Fluxes of carbon from the land to the ocean

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Outline

- Overview of SPARROW water quality modeling approach.
- SPARROW model of total organic carbon in conterminous USA
- Estimates of TOC and DOC loadings to regional-scale coastal watersheds
- Future Directions

SPAtially Referenced Regression on Watershed 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
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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

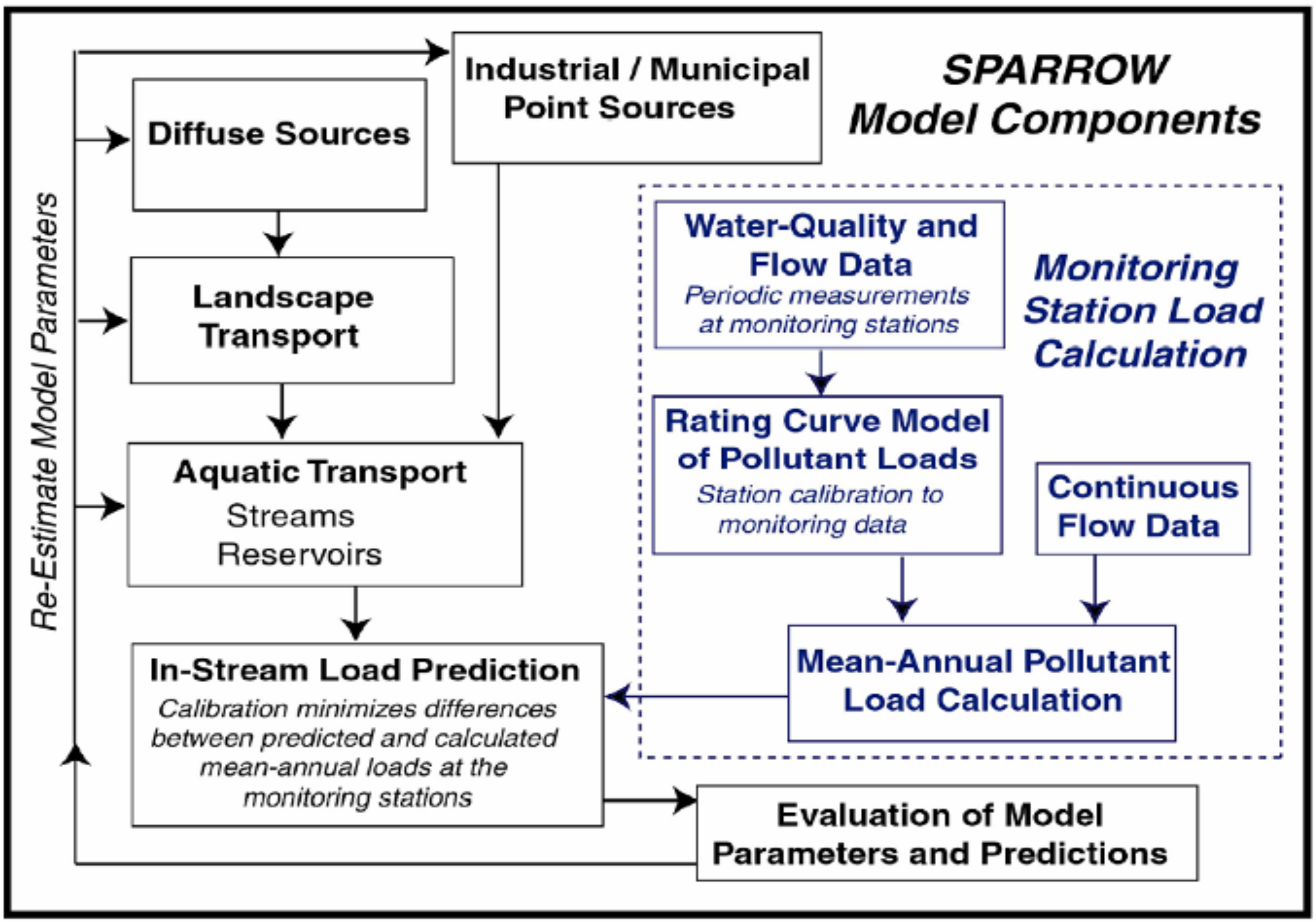
<u>SPA</u>tially <u>R</u>eferenced <u>R</u>egression <u>on</u> <u>W</u>atershed Attributes

SPARROW water quality model

Potential uses:

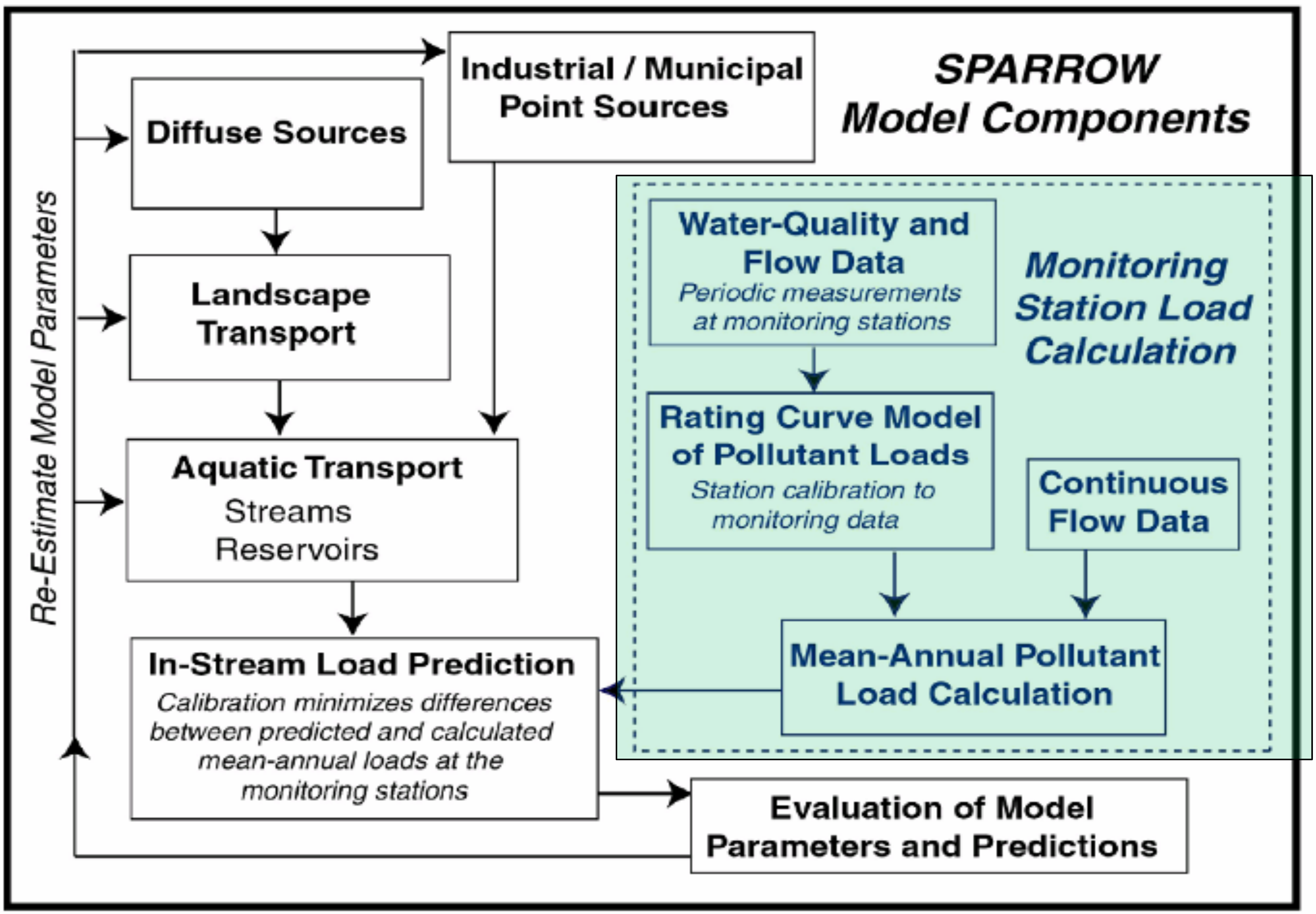
- Predicts mean annual loads, yields, and concentrations
(and uncertainties) in unmonitored stream reaches
- ..Apportions stream loads to major nutrient sources and upstream watersheds
- ..Assesses the effects of hydrological and biogeochemical processes on nutrient transport and fate in watersheds
- ..Simulates stream water-quality response to future changes in land use and climate
- ..Informs network monitoring and use of watershed management simulation models

SPARROW model components



Alexander et al. 2002

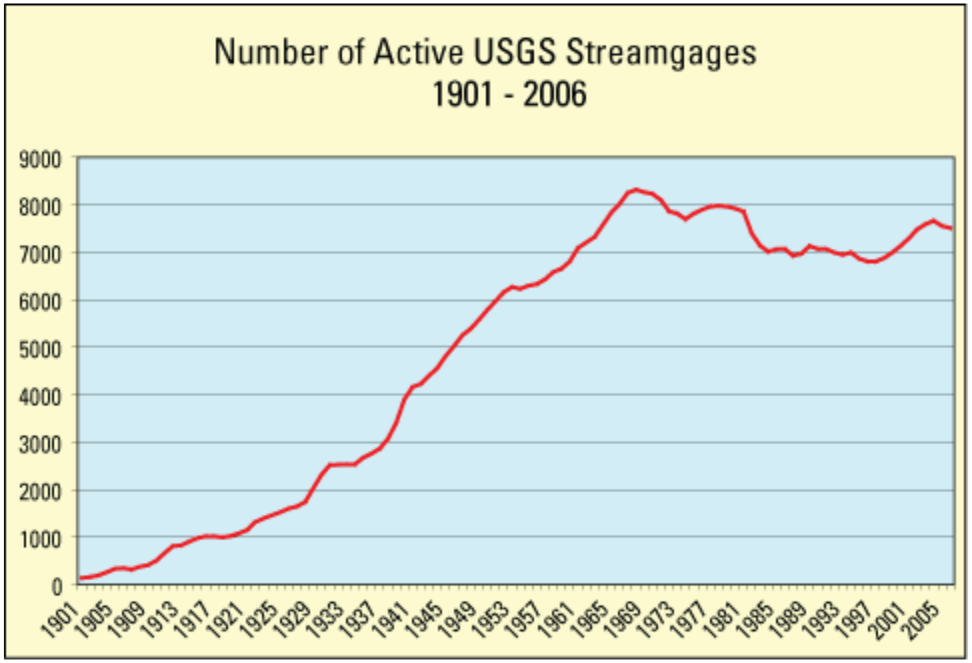
SPARROW model components



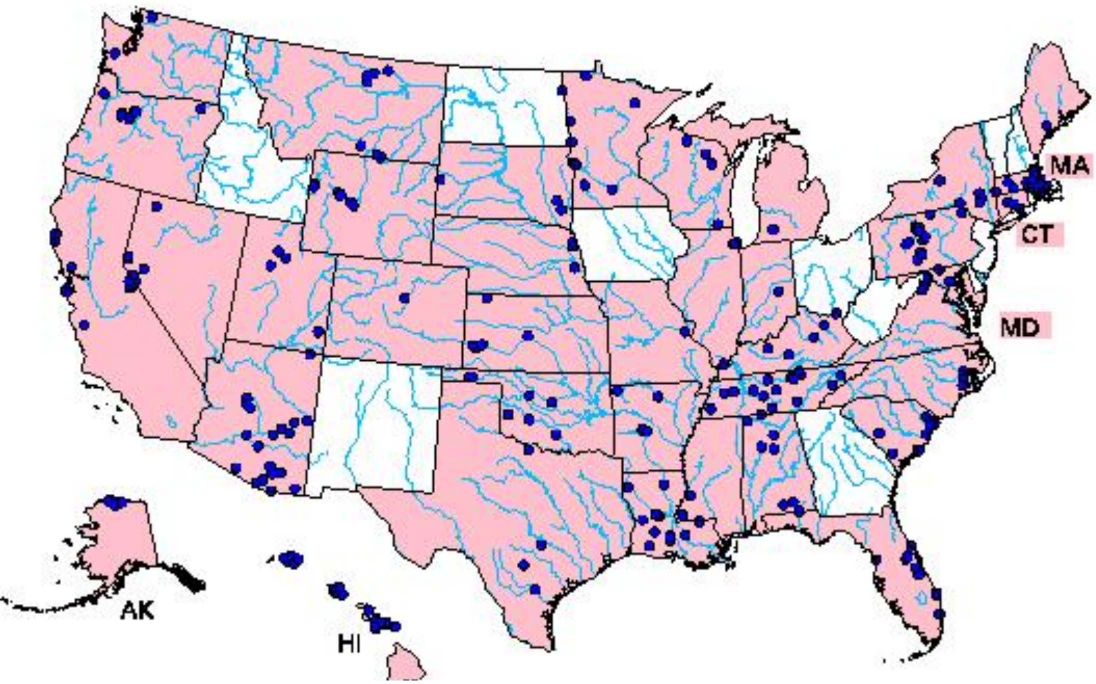
Alexander et al. 2002

Load = C * Q

Long term streamflow observations are essential



USGS stream gages 1900-2006
http://water.usgs.gov/nsip/history.html



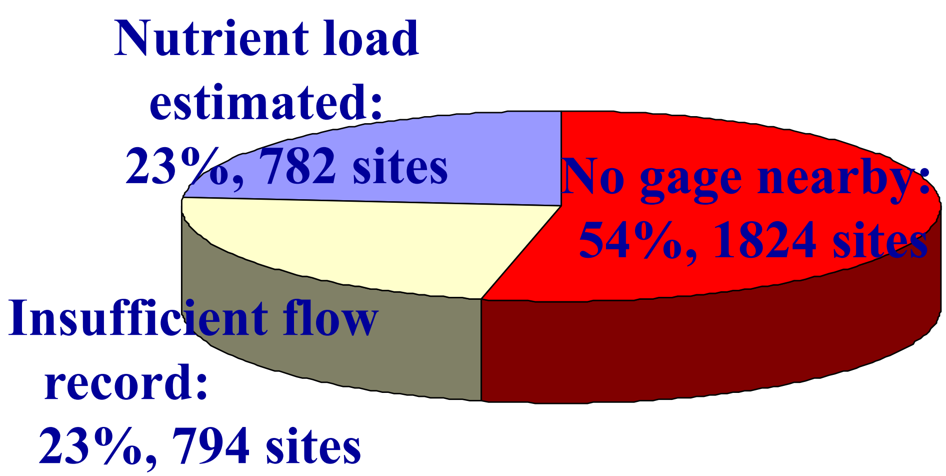
273 currently threatened stream gages , 12/11/2010
http://water.usgs.gov/osw/lost_streamgages.html

Lobby for Long-Term!

