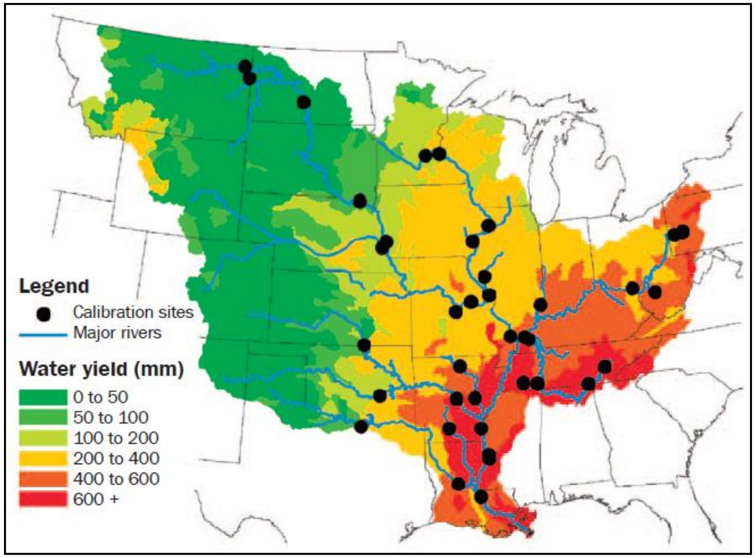
2,700 monitoring sites with
data from 73 agencies



Mississippi Basin
(850 to 1,150 sites)

Preston et al., *JAWRA*, 2011

SWAT Mississippi Basin Model
Water Calibration Sites



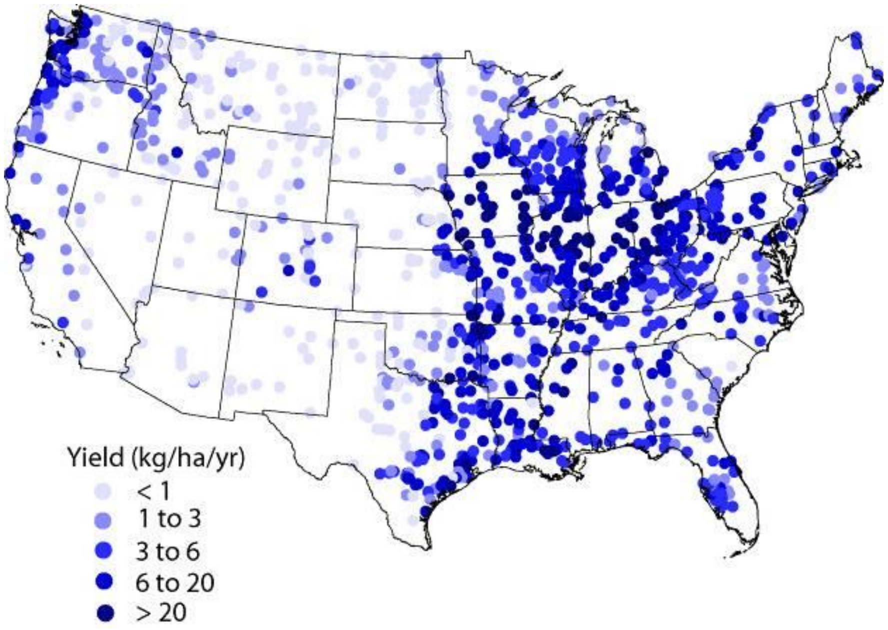
White et al., *JSWC*, 2014

Percent of sites with sufficient WQ and streamflow
data (10,500 sites >= 2 years quarterly data)

SPARROW applications to large basins increase data *quantity* (numbers of sites) and *quality* (variation in stream loads and explanatory factors)

