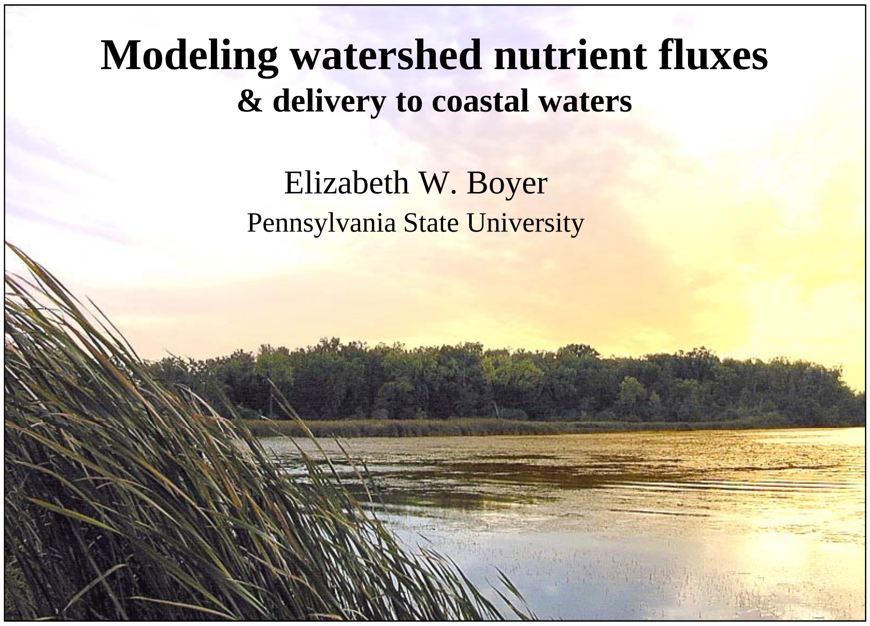


Modeling watershed nutrient fluxes
& delivery to coastal waters

Elizabeth W. Boyer
Pennsylvania State University

Collaborators

Richard Alexander
Gregory Schwarz
Richard Smith

US Geological Survey
National Water Quality Assessment Program

Outline

- Some noteworthy watershed modeling tools.
- Overview of SPARROW water quality modeling approach.
- Applications of SPARROW to quantify N & P loads to the Gulf of Mexico from Mississippi & Atchafalaya basins.
- Applications of SPARROW in progress to consider C loads at national scale.

Some watershed modeling approaches

SMHI HBV (& SOILN & ICE-CREAM)
http://www.smhi.se/sgn0106/if/hydrologi/hbv_np.htm

USGS Modular Modeling System (MMS)
http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/software/software.shtml

USDA Agricultural Policy EXtendender (APEX)
http://www.brc.tamus.edu/apex/index.html

USDA Soil Water Assessment Tool (SWAT)
http://www.brc.tamus.edu/swat/

CENTURY soil organic model
http://www.nrel.colostate.edu/projects/century5/

<u>**SPA**</u>tially **R**eferenced <u>**R**</u>egression <u>**o**</u>n <u>**W**</u>atershed Attributes
SPARROW water quality model

WATER RESOURCES RESEARCH, VOL. 33, NO. 12, PAGES 2781–2798, DECEMBER 1997

Regional interpretation of water-quality monitoring data

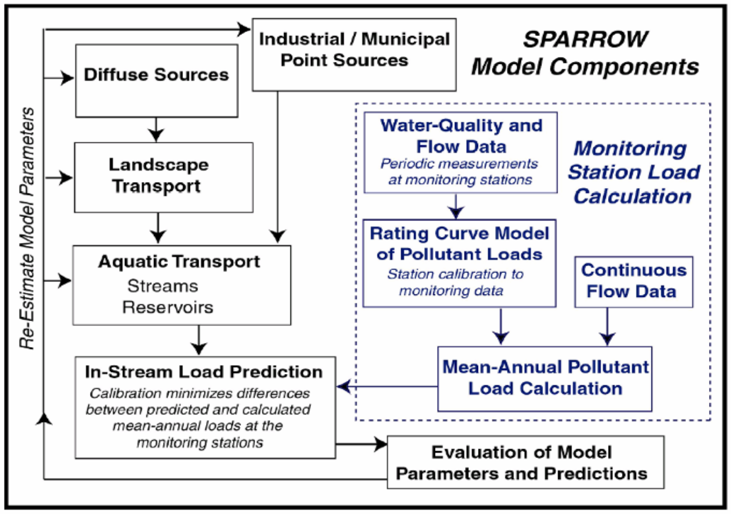
Richard A. Smith, Gregory E. Schwarz, and Richard B. Alexander
U.S. Geological Survey, Reston, Virginia