Long term flow & water quality observations are essential

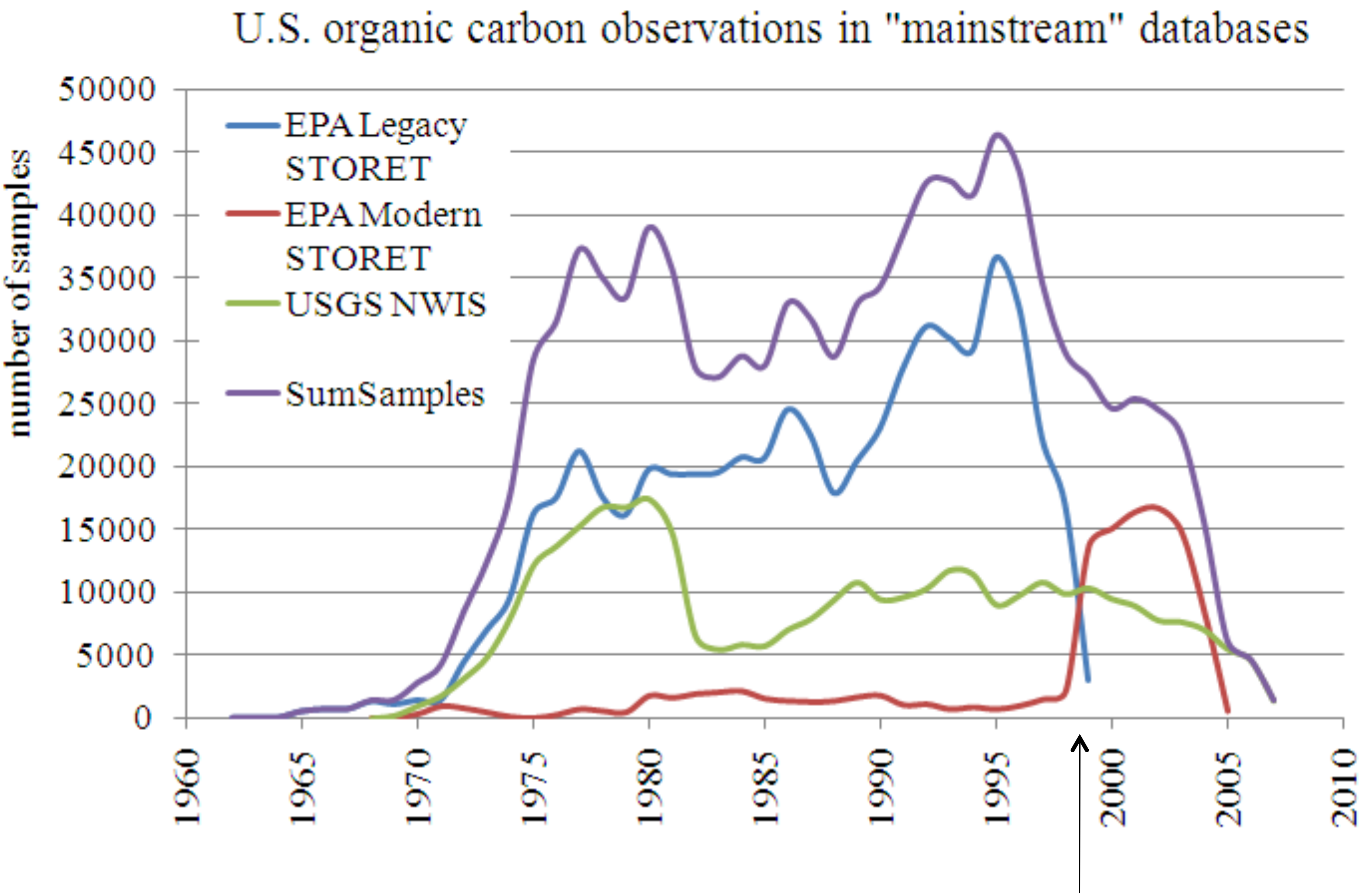
Example:

- Nutrient data retrieved from U.S. databases (EPA, USGS, state agencies) for 21,500 stream sites in SE USA for regional nutrient modeling.
- Of these 21,500, only 3400 sites (15%) with "sufficient" water-quality record (i.e., minimum quarterly sampling over 2 years)
- Of the 3400 "sufficient" sites:

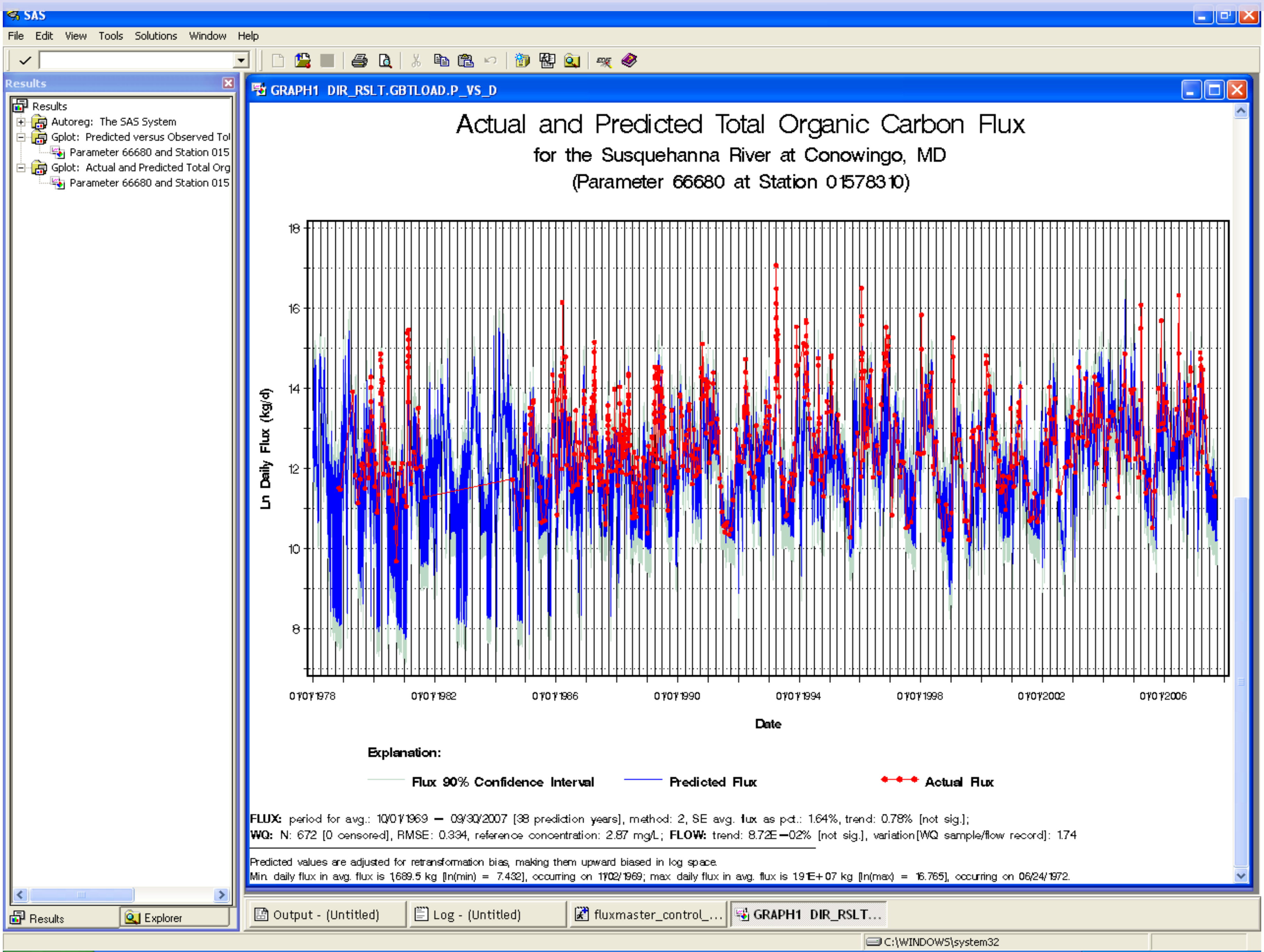


Source: Hoos et al. 2008

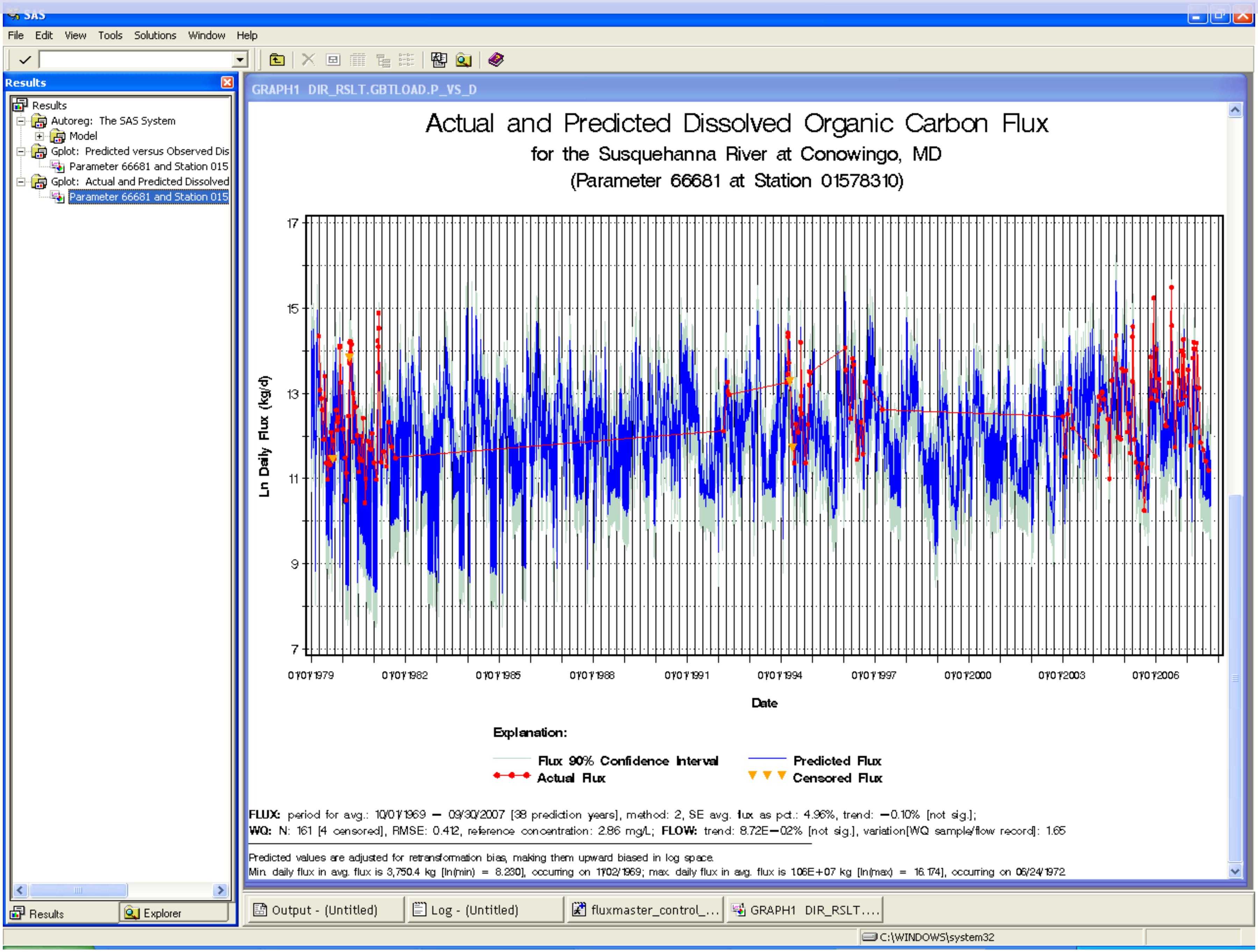
Long term flow & water quality observations are essential