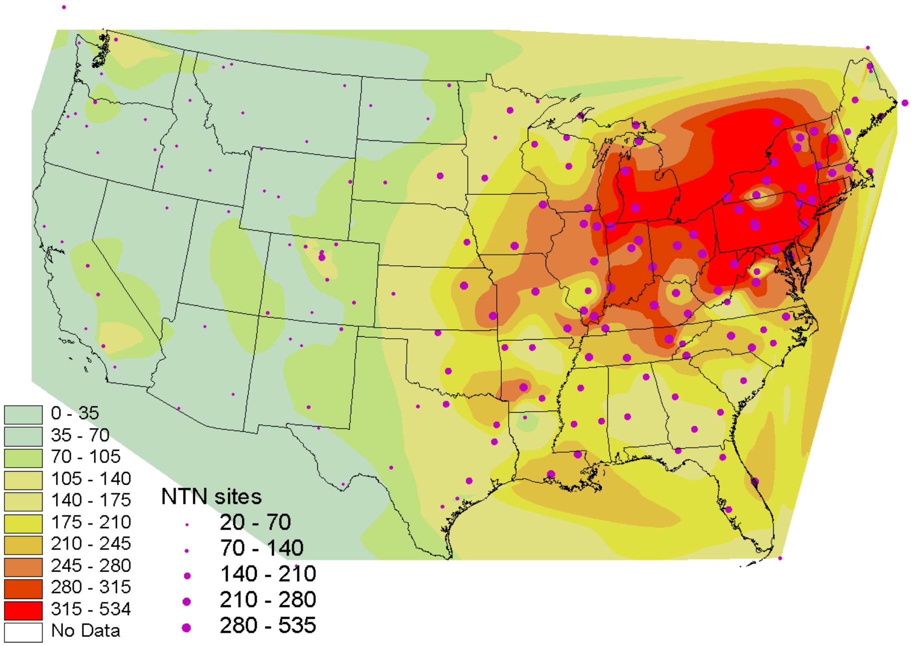
Response Variable

Total Nitrogen Stream Yield



Explanatory Variable

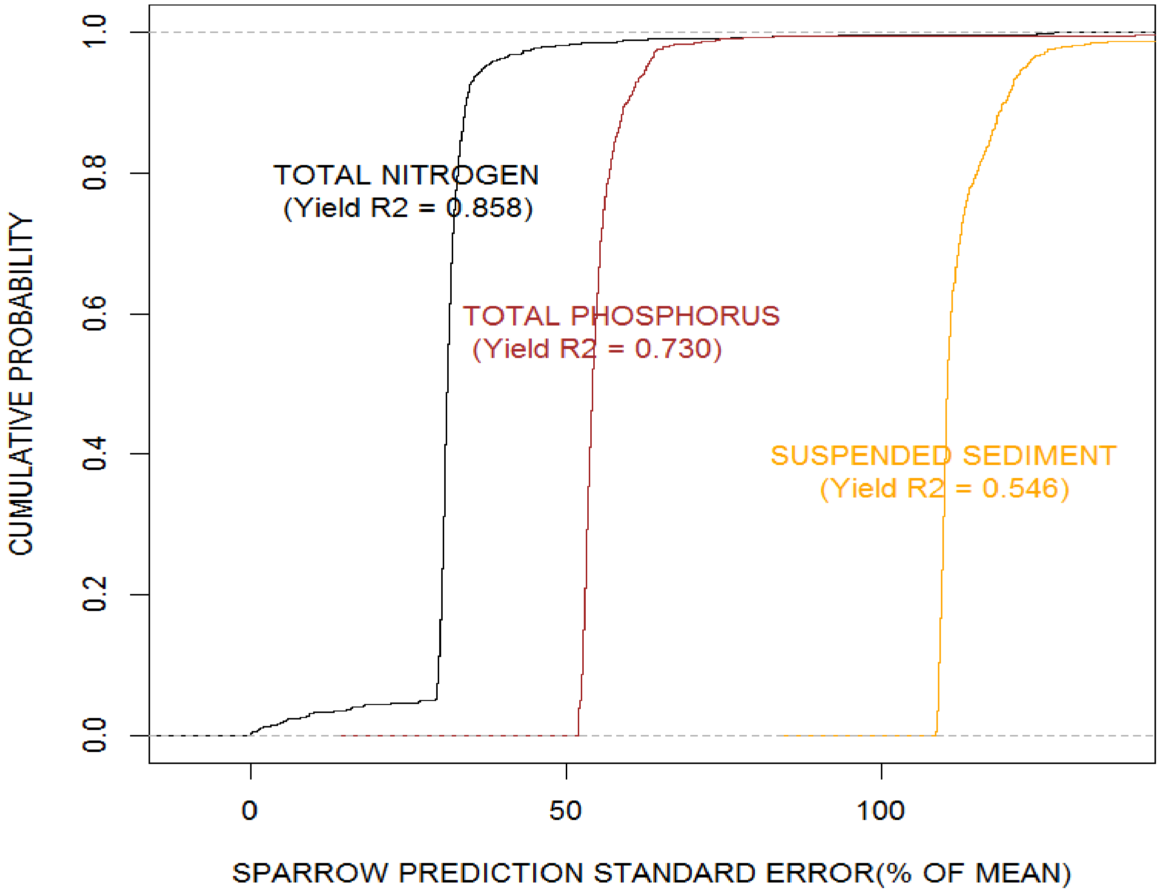
Wet Nitrate Deposition



SPARROW Load Prediction Uncertainties

Intrinsic Connections to Monitoring Load Accuracy

Streams in the Chesapeake Bay Watershed (NHD reaches)



Model Complexity (no. parameters)

Nitrogen:	13
Phosphorus:	11
Sediment:	7

Ator et al. 2011 (nitrogen, phosphorus); J. Brakebill, USGS, 2015 (sediment; unpublished model)

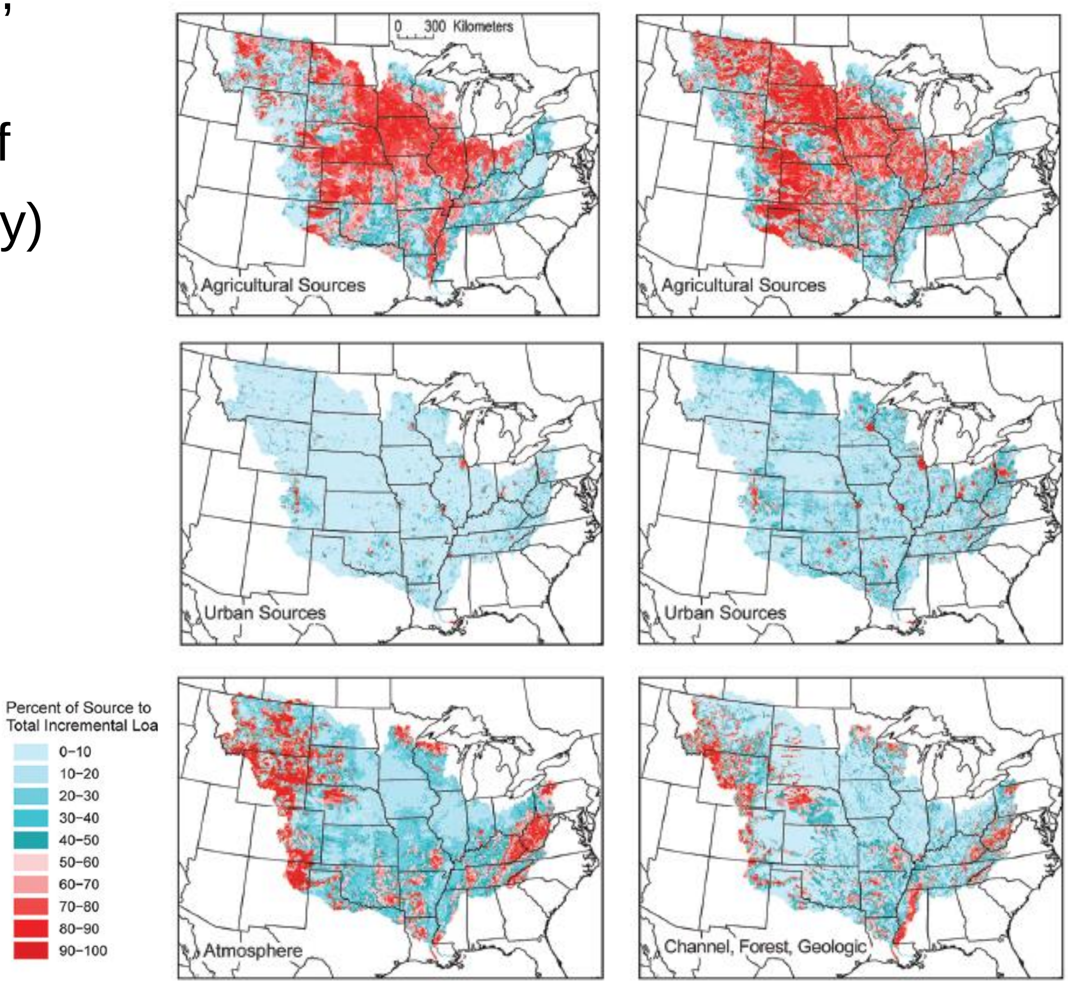
Major Nutrient Process Controls: Sources
Mississippi River Basin

Sources

- Agriculture – fertilizer, manure, crop type
- Urban – point, non-point runoff
- Atmospheric deposition (N only) – wet/dry; stationary / nonstationary
- Natural and anthropogenic background – forest (N atmos./fixation), geology / mining (soils / streambank erosion (P)

Mississippi River Basin

NITROGEN **PHOSPHORUS**



Robertson and Saad, JEQ, 2013

Major Nutrient Process Controls: Landscape

Mississippi River Basin

Land to Water Delivery

- **Climate** – precipitation, temperature
- **Hydrology** – excess overland flow, drainage density
- **Soil properties** – permeability, organic content, soil erodibility (K-factor)
- **Agricultural features** - tile drains, irrigation