Abstract. We describe a method for using spatially referenced regressions of contaminant transport on watershed attributes (SPARROW) in regional water-quality assessment. The method is designed to reduce the problems of data interpretation caused

<u>**SPA**</u>tially **R**eferenced <u>**R**</u>egression <u>**o**</u>n <u>**W**</u>atershed Attributes
SPARROW water quality model

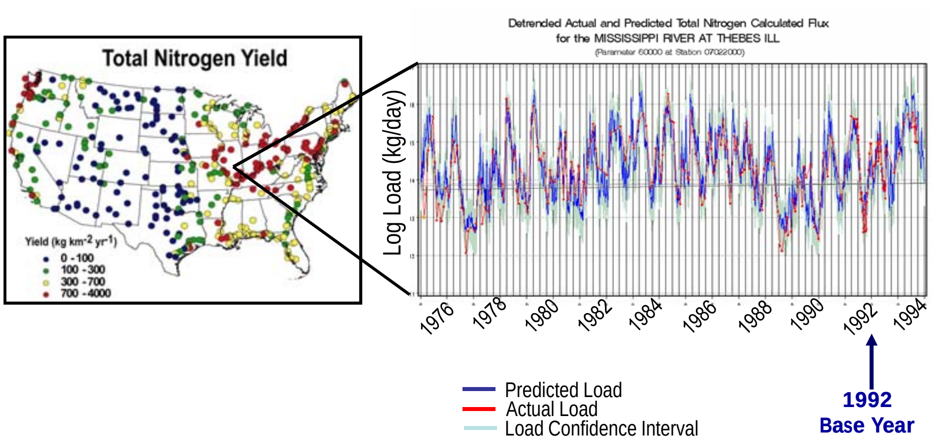
Potential applications:
- Reliably predict nutrient concentration, flux, yields in unmonitored streams; should be consistent with monitoring data
- Quantify the major sources in watersheds that contribute nutrients to surface waters
- Quantify the principal hydrological and biogeochemical controls on nutrient transport in watersheds
- Consider nutrient response to future changes in land use & climate

SPARROW model components



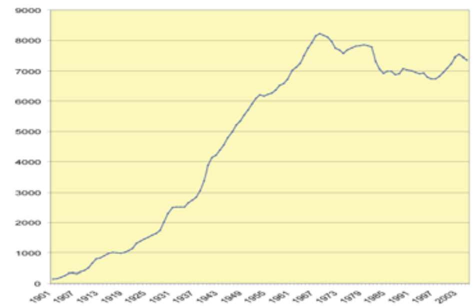
Alexander et al. 2002

SPARROW model components

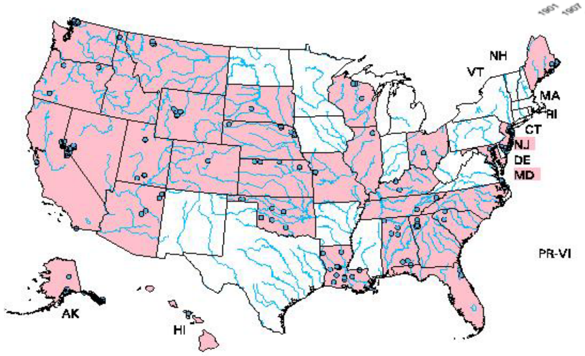


- Calibration to mean-annual conditions at stream monitoring sites
- e.g., The standardized mean nutrient load at each station is the load that would have occurred in 1992 if mean annual flow conditions from 1975-2000 had prevailed.