Long term flow & water quality observations are essential

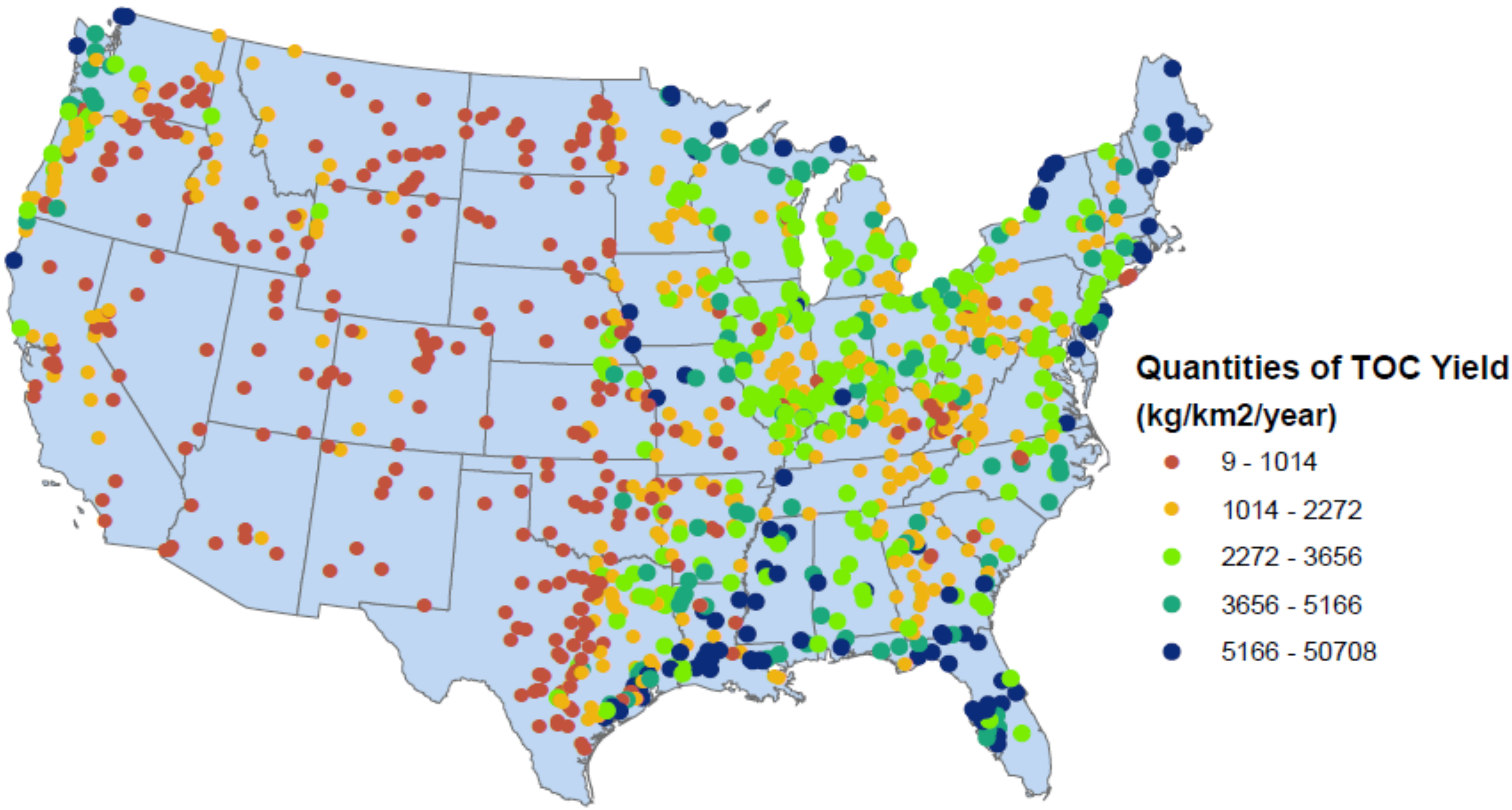


Long term flow & water quality observations are essential

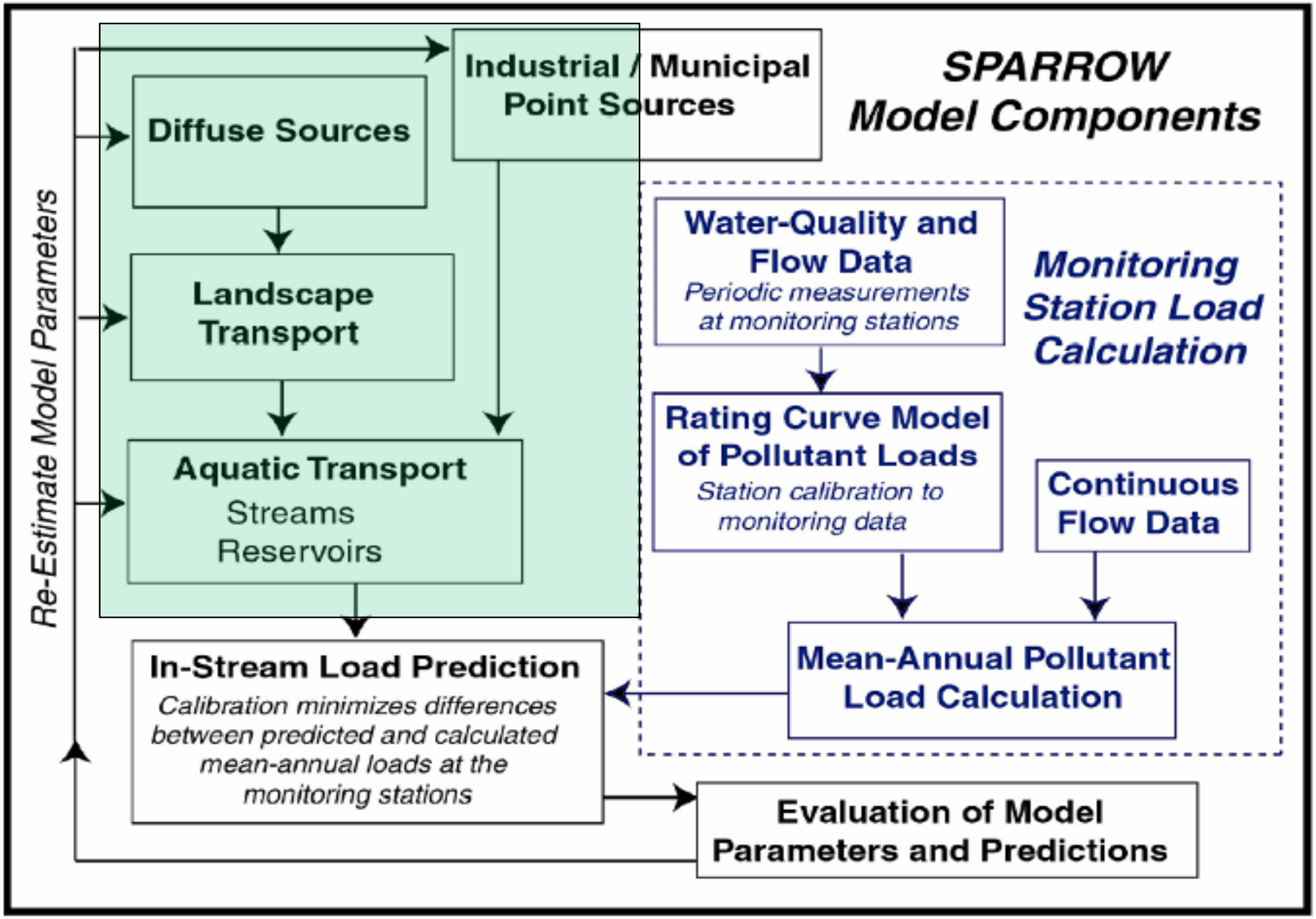


Long term water quality observations are essential

- Total organic carbon data retrieved from USGS – NWIS & EPA – STORET databases, for 1970-2008.
- 1125 sites (of about 5000 sites with TOC data) met criteria and were used:



SPARROW model components



Alexander et al. 2002

SPARROW model components – example sources

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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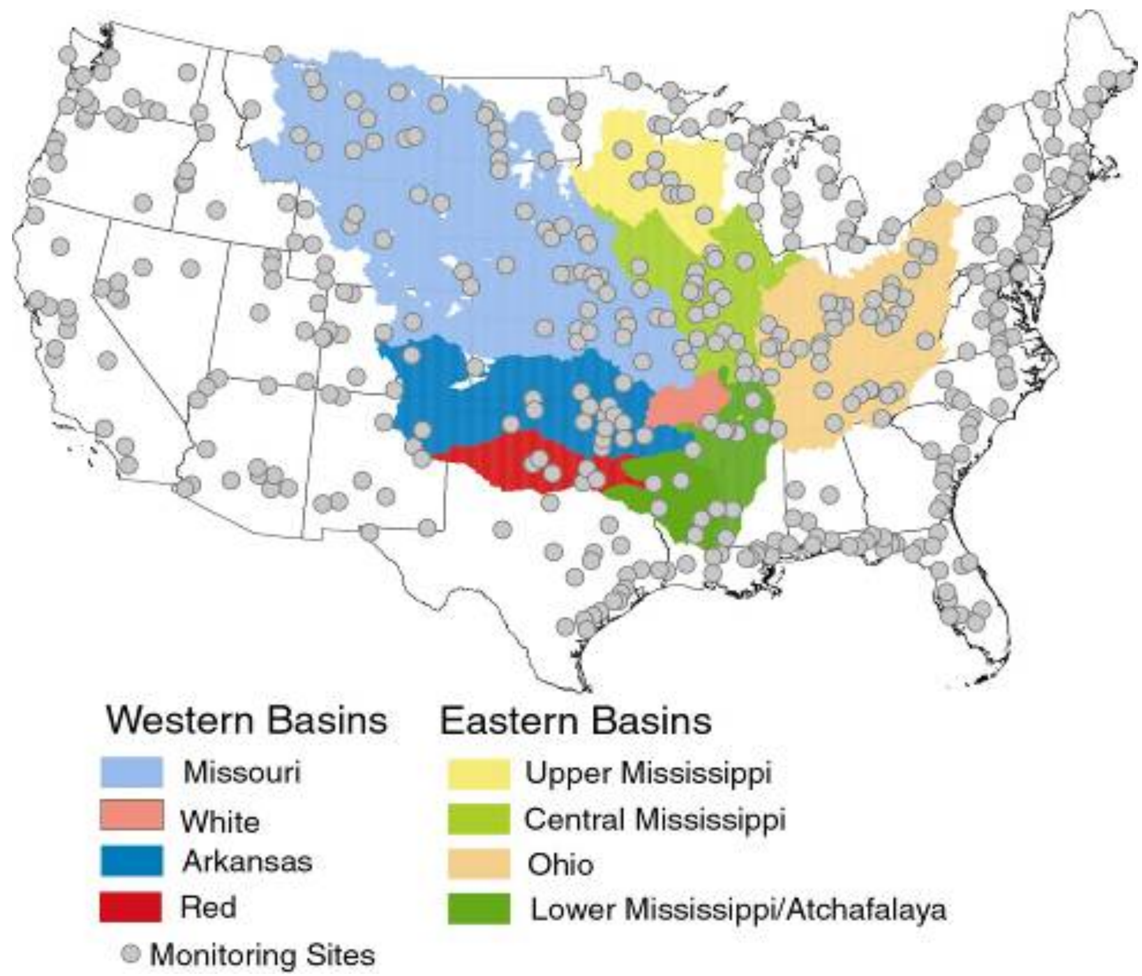
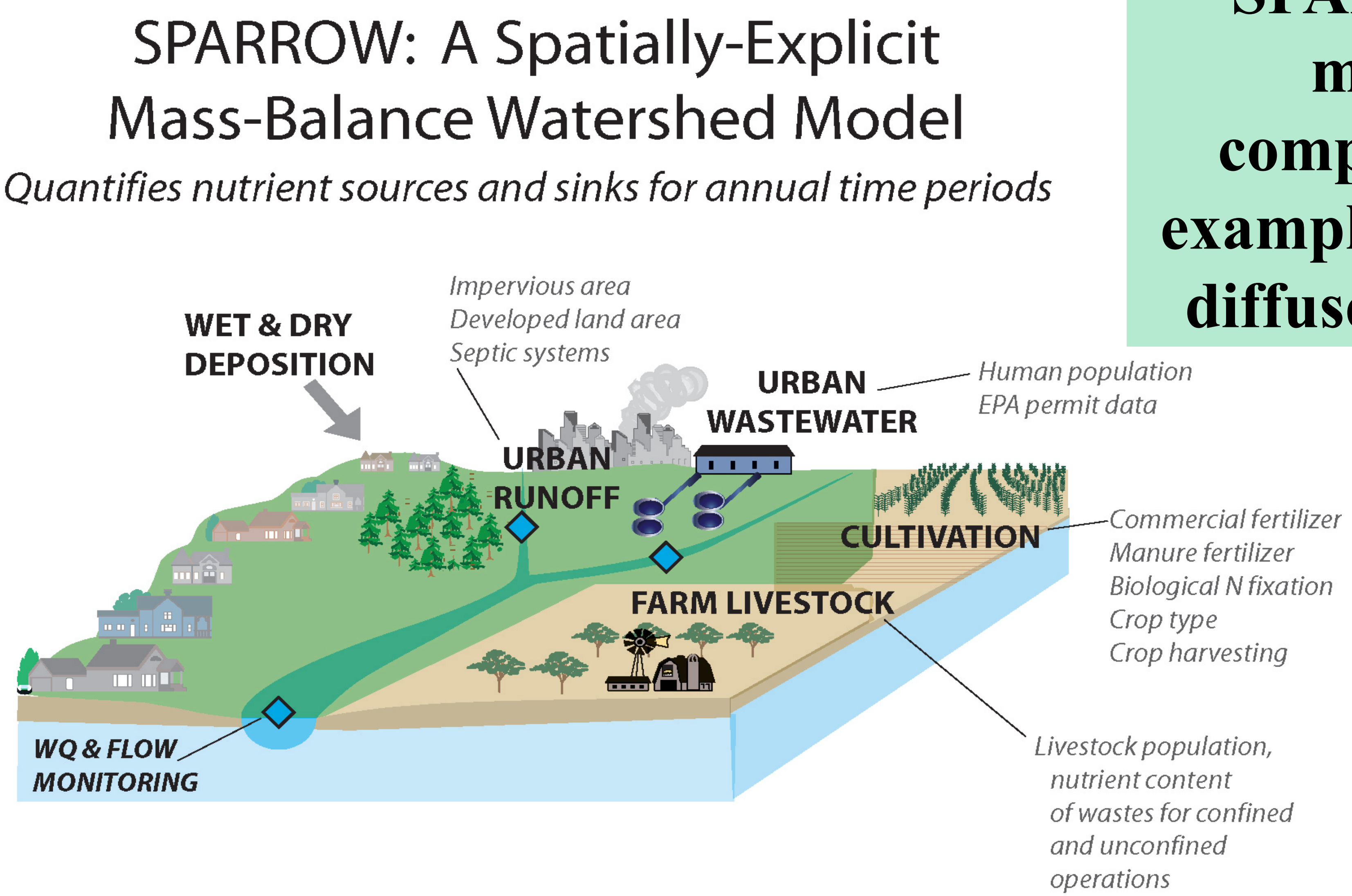