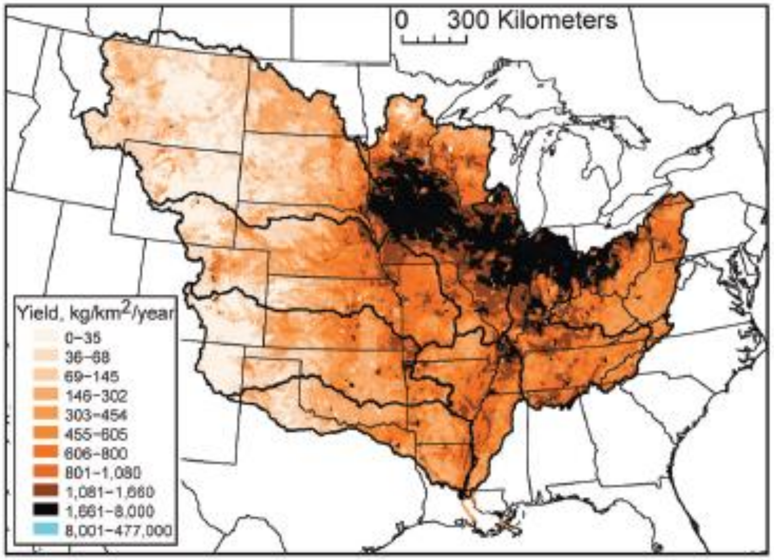
Aquatic Attenuation

- In-stream storage and removal
- Reservoir removal

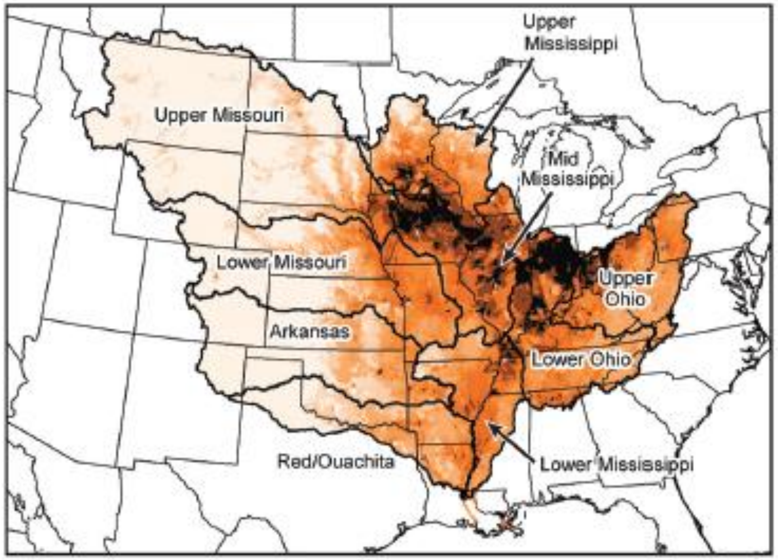
Robertson and Saad, JEQ, 2013

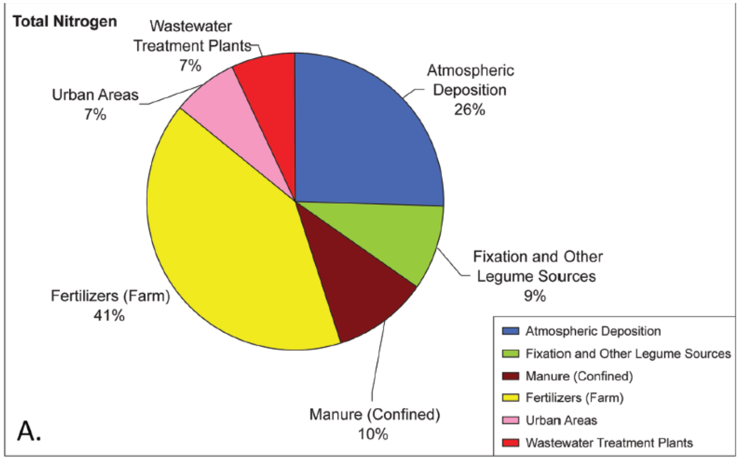
SPARROW Total Nitrogen Delivery to Gulf of Mexico