USGS National Streamflow Information Program

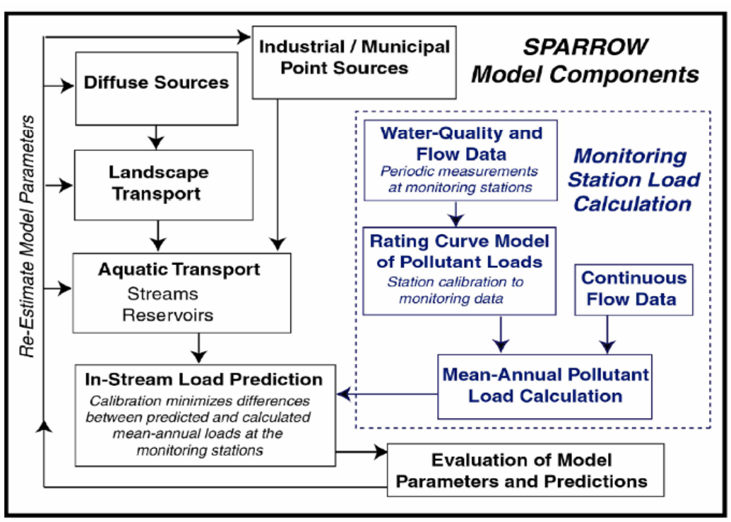


USGS stream gages 1900-2005
http://water.usgs.gov/nsip/history.html



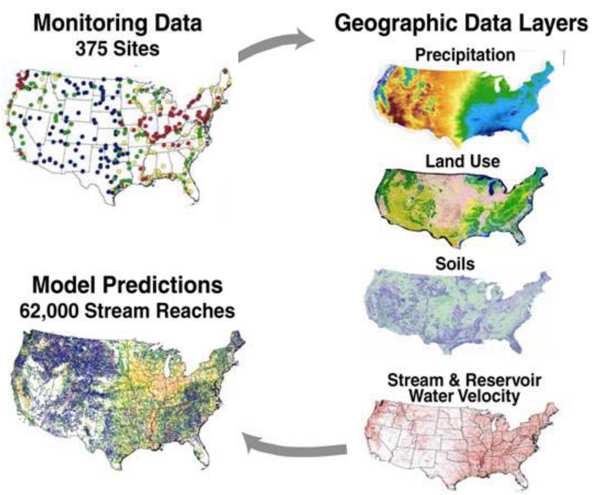
176 currently threatened stream gages
http://water.usgs.gov/osw/lost_streamgages.html

SPARROW model components



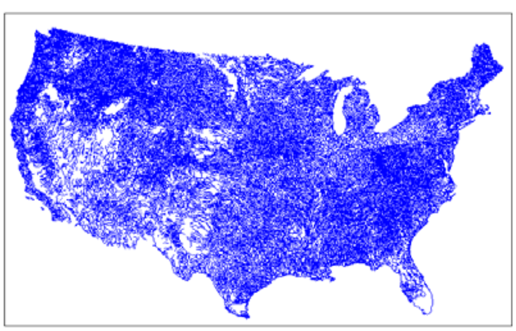
Alexander et al. 2002

SPARROW model predictions



- Represents terrestrial & aquatic processes; accounts for non-conservative transport in watersheds.
- Predictions of Loads, concentrations, stream & reservoir losses, source shares, uncertainties.
- Reflect long-term, net nutrient supply and loss processes

SPARROW model components



Spatial referencing is accomplished by linking all data to a geographically defined stream-reach data set.

Sources

Terrestrial Landscape

- Temperature
- Permeability
- Slope/Concavity
- Stream Density
- Wetlands
- Precipitation
- Irrigation
- Tile Drains

Aquatic Landscape

- Flow
- Velocity
- Reservoir retention

SPARROW mathematical form

reach-scale mass balance; relate watershed data to monitored loads

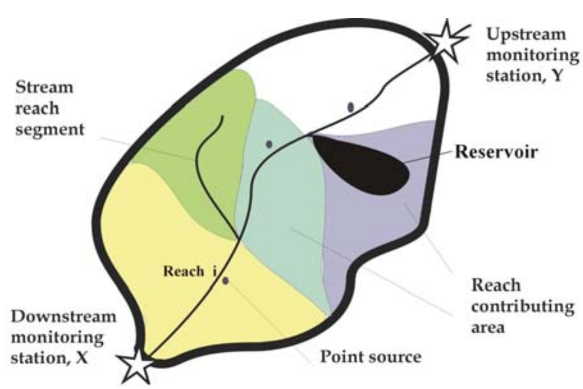
$$\underbrace{LOAD_i}_{\text{Stream Load}} = \left\{ \sum_{j \in J(i)} \left[\sum_{n=1}^{N} \underbrace{S_{n,j} \beta_n}_{\text{Sources}} \underbrace{\exp(-\alpha' Z_j)}_{\text{Land-to-water transport}} \right] \underbrace{\prod_m \exp(-\delta_m^s T_{i,j,m}) \prod_l 1/(1+\lambda^r q_{i,j,l}^{-1})}_{\text{Aquatic transport}} \right\} \underbrace{\exp(\varepsilon_i)}_{\text{Error}}$$

- The optimal set of rate coefficients are estimated, balancing the nutrient mass of the source inputs, stream loads, and storage/loss on land and in water.
- All calibrated parameters are simultaneously determined to best fit the data.