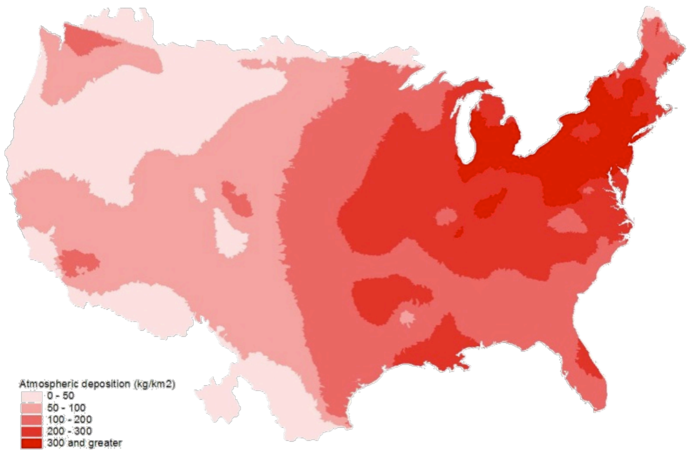
Alexander et al. 2008

SPARROW model components: example sources, diffuse & point

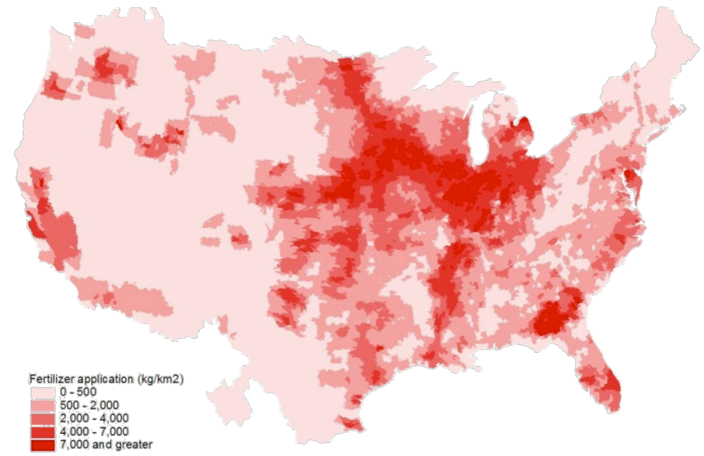


Example SPARROW significant point & diffuse sources (N model)

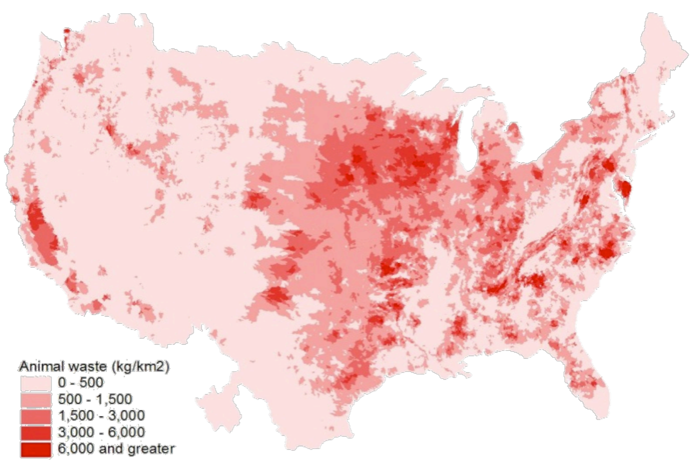
Atmospheric Deposition



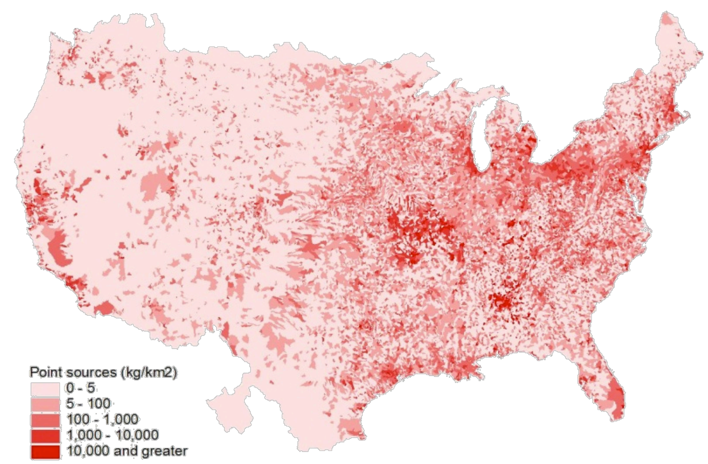
Fertilizer Application



Animal Waste



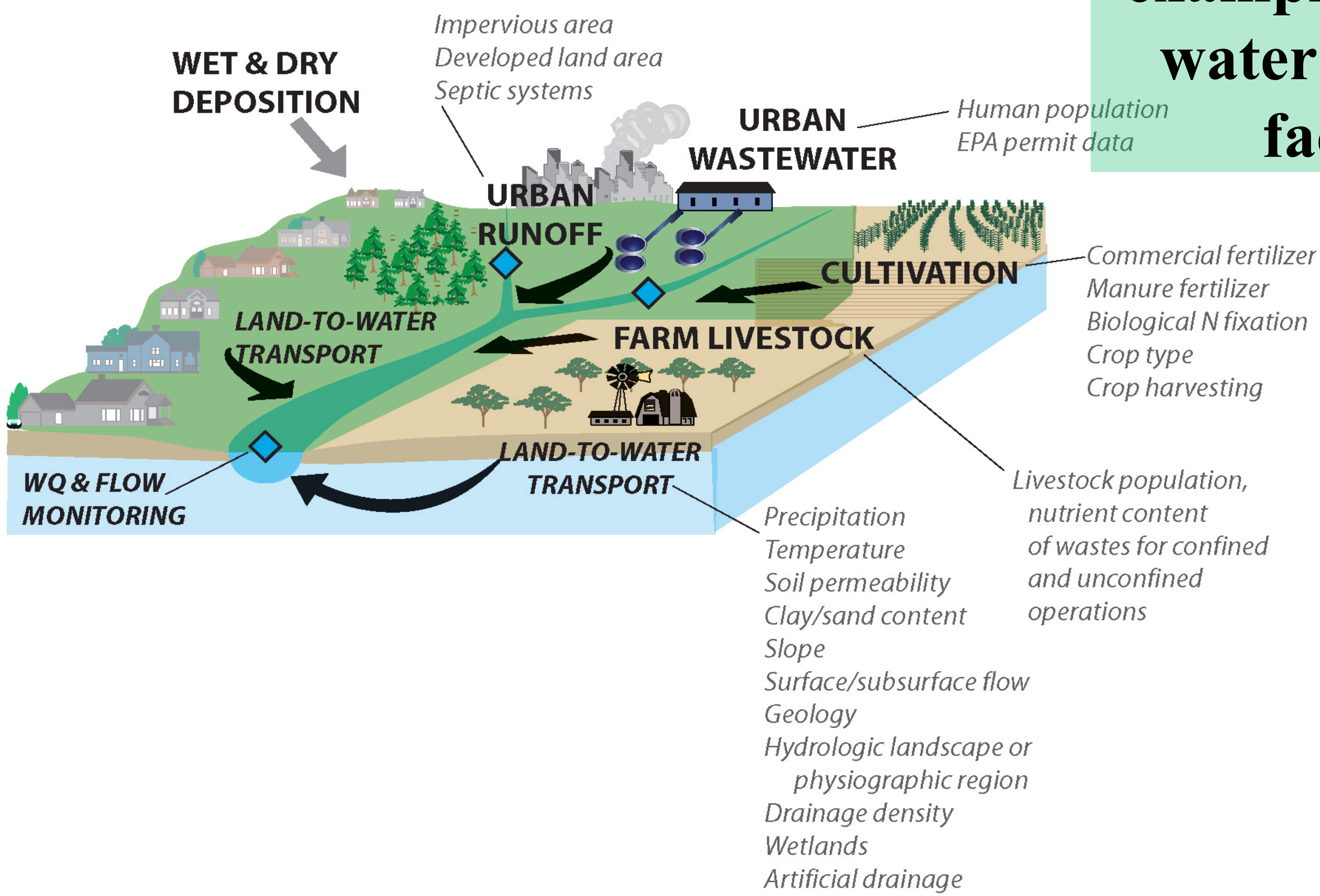
Point Sources



SPARROW model components: example land-to-water delivery factors

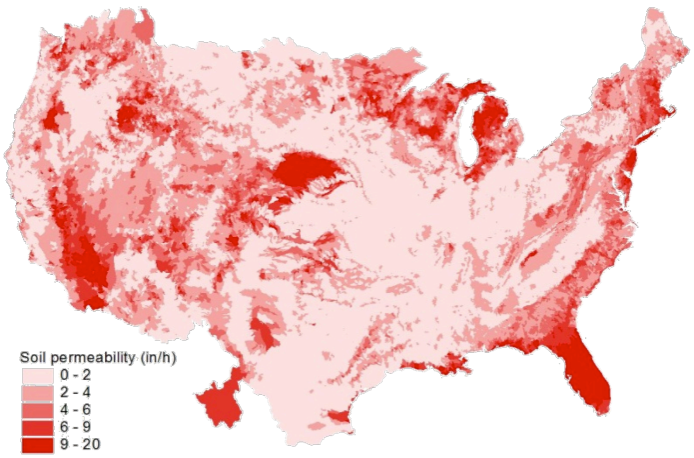
SPARROW: A Spatially-Explicit Mass-Balance Watershed Model

Quantifies nutrient sources and sinks for annual time periods



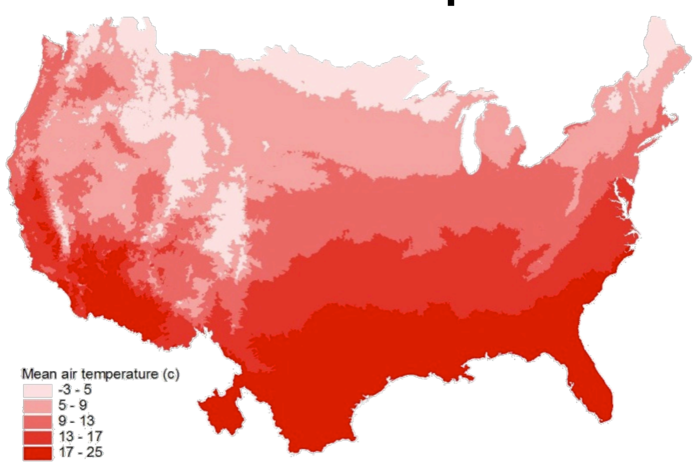
Example SPARROW significant land-to-water delivery variables (N model)

Soil Permeability

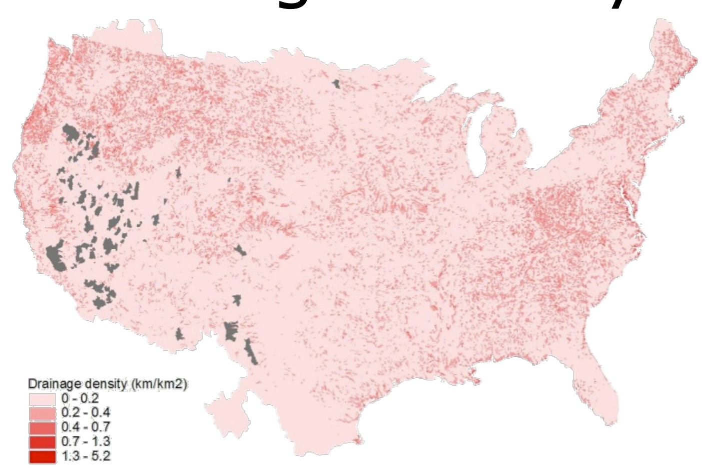


Artificial Drainage

Mean Air Temperature



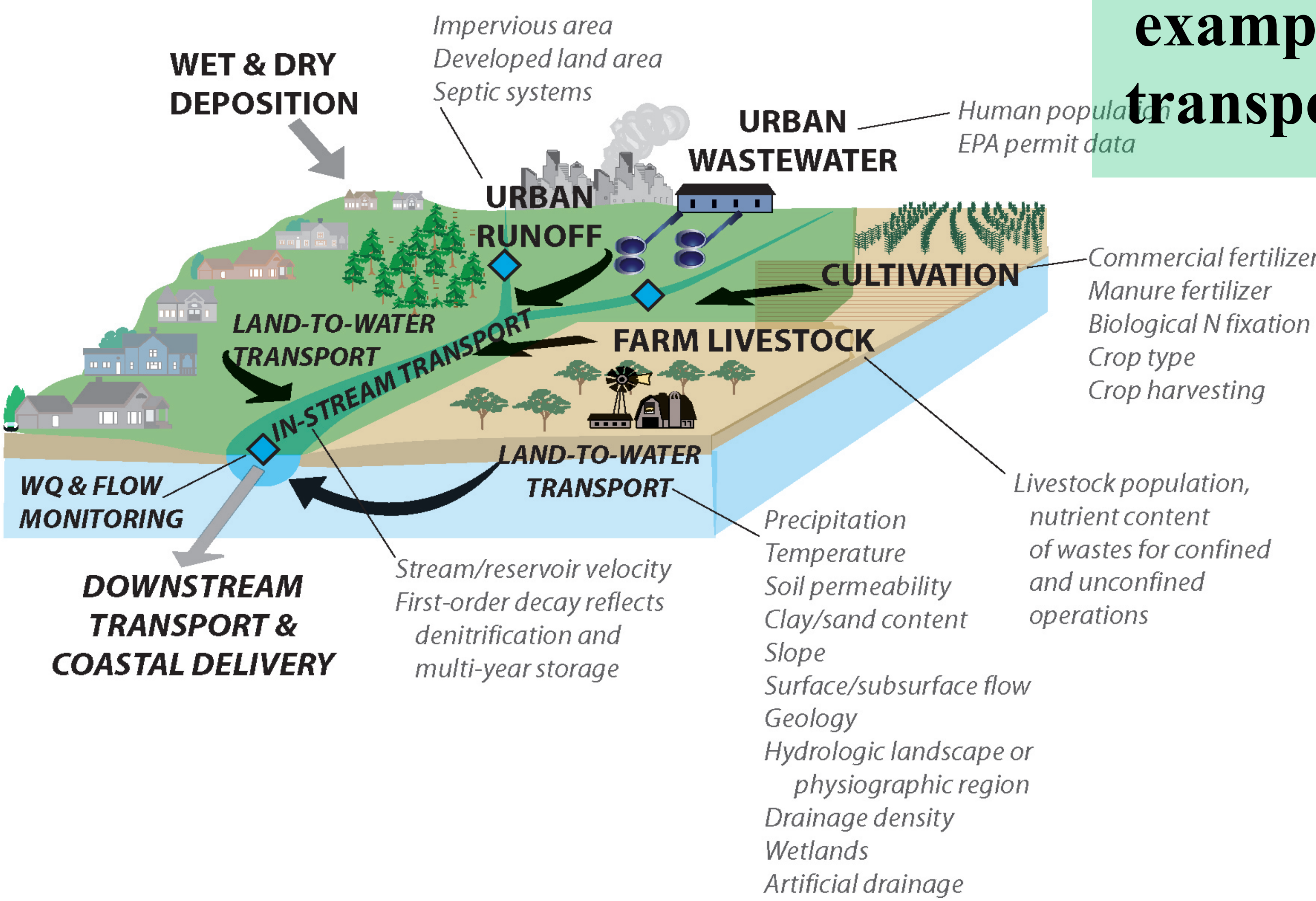
Drainage Density



SPARROW model components: example aquatic transport factors

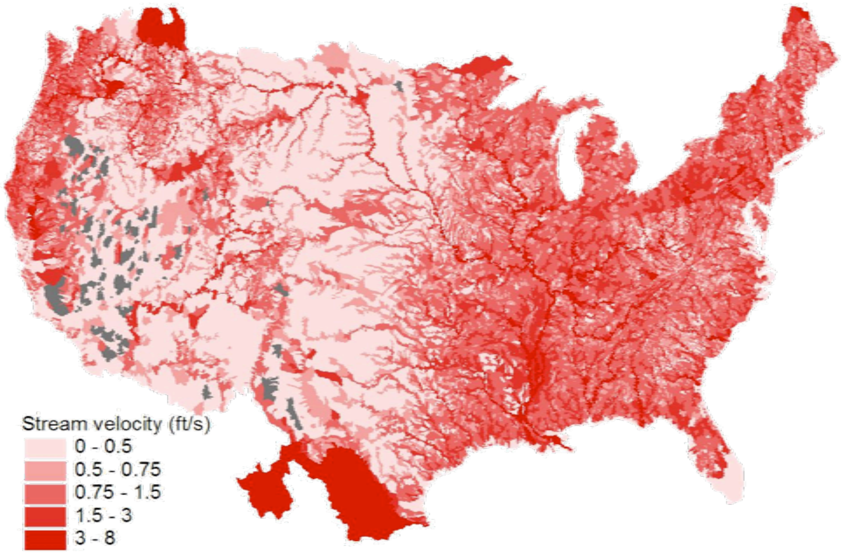
SPARROW: A Spatially-Explicit Mass-Balance Watershed Model