Incremental N Yield



Delivered Incremental N Yield



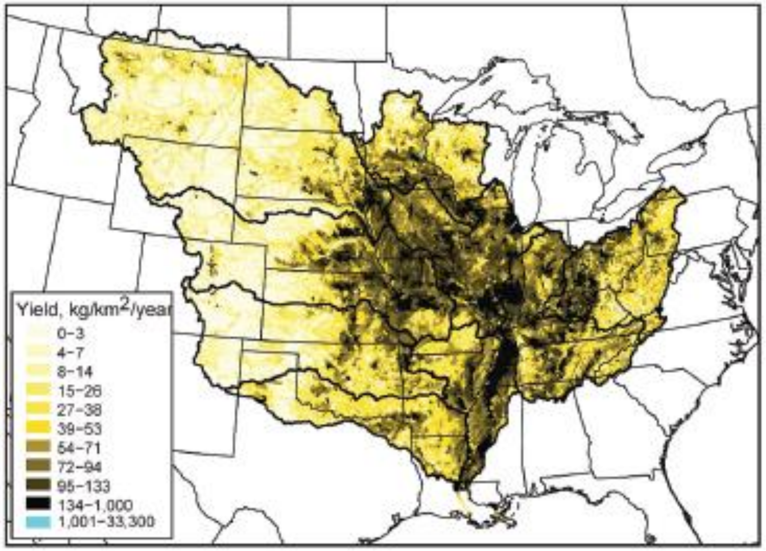


N Sources at Mississippi Outlet to Gulf of Mexico

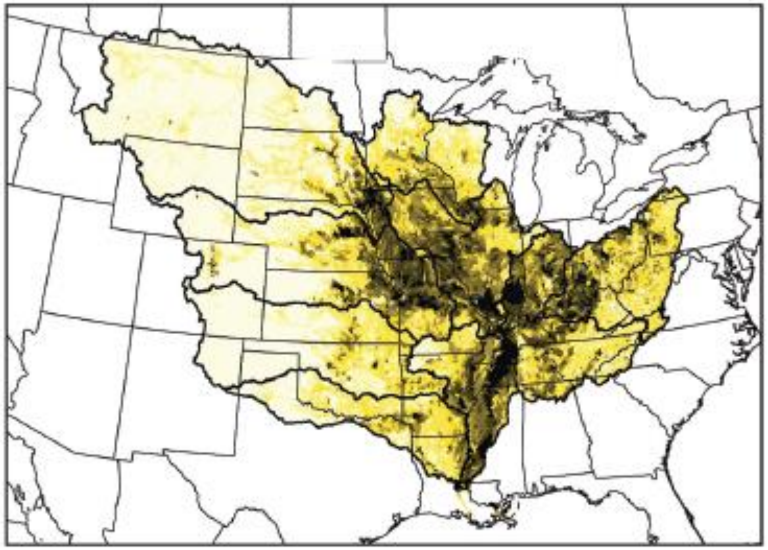
Robertson and Saad, JEQ, 2013

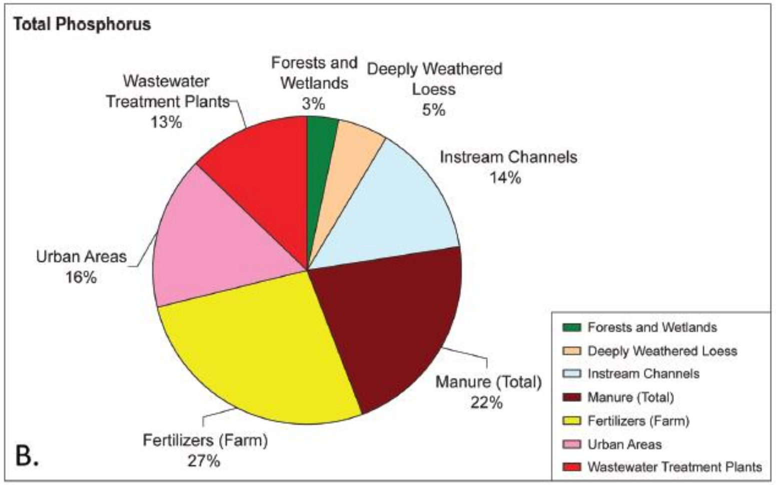
SPARROW Total Phosphorus Delivery to Gulf of Mexico

Incremental P Yield



Delivered Incremental P Yield





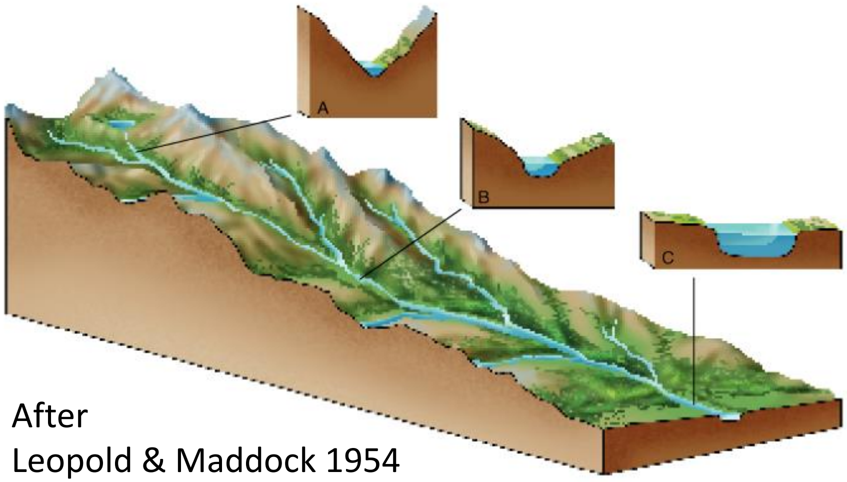
P Sources at Mississippi Outlet to Gulf of Mexico

Robertson and Saad, JEQ, 2013

Nutrient Process Controls: In-Stream Retention

Non-Conservative Transport:

- Modeled by first-order kinetics (exponential depletion), with a volumetrically based measure of removal—the reaction rate constant
- **Reaction rates are theoretically expected to decline with increases in stream size**



After
Leopold & Maddock 1954

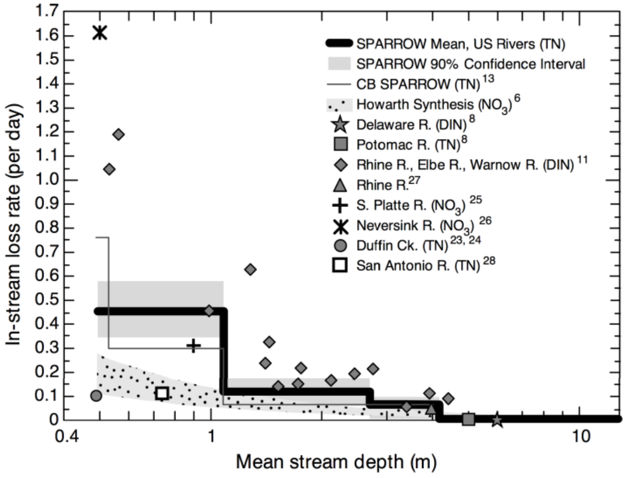
Hydrological Controls on Downstream Transport:

- Increase in depth, discharge, velocity, and water volume per unit of bottom surface area
- Less exchange and contact of nutrients with streambed
- Reduced processing and removal of N in hyporheic zone (denitrification) and P via settling and storage