SPARROW model components

aggregated reach-by-reach

Load leaving the reach	=	Load generated within upstream reaches and transported along the reach via the stream network	+	Load originating within the reach's incremental watershed and delivered to the end of reach segment



SPARROW predictions
example from the Mississippi River Basin

Environ. Sci. Technol. 2008, 42, 822–830

Differences in Phosphorus and Nitrogen Delivery to The Gulf of Mexico from the Mississippi River Basin

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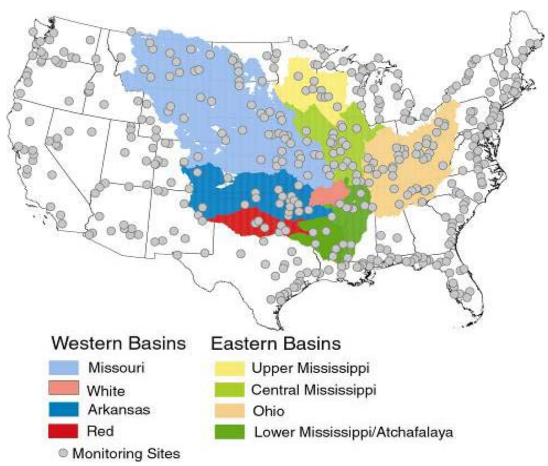
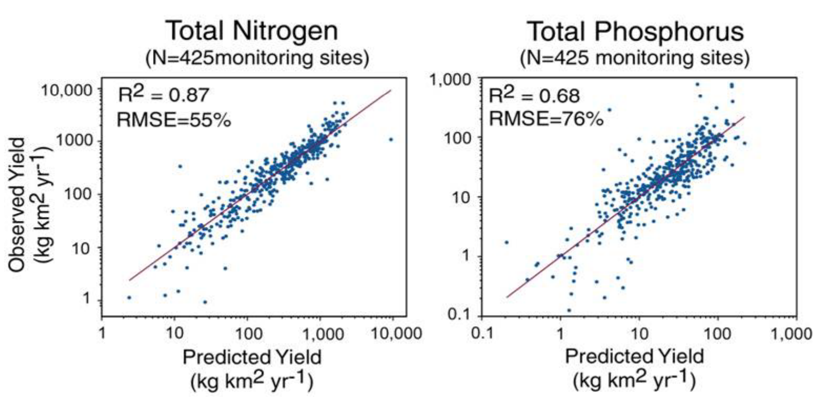
Received June 30, 2007. Revised manuscript received October 24, 2007. Accepted October 29, 2007.



Alexander et al. 2008

SPARROW nutrient model calibration
observed versus predicted riverine yields of N & P



18 model coefficients:
- 10 sources
- 6 landscape transport
- continuous stream and reservoir decay

15 model coefficients:
- 8 sources
- 5 landscape transport
- continuous stream and reservoir decay

Alexander et al. 2008

Statistically significant source & transport features

NUTRIENT SOURCES

- Urban and population-related sources
- Atmospheric N deposition
- Cultivated crops:
  - County farm fertilizer sales and expenditures; crop acreage
  - NLCD agricultural land use
  - State application rates (corn, soybeans, cotton, wheat, other crops)
  - Corn/soybean rotations
  - N_2 fixation – cultivated lands
  - Recoverable manure applied
- Non-recoverable animal manure on pasture/rangelands (unconfined wastes excreted; confined losses)
- Natural background and residual sources (lands in forest, barren, shrub)

LAND-TO-WATER DELIVERY

- Climate (precipitation, temperature)
- Soils (permeability)
- Topography/subsurface (slope, specific catchment area)
- Artificial drainage (tiles, ditches)

AQUATIC ATTENUATION

- Streams

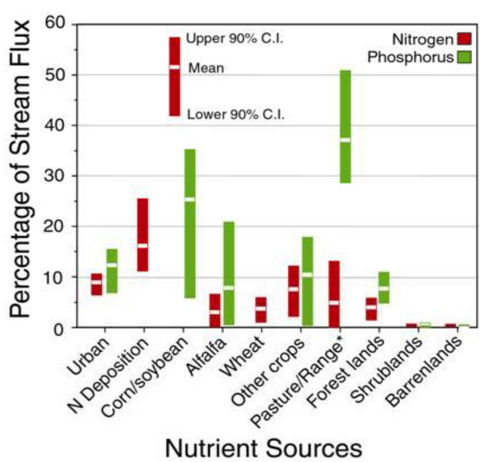
  First-order decay ~ f(water travel time, flow and depth)
- Reservoirs

  First-order decay ~ f(areal hydraulic load—ratio of outflow to surface area)

Alexander et al. 2008

Sources of nutrients delivered to Gulf of Mexico

Statistically-significant source shares explaining the variation of loads among reaches. N & P delivery are affected by different sources and land uses.