Quantifies nutrient sources and sinks for annual time periods

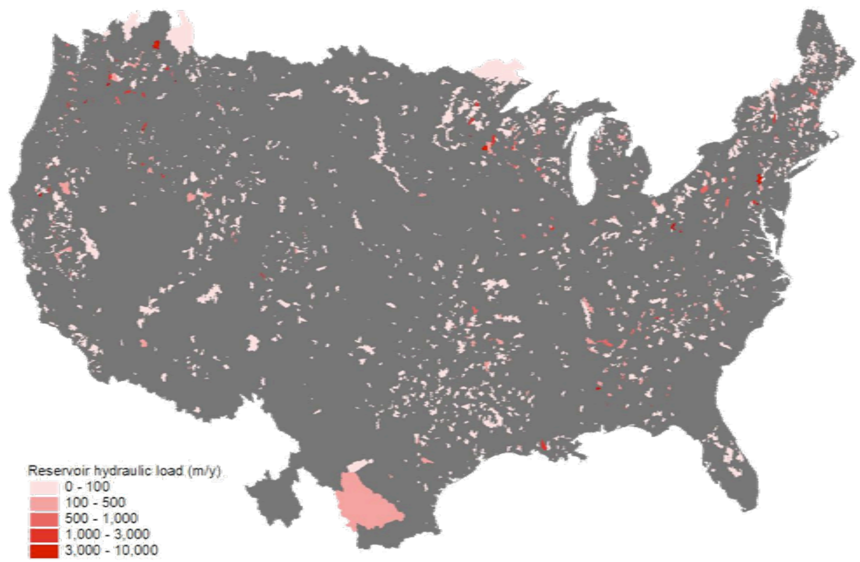


Example SPARROW significant aquatic transport factors (N model)

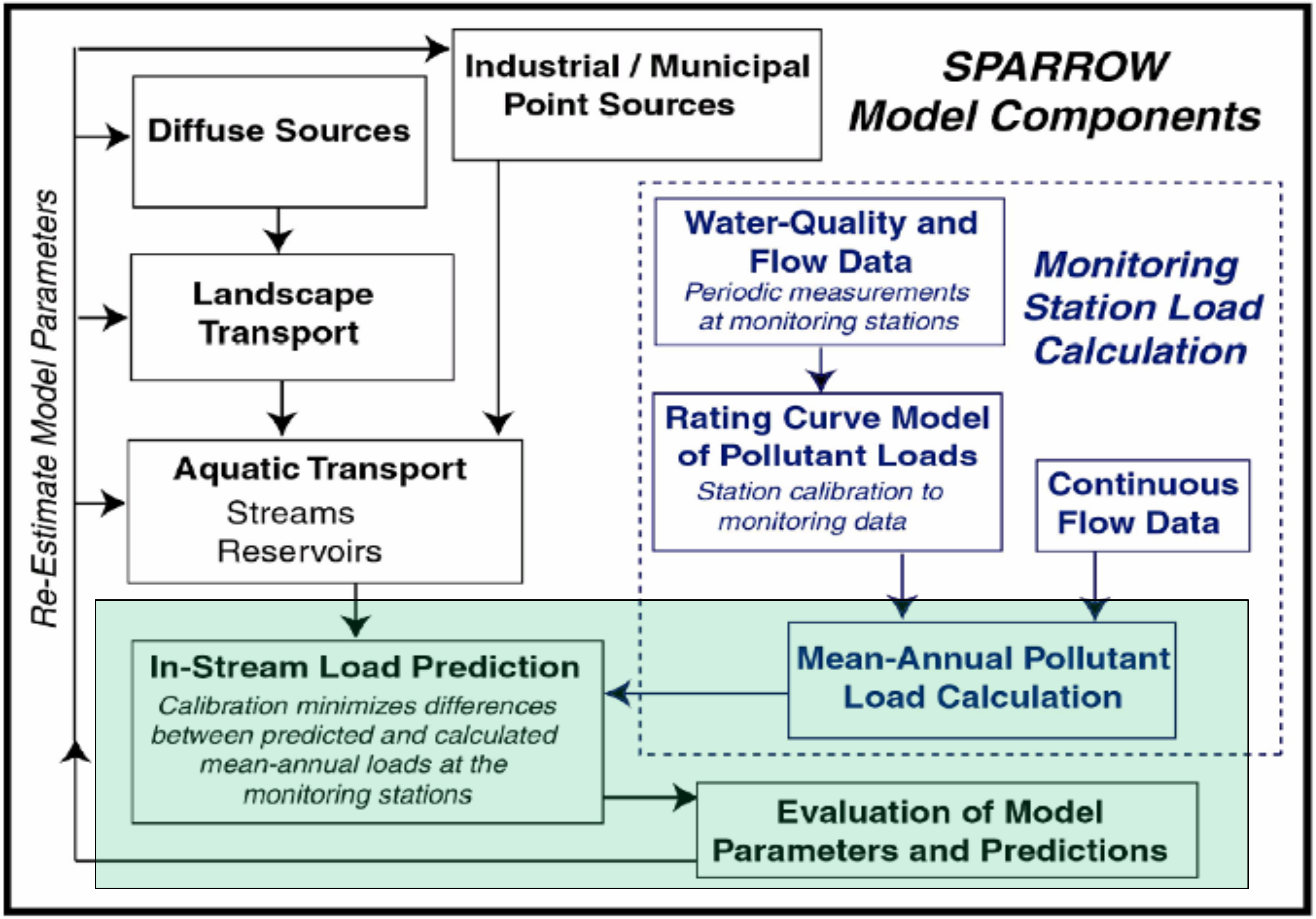
Stream Velocity



Reservoir Hydraulic Load



SPARROW model components



Alexander et al. 2002

SPARROW mathematical form

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

$$LOAD_i = \left\{ \sum_{j \in J(i)} \left[\sum_{n=1}^{N} S_{n,j} \beta_n \exp(-\alpha' Z_j) \right] \prod_m \exp(-\delta_m^s T_{i,j,m}) \prod_l 1/(1 + \lambda^r q_{i,j,l}^{-1}) \right\} \exp(\varepsilon_i)$$

Stream Load

Sources

Land-to-water transport

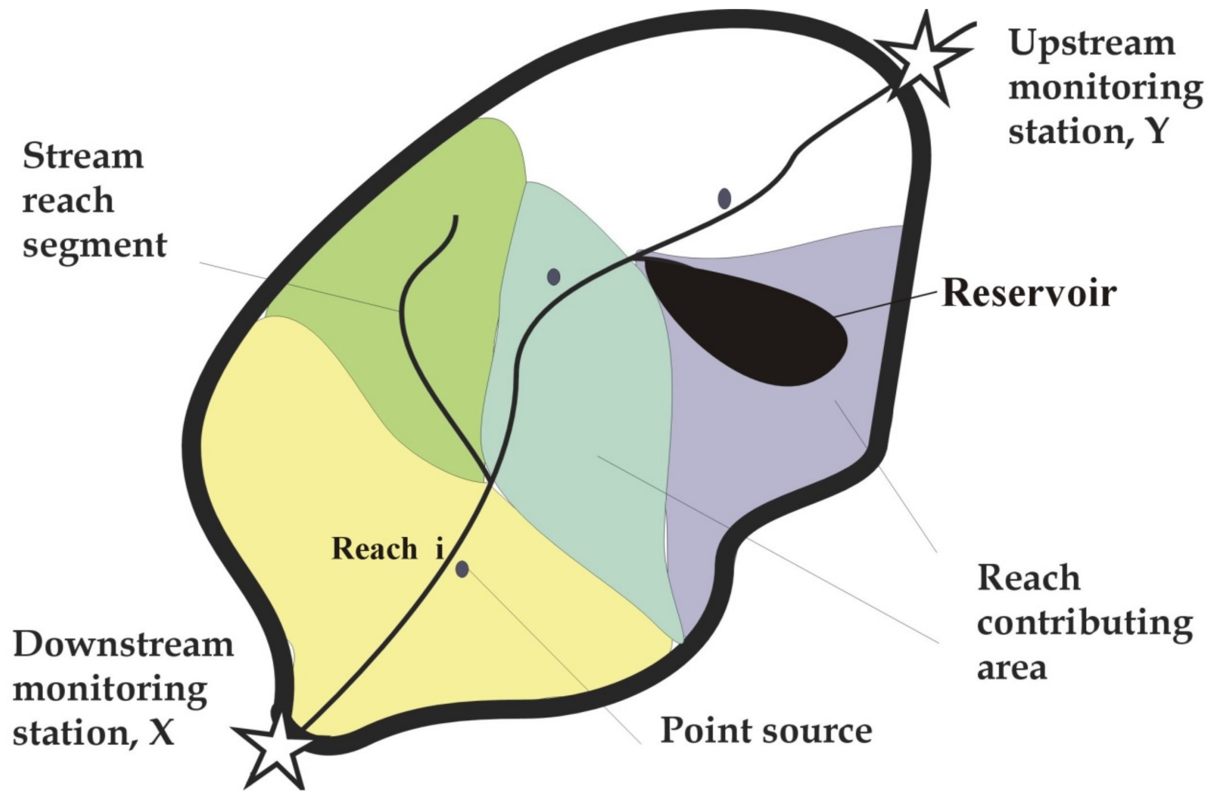
Aquatic transport

Error

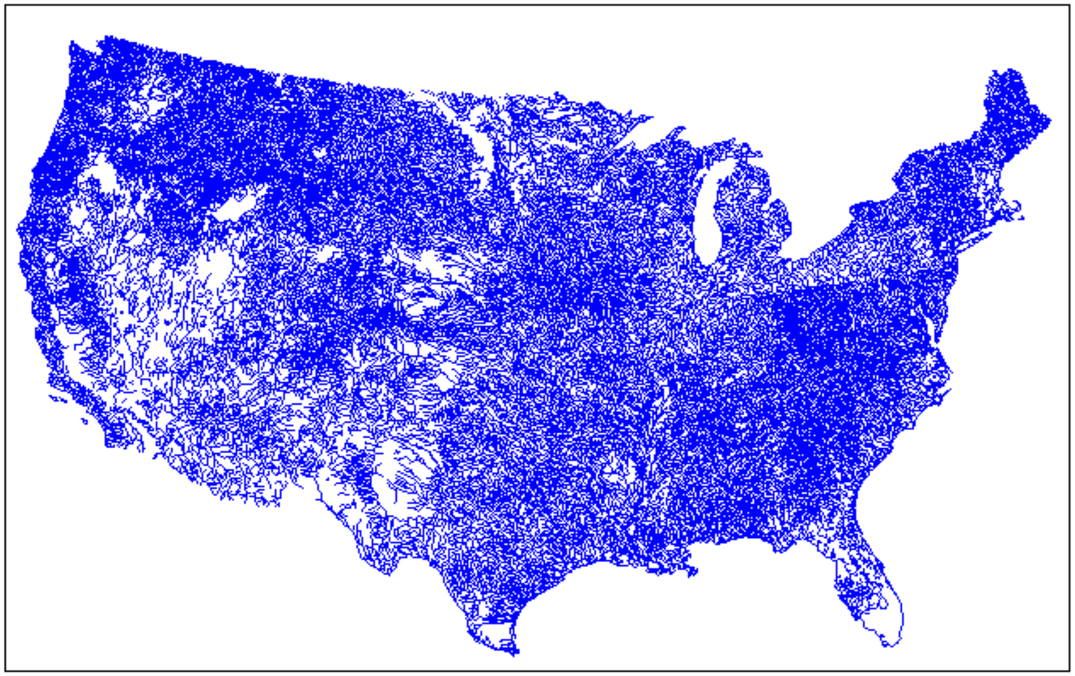
- mass balance form; nonlinear processes
- The optimal set of rate coefficients are estimated, balancing the nutrient mass of the source inputs, stream loads, and storage/loss on land and in water.
- All calibrated parameters are simultaneously determined to best fit the data.