Comparison of Reaction Rate Constants Among SPARROW Models and Literature

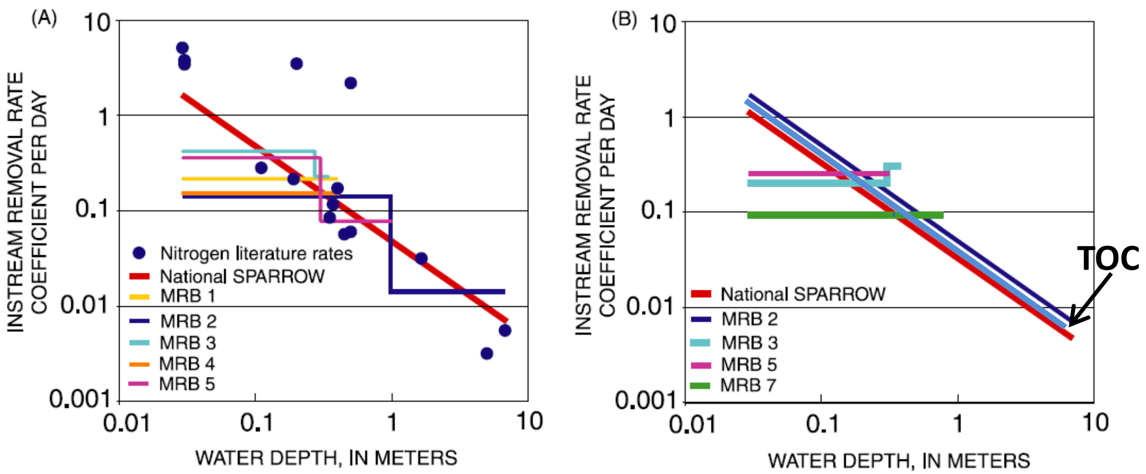
SPARROW Total N Model

and meta-analysis of field studies



Alexander et al., *Nature*, 2000

USA Regional SPARROW Models



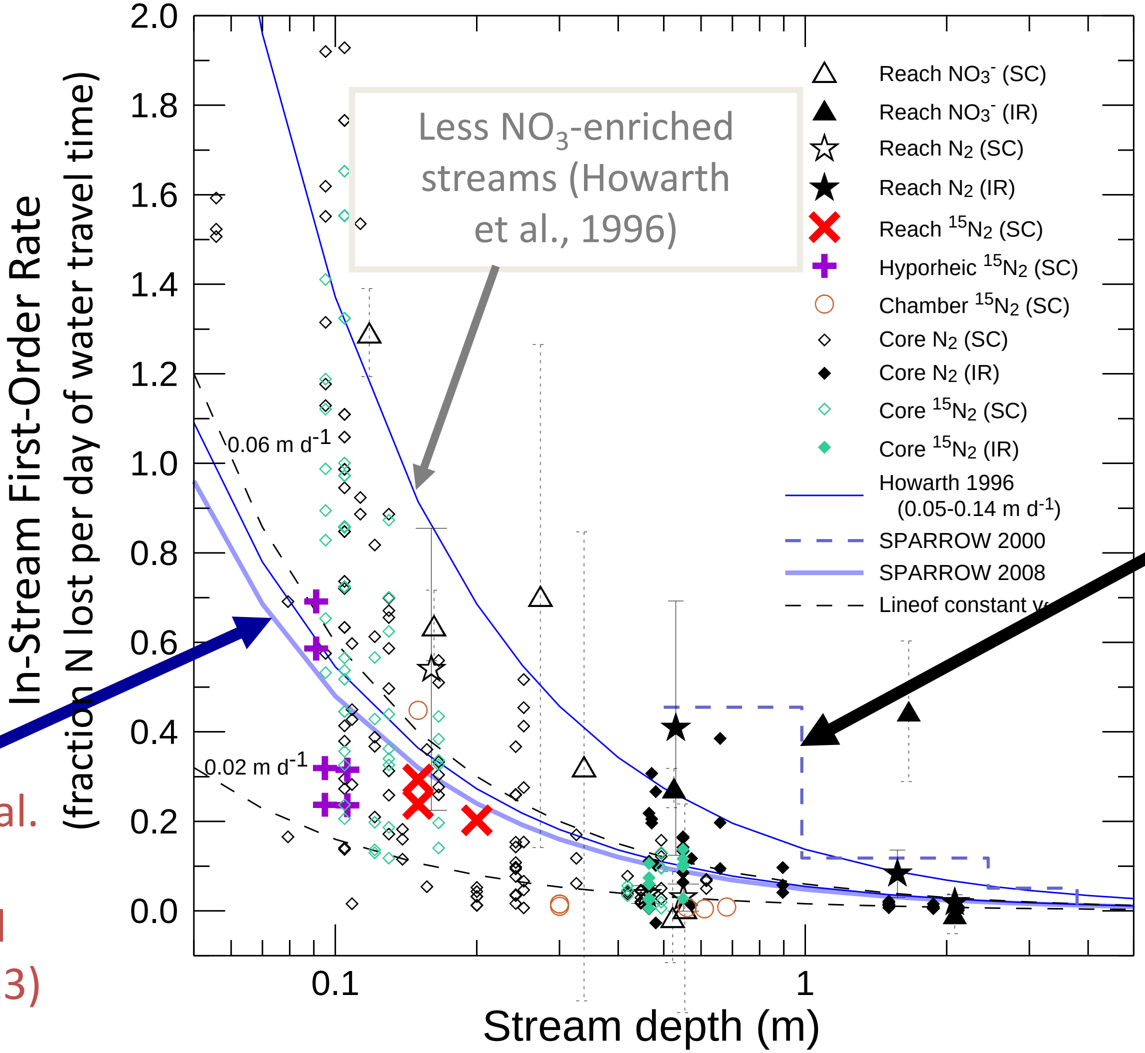
Total Nitrogen

Total Phosphorus

Preston et al., *JAWRA*, 2011

TOC (Total organic carbon): Shih et al., 2010

SPARROW and Literature Denitrification-Related Nitrogen Removal Rate Constants



Less NO$_3$-enriched streams (Howarth et al., 1996)

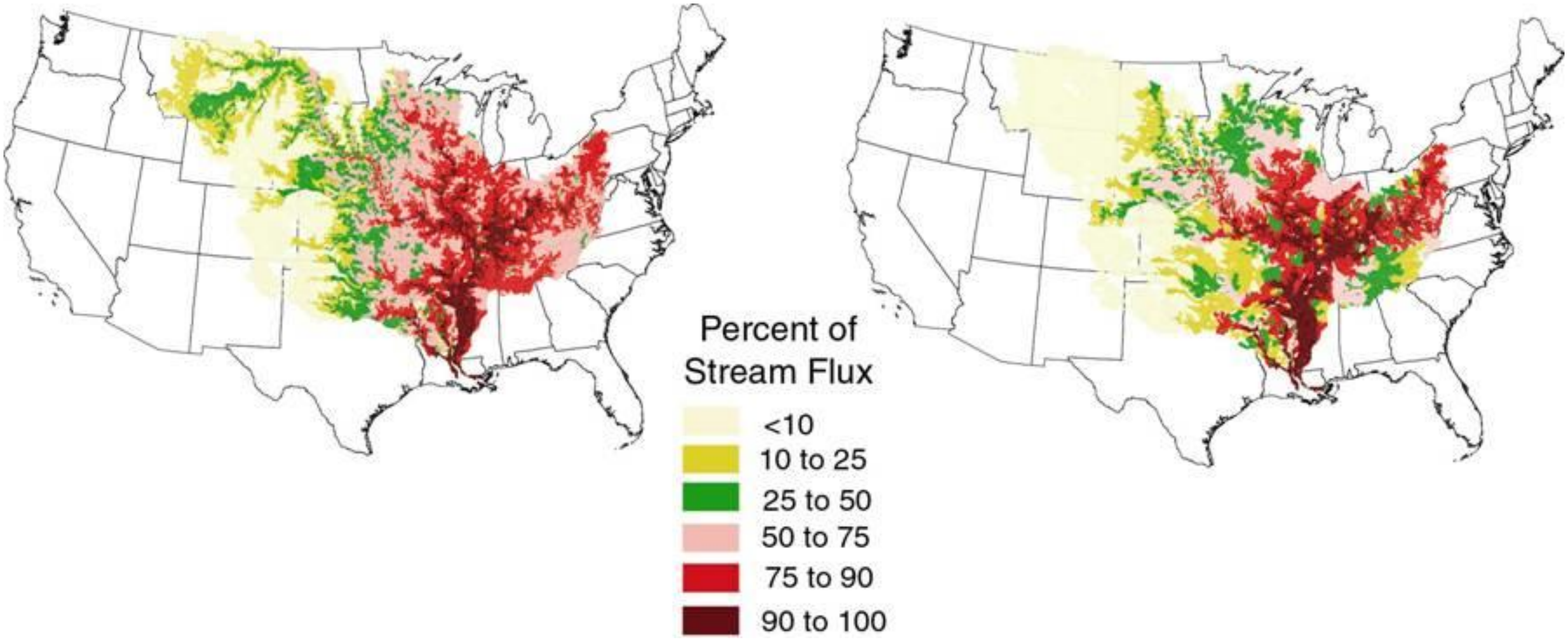
SPARROW (Alexander et al., Nature, 2000)