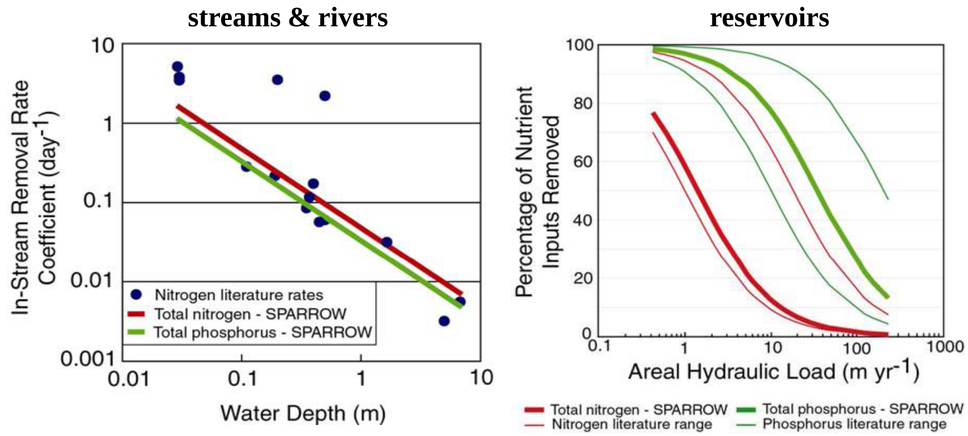


Alexander et al. 2008

*Non-recoverable animal manure

Aquatic nutrient removal

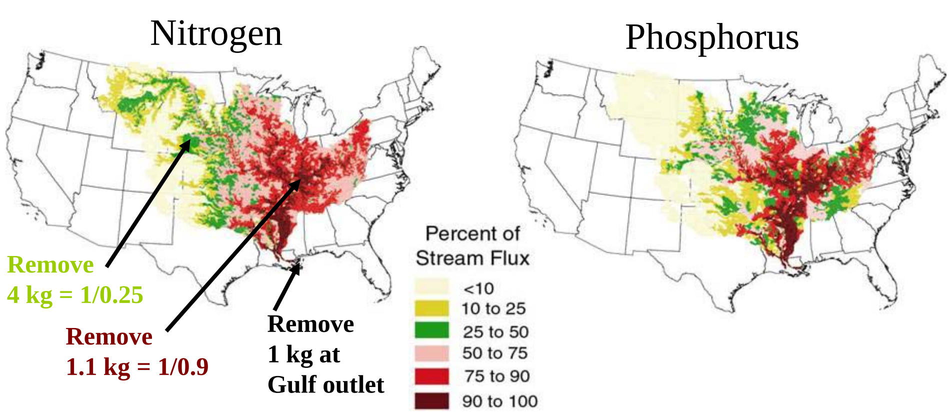
<u>modeled</u> estimates of aquatic N & P loss rates are consistent with <u>measurements</u> reported in the literature



Alexander et al. 2008

Nutrients to the Gulf of Mexico

<u>In-stream nutrient removal</u>: % of nutrient loads in stream reaches that are delivered downstream to Gulf of Mexico

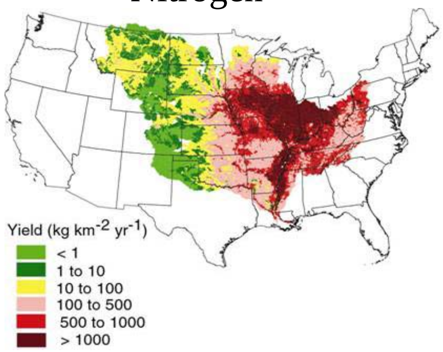


Alexander et al. 2008

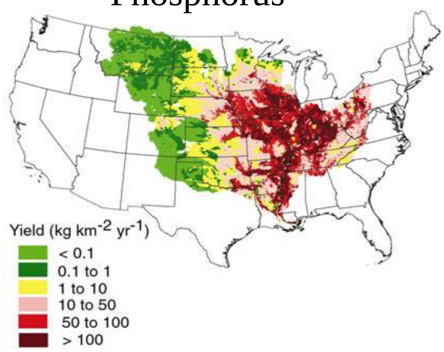
Nutrients to the Gulf of Mexico

Delivered nutrient masses: nutrient load from the reach network delivered downstream to Gulf of Mexico