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 model components



Diffuse & Point Sources

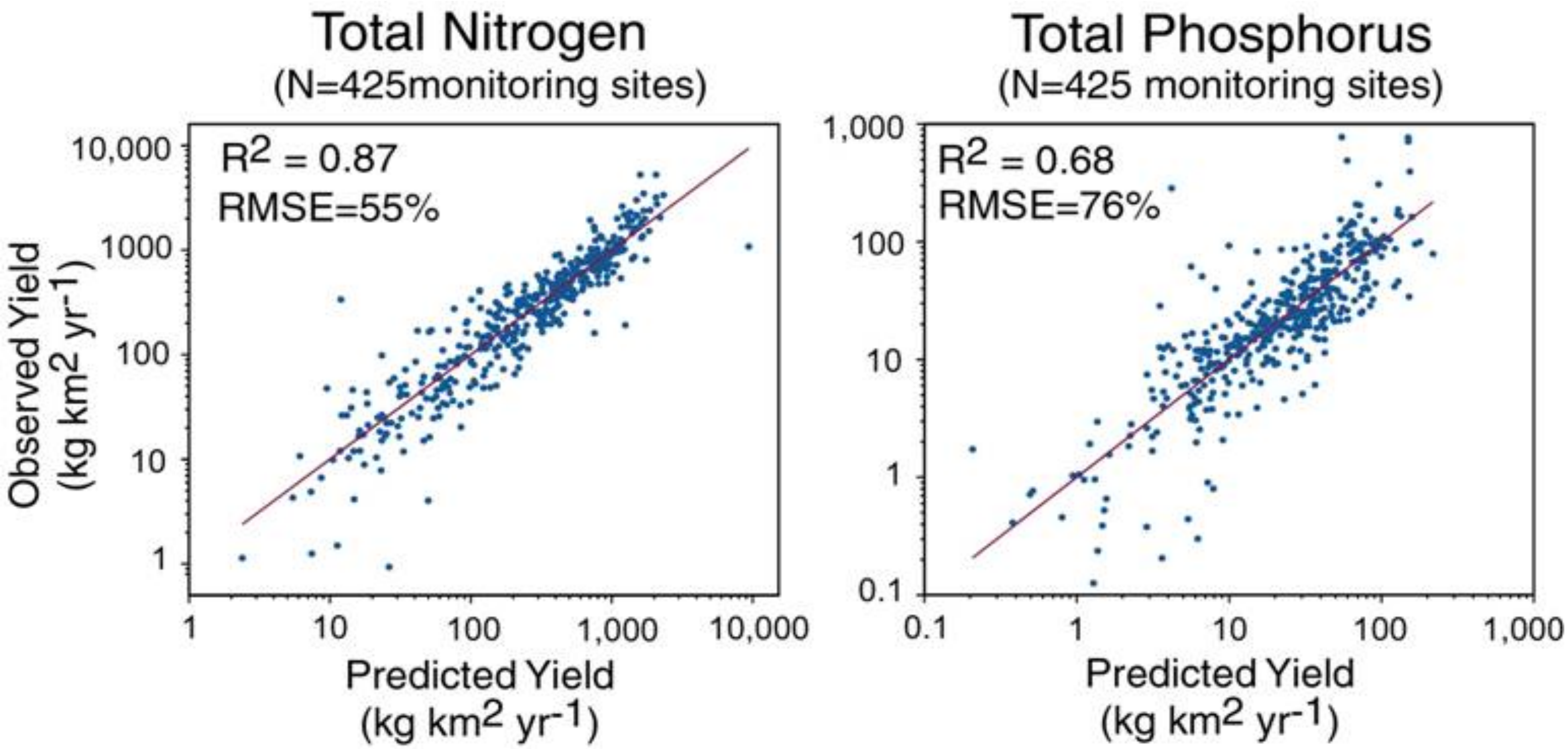
Terrestrial Landscape

Aquatic Landscape

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

Model Predictions
62,000 Stream Reaches

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

Development of SPARROW-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 delivered to coastal waters?
- How will changes in basic terrestrial ecosystem processes affect riverine C transport?

organic carbon delivered to upland streams

Dissolved organic matter (DOM) in streamwater is a fundamental water quality characteristic that:

- **Affects ecosystem status -- important in the energy budget, food chains, primary productivity, & redox status.**
- **Affects the acid-base status of many low-alkalinity freshwater streams.**
- **Affects fate & transport of other solutes (e.g. trace metals, nutrients)**

organic carbon delivered to coastal zone

More relevant to OCB group, developed initial, national-scale SPARROW model to explore how much organic carbon (total and dissolved) is transported in rivers and streams and ultimately delivered to the coastal margins of the conterminous US.

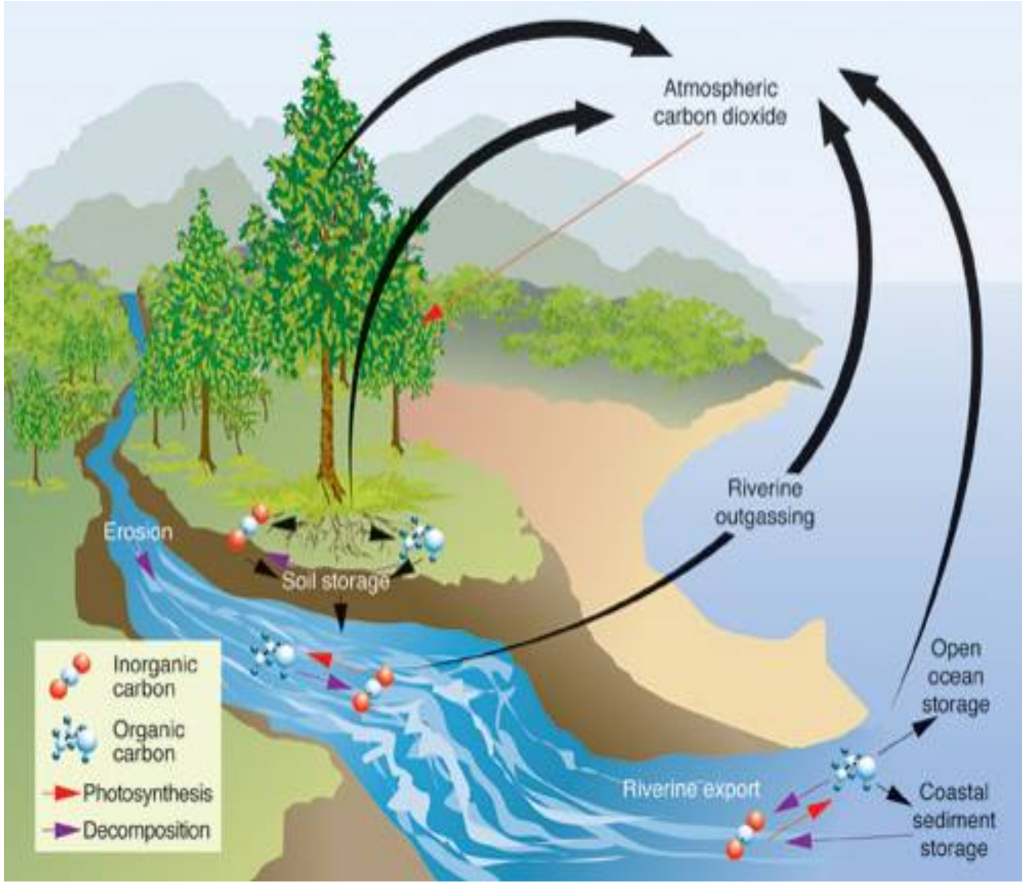


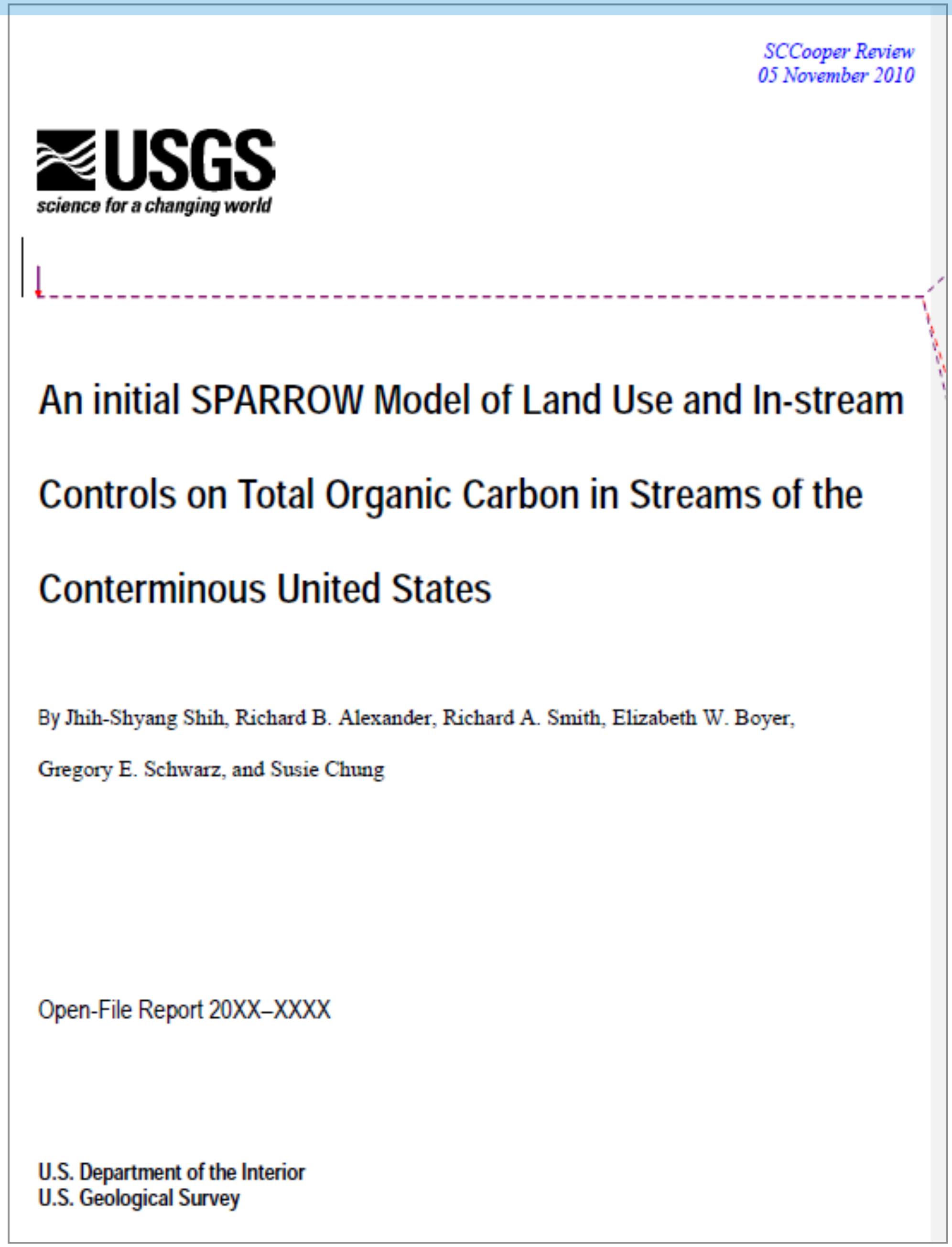
Figure by T. Brown, taken from https://www.llnl.gov/str/March06/Brown.html

organic carbon delivered to coastal zone

Results from our *initial* SPARROW carbon *model formulation* will be available in early 2011 in a USGS OFR.

Refinements of predictions of TOC, as well as DOC & DIC are underway.

Making estimates of C delivery to coastal reaches available to OCB synthesis groups.



SCCooper Review
05 November 2010

USGS
science for a changing world

An initial SPARROW Model of Land Use and In-stream Controls on Total Organic Carbon in Streams of the Conterminous United States

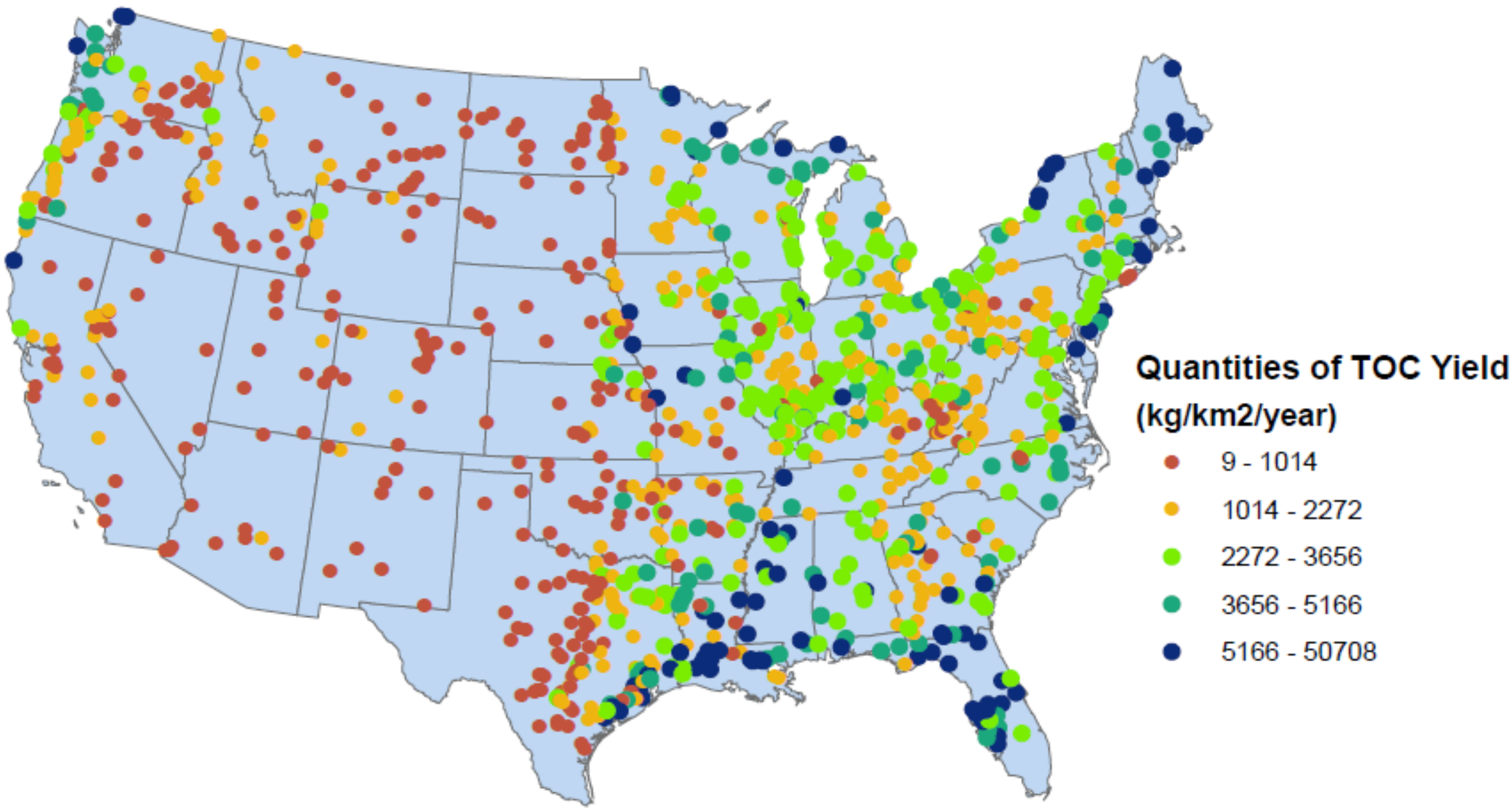
By Jhih-Shyang Shih, Richard B. Alexander, Richard A. Smith, Elizabeth W. Boyer, Gregory E. Schwarz, and Susie Chung