SPARROW (Alexander et al. *ES&T*, 2008; Robertson and Saad, *JEQ*, 2013)

Vf = 0.049 m d^{-1}

Point-estimates from N-enriched Iroquois R. & Sugar Creek, Indiana (Böhlke et al., *Biogeochem.*, 2009)

SPARROW estimates of effects of aquatic nutrient removal on the percentage of stream nutrient load delivered to the Gulf of Mexico



Nitrogen

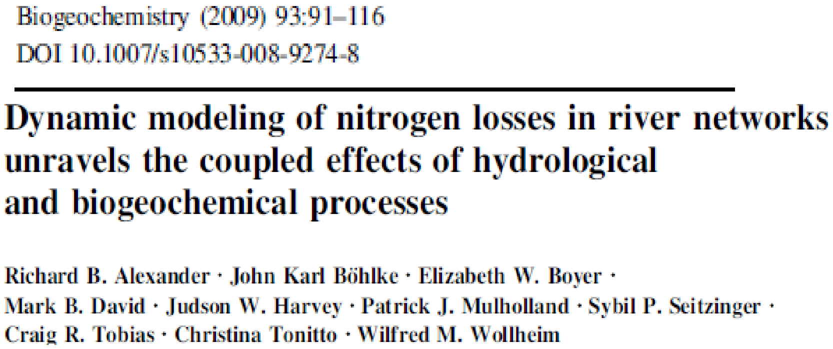
Phosphorus

Primarily hydrological controls (1st-order kinetics)

Alexander et al., ES&T, 2008

Biogeochemical controls are important!

Denitrification-related N removal is less efficient in nitrate-enriched streams



Biogeochemistry (2009) 93:91–116
DOI 10.1007/s10533-008-9274-8

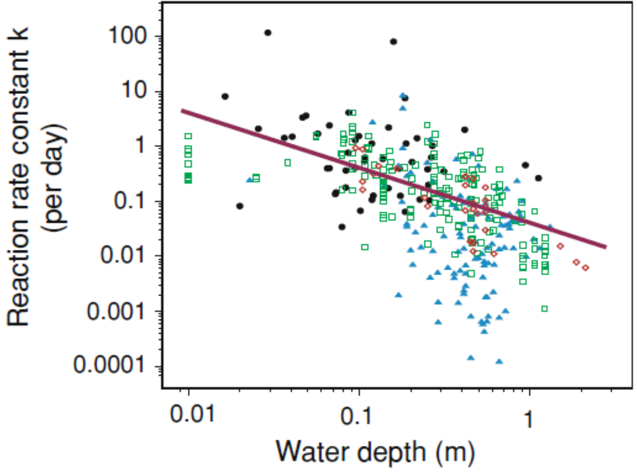
Dynamic modeling of nitrogen losses in river networks unravels the coupled effects of hydrological and biogeochemical processes

Richard B. Alexander · John Karl Böhlke · Elizabeth W. Boyer · Mark B. David · Judson W. Harvey · Patrick J. Mulholland · Sybil P. Seitzinger · Craig R. Tobias · Christina Tonitto · Wilfred M. Wollheim

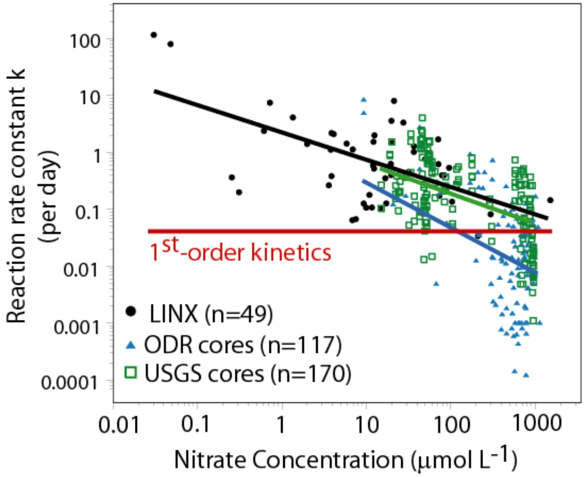
Meta-analysis of leading field datasets

LINX – Mulholland et al. 2008, Nature
USGS – Smith et al., 2006, Ecol Apps.
ODR – Royer et al. 2004, JEQ; others

Hydrological controls (1st-order kinetics)



Biogeochemical controls



Hydrological and biogeochemical processes equally affect N removal rates

Biogeochemical controls lead to greater downstream connectivity in agricultural, N-enriched watersheds

Sugar Creek, Indiana

Seasonal simulation modeling in watersheds with diverse land use

SUGAR CREEK

(NO_3 100 -1200 μmol N L^{-1})

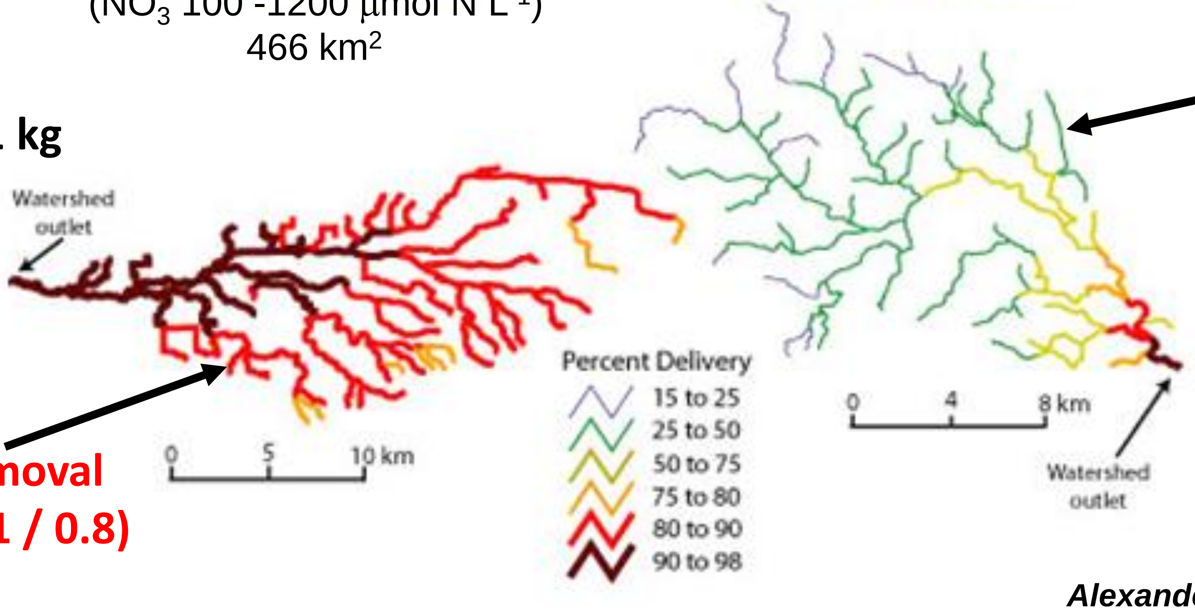
466 km^2

NASHUA RIVER

(NO_3 10 -15 μmol N L^{-1})

282 km^2

To remove 1 kg at outlet



requires removal of 1.25 kg (1 / 0.8)

requires removal of 4 kg (1 / 0.25)

To remove 1 kg at outlet

Alexander et al. 2009, Biogeochem.