Nitrogen



Phosphorus



Alexander et al. 2008

Nutrients to the Gulf of Mexico

- Agricultural sources in the watershed contribute more than 70% of the N & P delivered to the Gulf of Mexico
- Important differences in land uses that contribute N & P
- Disproportionate loads from individual geographic areas (9-of-31 states contribute more than 75% of the N & P, but comprise only 1/3 of the drainage area)
- Important hydrological controls on nutrient delivery (non-conservative transport of N & P in streams & reservoirs)

Alexander et al. 2008

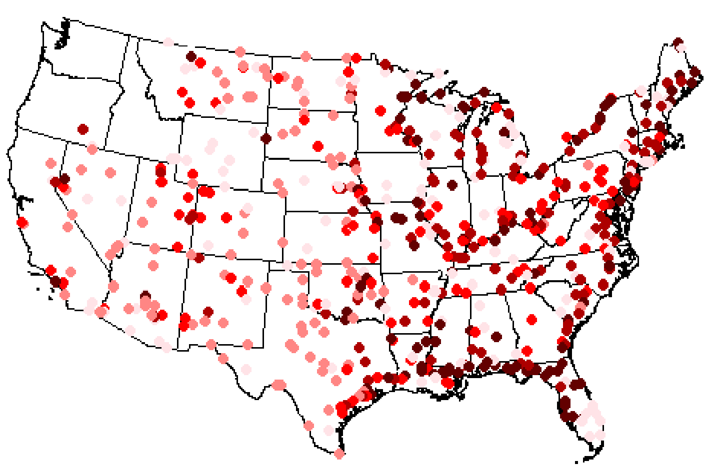
SPARROW development
example for national carbon models

- What changes are occurring, and why? Trends in C concentrations (& fluxes) in rivers suggest changes in terrestrial C reserves.
- How much C is stored in aquatic systems anyway, and how much is transported to coastal waters?
- How will changes in basic terrestrial ecosystem processes affect riverine C transport?

Boyer et al., in prep.

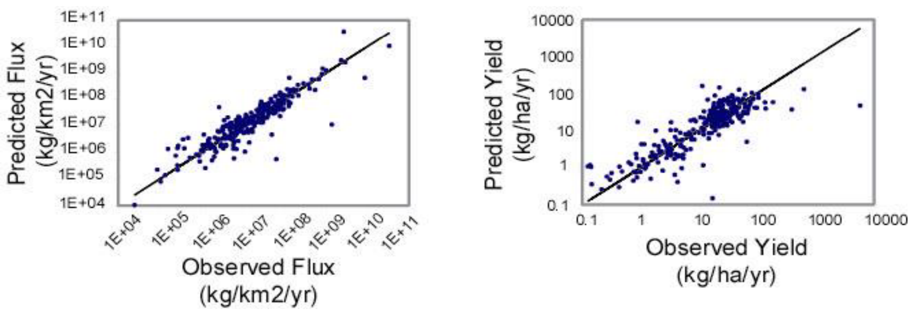
SPARROW development
example for national carbon models

269 stations used for initial calibration of OC models



Boyer et al., in prep.

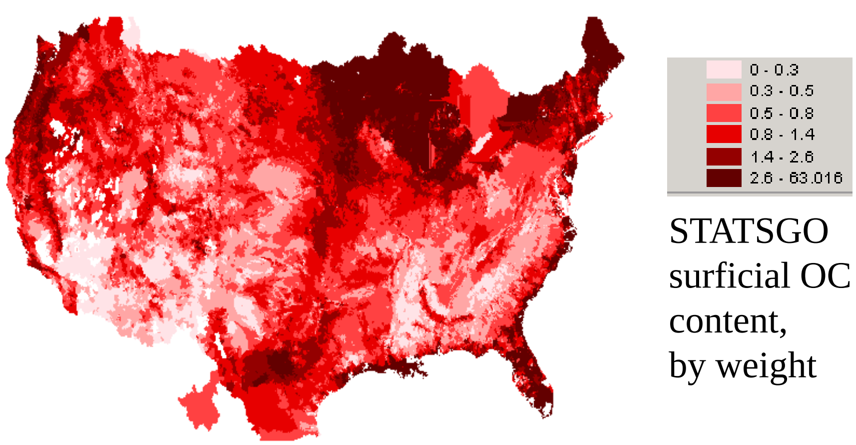
Initial DOC model calibration



R^2=81%; RMSE=88%; n=269

Boyer et al., in prep.