Open-File Report 20XX–XXXX

U.S. Department of the Interior
U.S. Geological Survey

Calibration sites currently included in TOC model

- Total organic carbon data retrieved from USGS – NWIS & EPA – STORET databases, for 1970-2008.
- 1125 sites (of about 5000 sites with TOC data) met criteria and were used:



Terrestrial C sources: proxies by land area

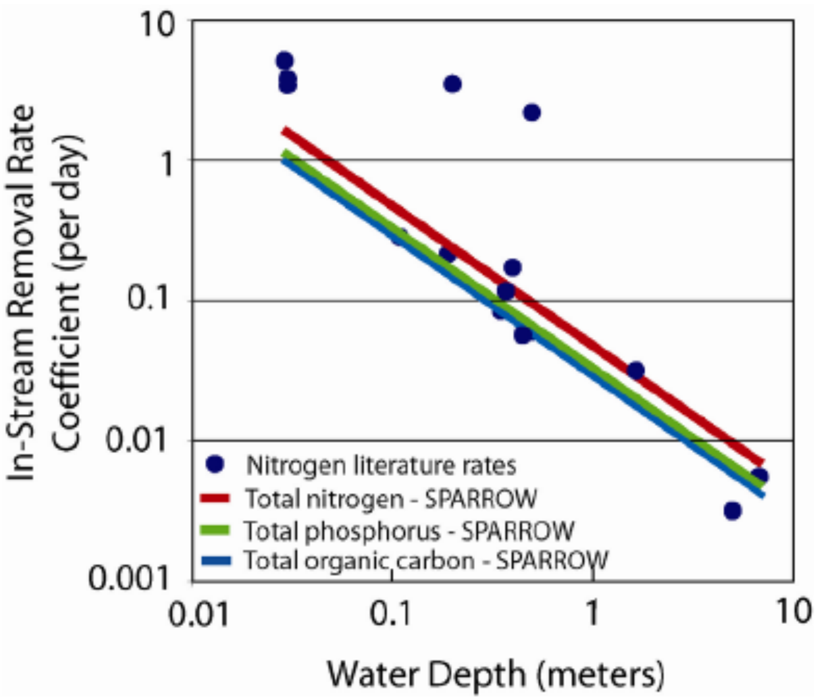
Carbon source	Definition
Agricultural land ()	Area of row crops; small grains; fallow; pasture; and orchards-vineyards-other.
Forest land	Area of deciduous, evergreen, mixed forest.
Range and grass lands	Area of shrub lands and herbaceous grass lands.
Urban land	Area of low-intensity residential, high-intensity residential, and commercial-industrial-transportation land; urban-residential grasses.
Wetlands	Area of woody wetlands; emergent herbaceous wetlands.
Photosynthesis in streams	Based on total phosphorus concentration, solar irradiance, and channel dimensions.
Photosynthesis in reservoirs	Estimated surface area.[2]

Aquatic C sources: in-stream C production

- 1st approximation of C production via photosynthesis accounts for:
  - Reach-level variation in total P (from SPARROW) and chlorophyll
  - Geographical variation in incident light
  - Light attenuation by chlorophyll and non-algal material over river depth
  - Rate of light energy trapping by chlorophyll
  - Rate of carbon fixation per unit of light energy trapped

- Adapted from Smith (1980, *Ecological Modeling*, a mechanistic model of primary production in natural waters), linked to Van Nieuwenhuyse & Jones (1997, Can J. Fish. Aquat. Sci, an empirical model of stream chlorophyll)

Aquatic C sources: in-stream C losses



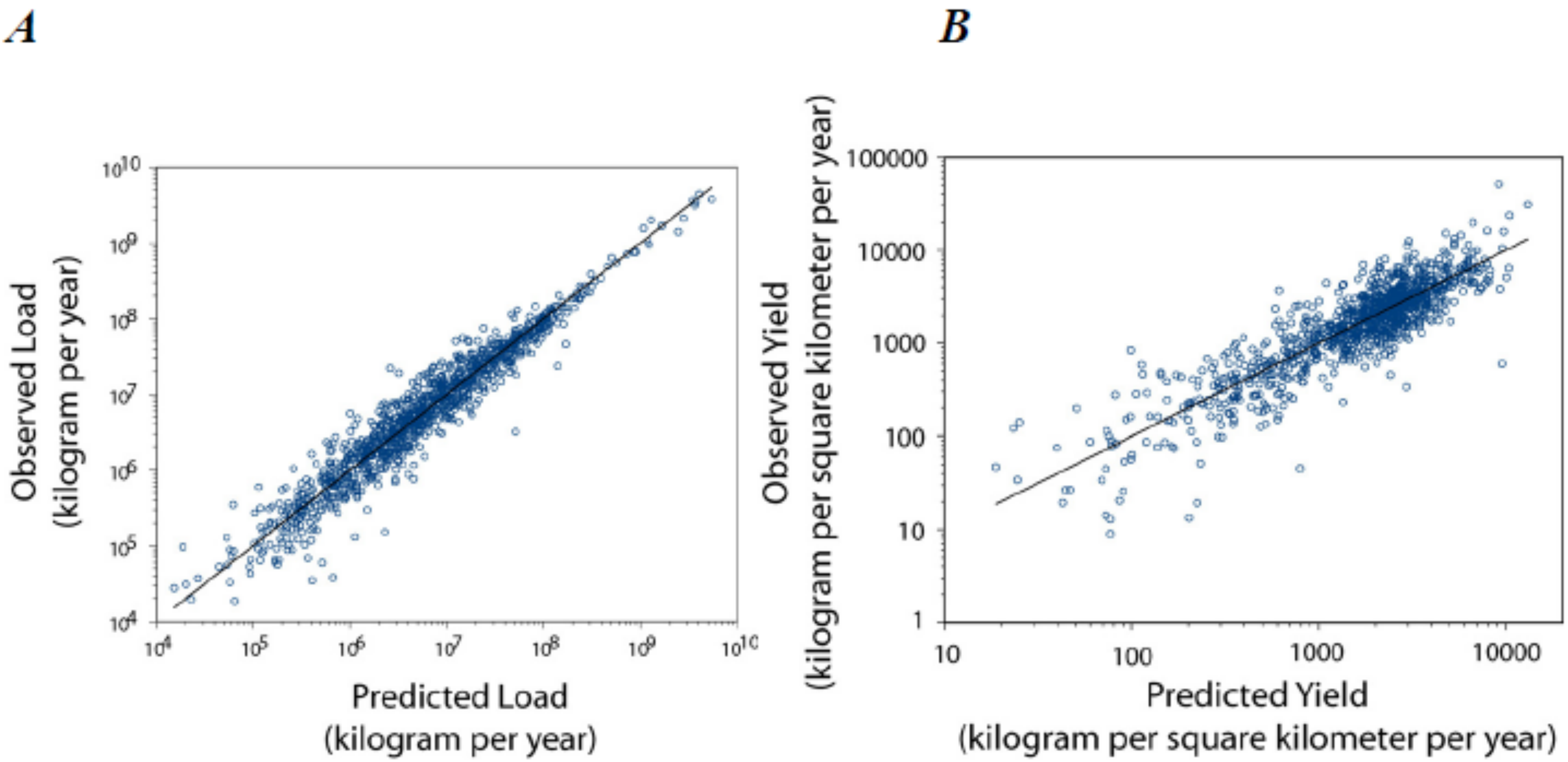
SPARROW estimates of in-stream, net removal rate for TOC compared w/ other sparrow models.

The net rates of TOC removal in streams decrease with increases in water depth.

B contrast, the net removal rate for reservoirs was estimated to be zero and was not statistically significant. This suggests that production and loss processed may be approximately balanced on average.

The estimated TOC mass-transfer coefficient for streams was 0.034 m day^{-1} (12.4 m yr^{-1}), which corresponds to the series of reaction rate coefficients (units of per day) as shown for a range of water depths in streams in the river network.

TOC model calibration, to 1125 sites



Model accuracy plots for total organic carbon loadings from SPARROW model.

A) observed and predicted load (mass/time); $R^2 = 0.93$

B) observed and predicted yield (mass/area/time); $R^2 = 0.77$

Model includes statistically-significant Sources, Land-to-water delivery factors, and In-stream factors

Parameter	Coefficient units[1]	Estimate	Standard Error	t value	Level of Statistic Significance, p
Agriculture	kg km^{-2} yr^{-1}	1454	167	8.65	0.000
Forest, deciduous	kg km^{-2} yr^{-1}	1061	191	5.54	0.002
Forest, evergreen	kg km^{-2} yr^{-1}	1378	167	8.21	0.000
Forest, mixed	kg km^{-2} yr^{-1}	2568	627	4.09	0.001
Urban	kg km^{-2} yr^{-1}	4777	778	6.14	0.000
Wetlands	kg km^{-2} yr^{-1}	25,008	2529	9.89	0.000
In-stream photosynthesis	dimensionless	1.10	0.13	8.67	0.000
Soil permeability	log (cm hr^{-1})	-0.1407	0.0368	-3.82	0.000
Precipitation	cm	0.0047	0.0006	7.51	0.000
Artificial drainage	percent area	0.0116	0.0031	3.82	0.001
Drainage density	log (km^{-1})	0.4407	0.0545	8.08	0.000
Land slope	log (percent)	-0.0023	0.0040	-0.58	0.5620
In-stream carbon removal	per day	0.0338	0.0036	9.31	0.000
Log root mean square error		0.540			
Number of observations		1125			
Adjusted R-squared		0.928			
Yield R-squared		0.77			

[1]kg = kilogram; km = kilometers; yr = year; cm=centimeters; hr=hour

generates hypotheses about importance of various land-uses

Parameter	Coefficient units[1]	Estimate
Agriculture	kg km^{-2} yr^{-1}	1454
Forest, deciduous	kg km^{-2} yr^{-1}	1061
Forest, evergreen	kg km^{-2} yr^{-1}	1378
Forest, mixed	kg km^{-2} yr^{-1}	2568
Urban	kg km^{-2} yr^{-1}	4777
Wetlands	kg km^{-2} yr^{-1}	25,008

Among these sources with comparable units, we find that **wetlands** make the largest mass contribution per unit area (or yield) to the stream organic carbon load, followed in declining order by **urban lands, mixed forests, agricultural lands, evergreen forests, and deciduous forests .**

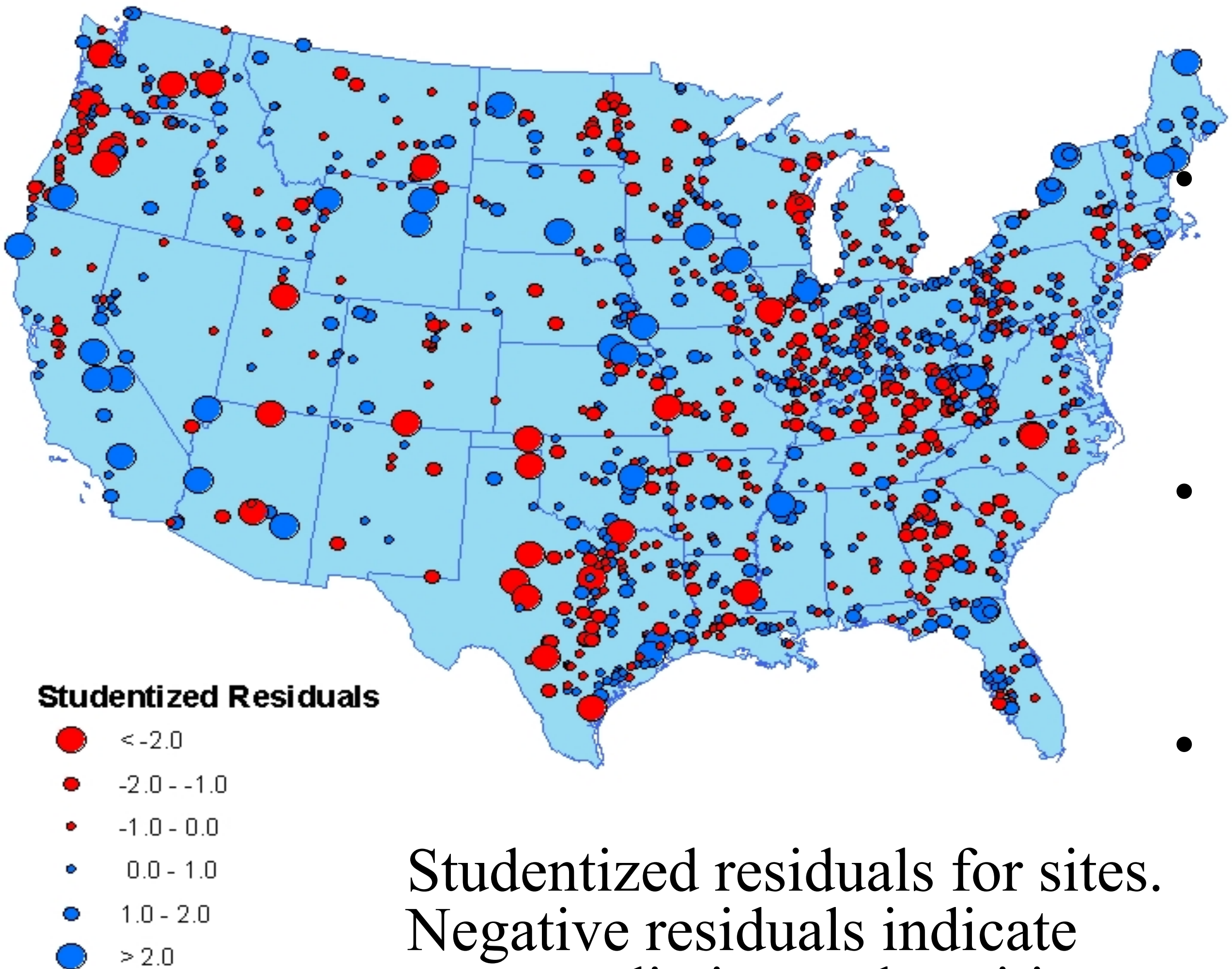
generates hypotheses about importance of various land-uses

Watershed land-cover type	Percentiles of total organic carbon yield exported from SPARROW watersheds[1] (kg ha^{-1} yr^{-1})						Literature Yields[2] (kg ha^{-1} yr^{-1})[3]
	No. of watersheds	10th	25th	50th	75th	90th	Range of values
Agriculture	1,841	15.1	19.1	24.5	34.7	59.9	14.1–19.5[2]
Forest Deciduous	70	12.1	14.0	16.2	21.4	34.0	4–80[4]
Forest Evergreen	248	13.6	16.1	20.3	28.6	56.0	14–500[4]
Range	3,203	0.1	0.3	0.8	2.3	8.2	4–13[4]
Urban	143	36.3	48.3	73.3	108.6	329.3	19–146[4]
Wetlands	191	160.3	276.4	476.3	801.6	2180.0	50–220[5]

Results are generally consistent with the magnitude and relative ordering of organic carbon exports for small catchments in these land use types.