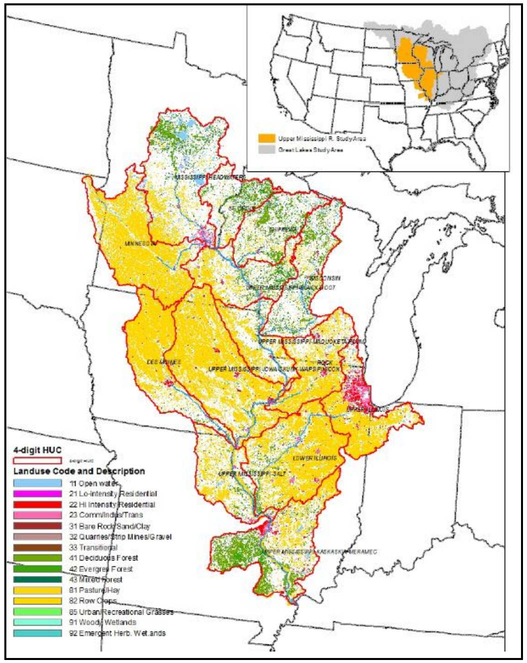
Regional Evidence of Stream Nutrient Response to Agricultural Management

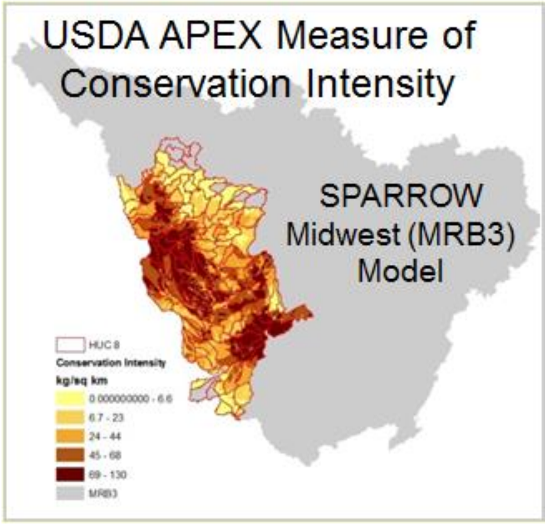
Environmental Science & Technology
Article
pubs.acs.org/est

Regional Effects of Agricultural Conservation Practices on Nutrient Transport in the Upper Mississippi River Basin

Ana María García,[*,†] Richard B. Alexander,[‡] Jeffrey G. Arnold,[§] Lee Norfleet,[∥] Michael J. White,[§] Dale M. Robertson,[⊥] and Gregory Schwarz[‡]

Land Use in Midwest



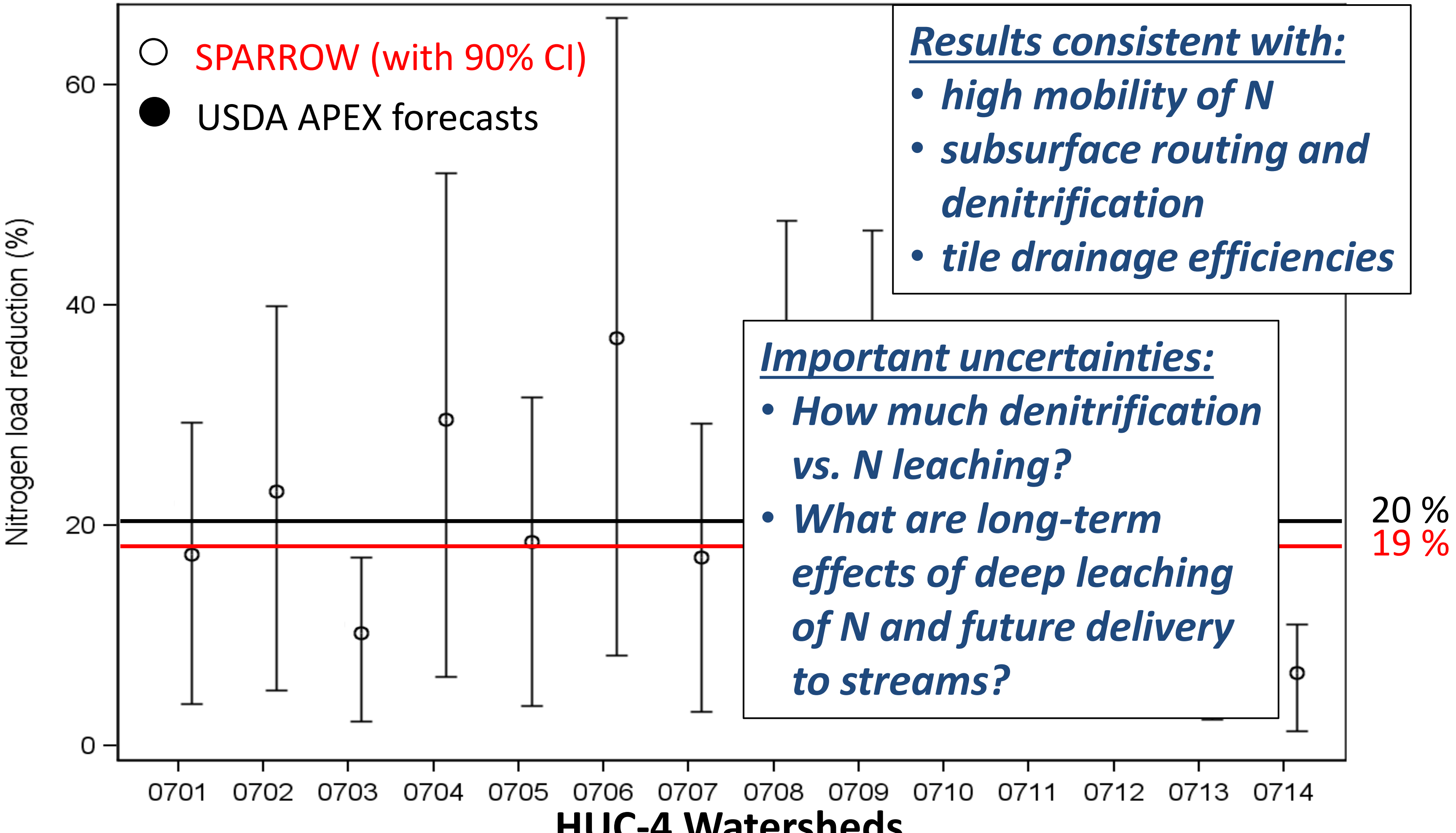


- SPARROW sequentially coupled with field-scale APEX model
- APEX predicts “technologically feasible” effects of conservation practices on farm nutrient loads (reductions = loads with and w/o conservation)
- SPARROW estimates mean annual stream nutrient response to spatial variability in conservation load reductions (land-to-water delivery) as predicted by APEX
- An empirical evaluation, based on *space for time substitution*
- Results complementary to USDA simulation (forecasting) measures of conservation effects