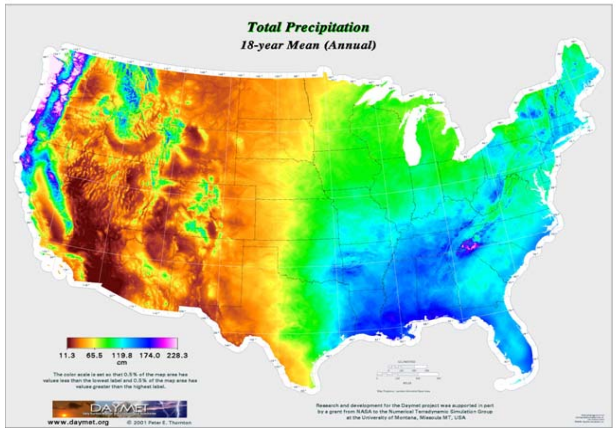
Soil characteristics are statistically-important <u>source</u> terms



STATSGO surficial OC content, % by weight

Boyer et al., in prep.

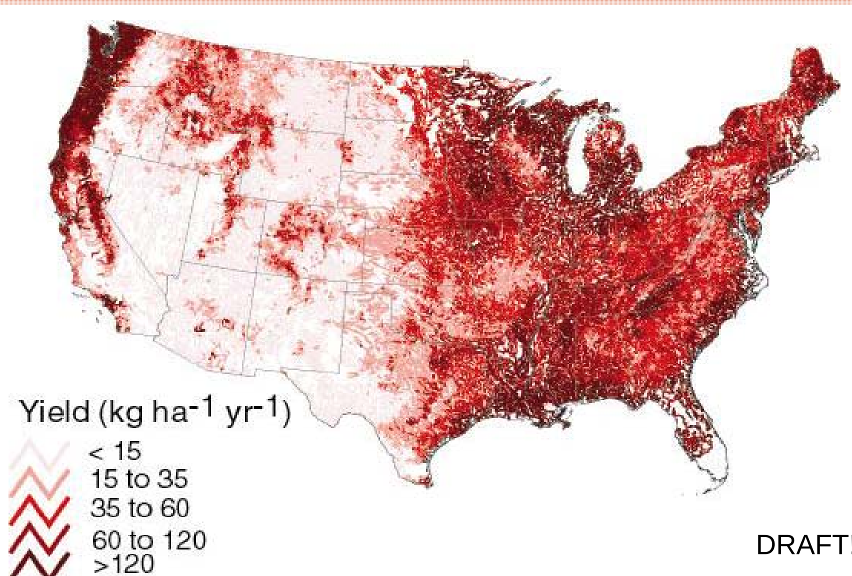
Hydrological metrics are statistically-important land-to-water-delivery terms



Precipitation & drainage density both are significant with higher exports from wetter areas.

Boyer et al., in prep.

Initial predictions of DOC yields

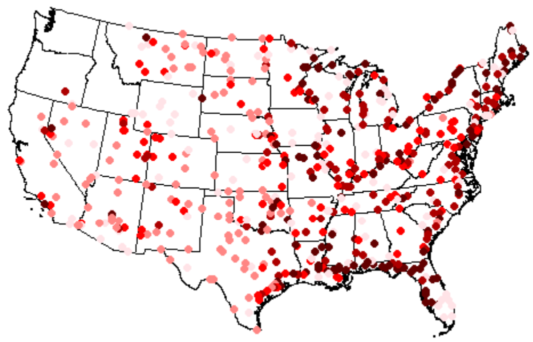


DRAFT!

Boyer et al., in prep.

Current efforts to improve predictability

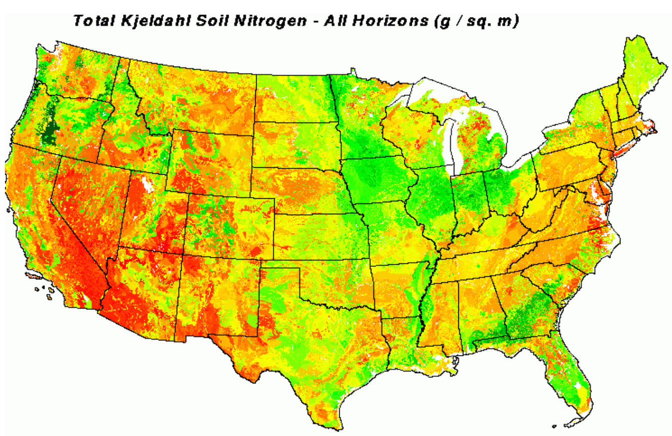
<u>Calibration data</u>: Increase number of stations included.