[a] The land-cover types represent the following percentages of the land area in SPARROW watersheds: agricultural land (>90%), forest (>95%), urban (>90%), wetlands (>95%), and range (95%). [b]Dalzell et al. 2007. [c]Hope et al. 1994; North America, New Zealand, Russia (total organic carbon). [d]Mulholland 2003 (dissolved organic carbon).

Residuals to consider bias in predictions



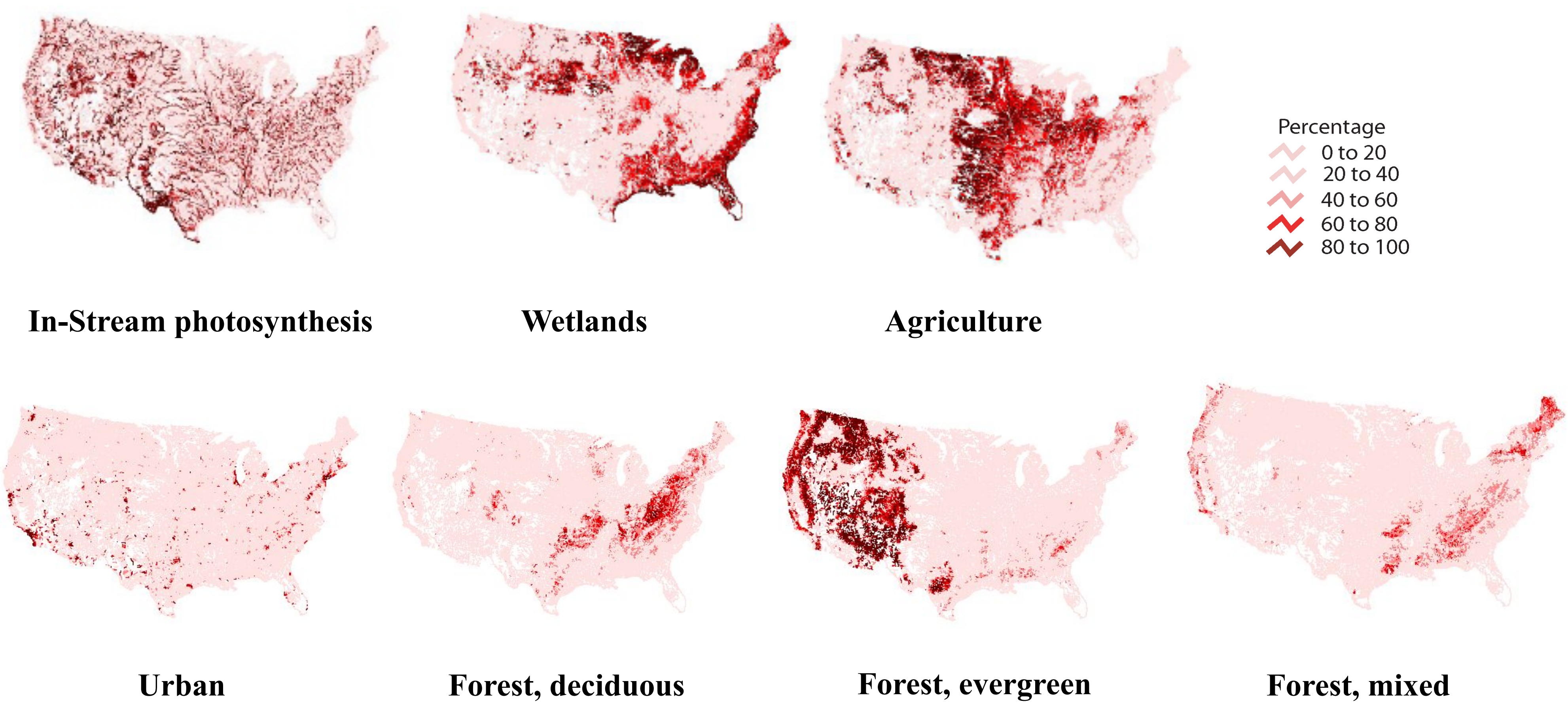
Studentized residuals for sites. Negative residuals indicate over-prediction and positive values indicate under-prediction of the mean annual total organic carbon stream load.

- Evidence of prediction biases in selected regional watersheds,
- Overpredication at sites in areas of the Pacific Northwest, western Texas, Ohio basin, and the Southeast.
- Underprediction in southern California, central United States, and the extreme Northeast.
- Related to temporal differences in the environmental conditions reflected by the period of record covered by the various monitoring stations.

TOC simulations

TOC incremental yield

TOC Source Shares for Selected Parameters



Expressed as a mean of the reach-level source share percentages: The stream photosynthesis source is the largest overall source (22.4%), followed by (in order) wetlands (19.9%), agriculture (19.9), evergreen forest (19.7), mixed forest (6.4), deciduous forest (7.5), and urban land (4.3).

TOC Yields and Source Shares Delivered to Coastal Areas from seven major regional drainages

Region	Drainage area (km²)[1]	Delivered yield (kg/ha/yr)[2]	Source share percentage					
			Agriculture	Forest	Urban	Wetland	Stream photosynthesis	All terrestrial[3]
North Atlantic	446,500	34	7	29	10	32	22	78
SouthAtlantic- Gulf	730,000	59	5	13	3	58	21	79
Miss.-Atch.-Red[4]	3,248,700	32	14	7	2	22	54	46
Texas-Gulf	925,400	11	14	12	5	34	36	64
Pacific Northwest	713,700	17	6	39	3	5	48	52
California	234,200	15	8	39	10	7	37	63
Great Lakes	313,100	38	15	11	4	60	10	90

[1]Square kilometer.

Relation between TOC and DOC in water regions

			Mean Concentration (mg/L)		
HUC2	Name	Number of Sites	DOC	TOC	Ratio
1	Northeast	34	13.65	14.24	0.90
2	Mid-Atlantic	131	4.58	5.63	0.83
3	Southeast	142	9.86	11.15	0.86
4	Great Lakes	66	8.62	9.75	0.89
5	Ohio	64	3.49	4.59	0.79
6	Tennessee	27	3.24	4.29	0.80
7	Upper Miss.	52	6.60	8.80	0.76
8	Lower Miss.	30	6.70	8.71	0.78
9	Souris-Red-Rainy	23	13.41	14.51	0.92
10	Missouri	100	7.88	10.52	0.79
11	Red-White	44	5.53	7.48	0.80
12	Texas Gulf	34	6.70	8.34	0.83
13	Rio Grande	8	5.33	9.52	0.74
14	Upper Colorado	14	5.33	8.60	0.77
15	Lower Colorado	16	6.84	17.31	0.73
16	Great Basin	16	5.56	6.35	0.85
17	Pacific Northwest	37	2.89	3.41	0.85
18	California	22	5.87	7.08	0.85

Conclusions

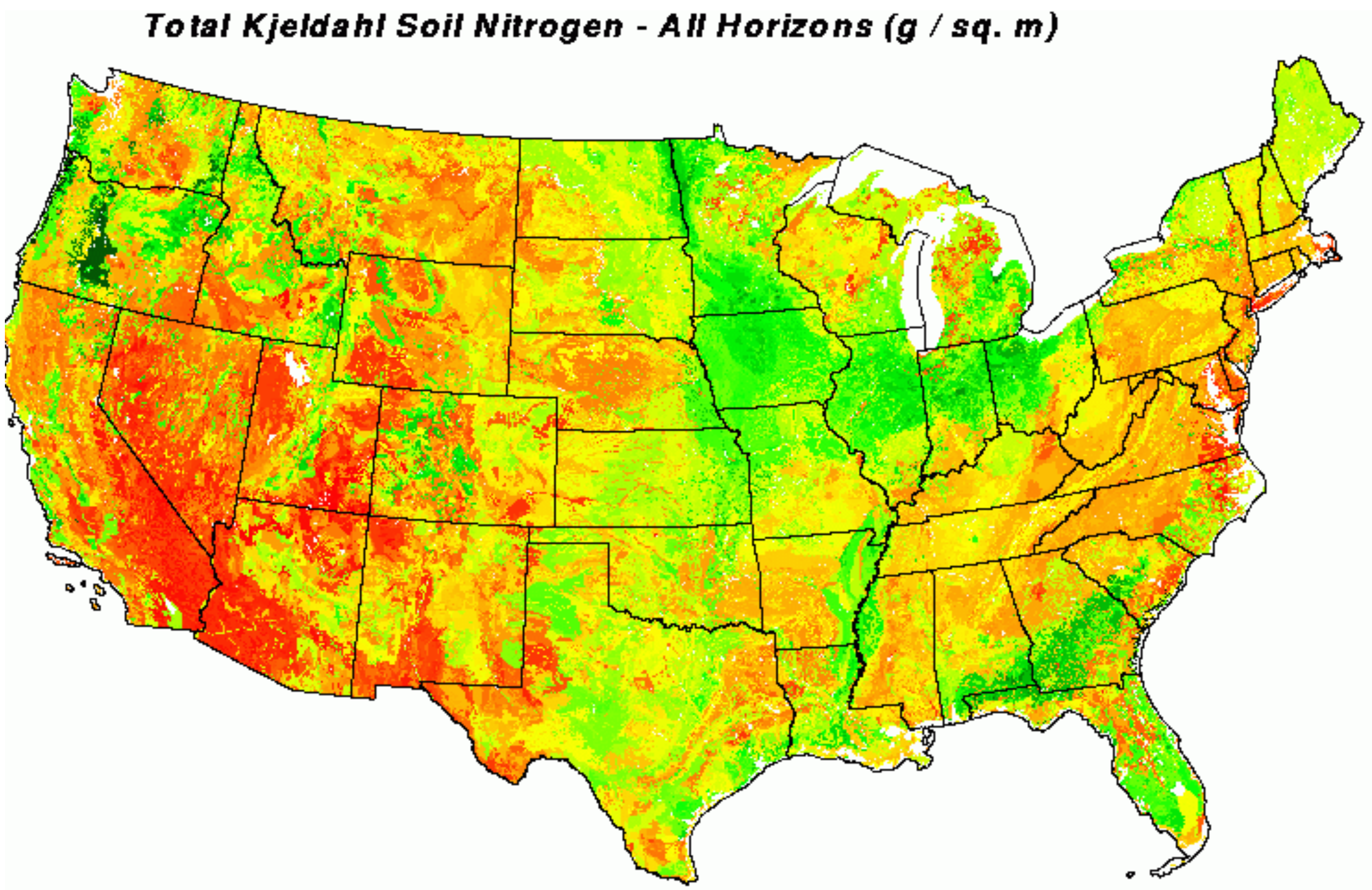
- TOC loadings have been estimated across USA using the SPARROW model. Refinements are underway. Other carbon models (DOC, DIC) underway.
- Results available to OCB synthesis efforts
- SPARROW models allow us to:
  - Quantify carbon fluxes and sources over space & time, with estimates of uncertainty
  - Explore impacts of land use change and climatic variability
  - Consider scenarios of energy policy & land management

Current efforts to improve predictability

- More calibration sites
- More headwater sites
- Improved load estimates

Current efforts to improve predictability

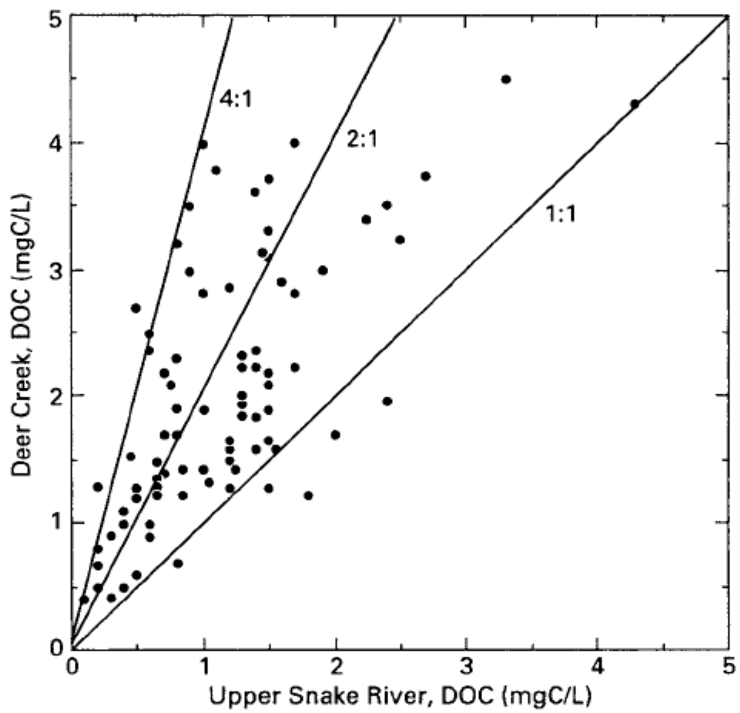
OC <u>sources</u>: net primary productivity, Soil C:N ratio, soil nitrogen, other soil elements



Boyer et al., in prep.

Current efforts to improve predictability

Aquatic Transport: Attenuation of sediments in reservoirs, geochemical reactions in streambed



Relationships to streambed geochemical environment control water column DOC concentrations

McKnight et al. 2002

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.

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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***