Garcia et al., 2016, ES&T

Regional Evidence of Stream Nutrient Response to Conservation Practices: Total Nitrogen

Watersheds in Upper Mississippi River Basin



Results consistent with:

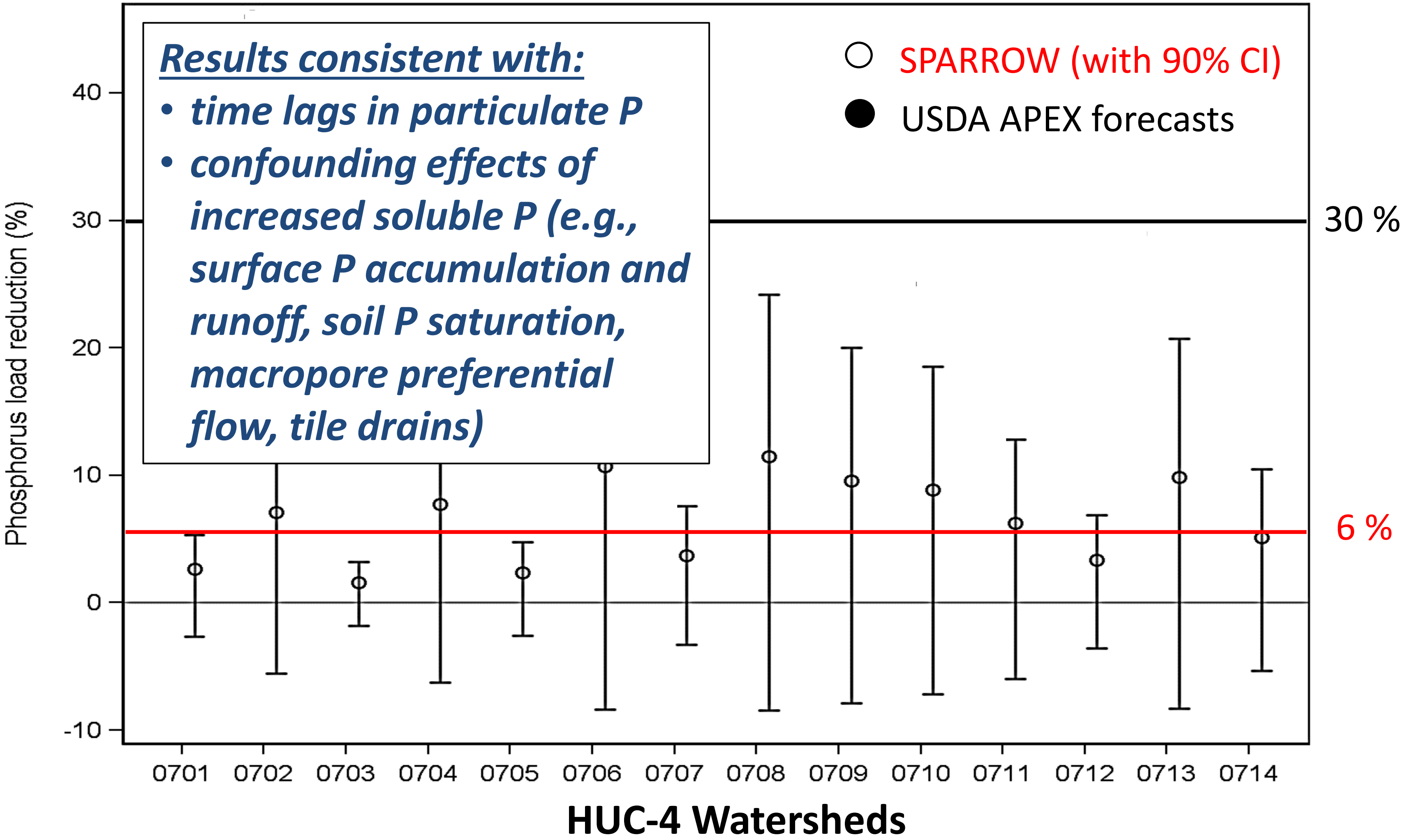
- ***high mobility of N***
- ***subsurface routing and denitrification***
- ***tile drainage efficiencies***

Important uncertainties:

- ***How much denitrification vs. N leaching?***
- ***What are long-term effects of deep leaching of N and future delivery to streams?***

Garcia et al. 2016, ES&T

Regional Evidence of Stream Nutrient Response to Conservation Practices: Total Phosphorus



Watersheds in Upper Mississippi River Basin

Results consistent with:

- ***time lags in particulate P***
- ***confounding effects of increased soluble P (e.g., surface P accumulation and runoff, soil P saturation, macropore preferential flow, tile drains)***

Garcia et al. 2016, ES&T

Conclusions: Nutrient Retention Modeling Mississippi Basin Case Study

- **Multi-scale modeling has informed understanding of the nutrient response to environmental processes and management actions:**
  - SPARROW hybrid modeling (process constrained, statistically estimated) has played a prominent role in advancing the understanding of nutrient sources and transport in Mississippi Basin
  - Expanded hybrid models, with selected mechanistic components and statistical optimization, offer a flexible and informative conceptual approach going forward Need to answer: "How much model complexity is supported by the data?"
- **Transport is controlled by complex interactions of nutrient sources and hydrological and biogeochemical processes across large spatial scales:**
  - Headwaters to large catchments across diverse terrestrial and aquatic environments
  - In-stream removal scales with stream size and concentration (land use), and reservoir removal scales with water velocity
  - N and P show contrasting reservoir rates: larger N in streams and larger P in reservoirs
  - Downstream reduction goals should acknowledge the diverse mix of N and P sources
- **Regional-scale effects of farm conservation on N and P differ:**
  - Indicate important differences in processes and legacy effects
  - Potentially complicate measurement and management of environmental progress

Conclusions: Evolving SPARROW Modeling

On-going efforts to improve prediction and forecasting accuracy and provide robust methods for guiding management actions and reporting:

- Extension of Upper Mississippi study of conservation effects to other USA regions (SPARROW-APEX sequential coupling)
- Hybrid dynamic (seasonal) SPARROW models linked with ground water (MODFLOW) N residence times (e.g., models show lag times of 1 year to 3 decades in Chesapeake Bay watershed); coupling with APLE model for P residence times
- Stream transport: non-first order kinetics; river corridor properties
- Hierarchical model structures (Bayesian SPARROW) to address space/time variability (scaling) in process effects and uncertainties
- Simultaneous multiple species (N, P, carbon, streamflow)
- Stakeholder engagement with dynamic SPARROW models (decision support); nutrient loading to Southeast USA estuaries

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