Boyer et al., in prep.

Current efforts to improve predictability

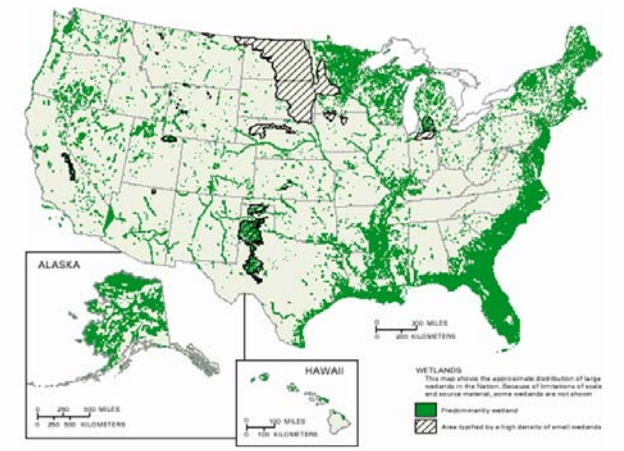
OC <u>sources</u>: net primary productivity, Soil C:N ratio, soil nitrogen, other soil elements



Boyer et al., in prep.

Current efforts to improve predictability

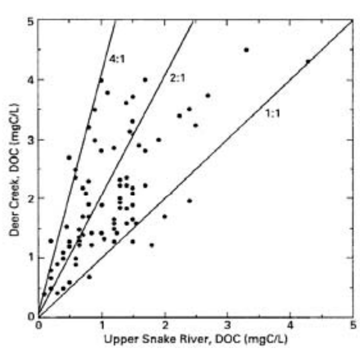
OC <u>sources</u> or <u>land-to-water-delivery</u>: wetlands



Winter et al. 1998

Current efforts to improve predictability

<u>Aquatic Transport</u>: Attenuation of sediments in reservoirs, geochemical reactions in streambed



Relationships to streambed geochemical environment control water column DOC concentrations

McKnight et al. 2002

All together, now

Contemporary estimates of C transported in rivers from Mississippi Basin to GOM

	Raymond et al. 2008	Bianchi et al. 2004		Trefry et al. 1994	
Tg DOC		3.1	79%	2.0	34%
Tg POC		0.8	21%	3.8	66%
Tg DOC+POC		**3.9**	19%	**5.8**	25%
Tg DIC	**17**		81%		75%
Tg C	21			23	

Note – these are draft estimates from a quick read of these papers, to put Mississippi fluxes into context.

All together, now

US Carbon Budget: Sinks of carbon for 1990 in the Contiguous USA, in Pg C yr^{-1} (from Pacala et al. 2001)

Category	Low	High	Land area 1980–90 (10^6 ha)	Houghton *et al.* (8)	Birdsey and Heath (12)
Forest trees	0.11	0.15	247–247	0.06*	0.11
Other forest organic matter	0.03	0.15	247–247	−0.01	0.18
Cropland soils	0.00	0.04	185–183	0.14	–
Nonforest, noncropland (woody encroachment)	0.12†	0.13†	334–336‡	0.12	–
Wood products	0.03	0.07	–	0.03	0.03
Reservoirs, alluvium, colluvium	0.01	0.04	–	–	–
Exports minus imports of	0.04	0.09	–	–	–
Fixed in United States but exported by rivers	0.03	0.04	–	–	–
Apparent§ U.S. sink without	0.25	0.58	766	0.15–0.23‖	0.31

	Mpi	CoUSA
DOC+POC Tg	4-6	<10
DIC Tg	17-20	30-40

At the end of the day

- Transfers of C via land-to-water are orders of magnitude lower than transfers from land-to-atmosphere.
- Small shifts in the C balance of the terrestrial landscape will result in disproportionately-large changes in aquatic C export.
- Important implications for water quality & ecosystems.

Boyer et al., in prep.

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SPARROW MODEL
Home page: *http://water.usgs.gov/nawqa/sparrow*
Documentation (theory, application, user manual): *http://pubs.usgs.gov/tm/2006/tm6b3/*
Software: *http://water.usgs.gov/nawqa/sparrow/sparrow-mod.html*