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SUPPORTING CHESAPEAKE BAY RESTORATION BY MODELING NUTRIENT AND SEDIMENT SOURCES AND TRANSPORT

Applications and Results of SPARROW Models

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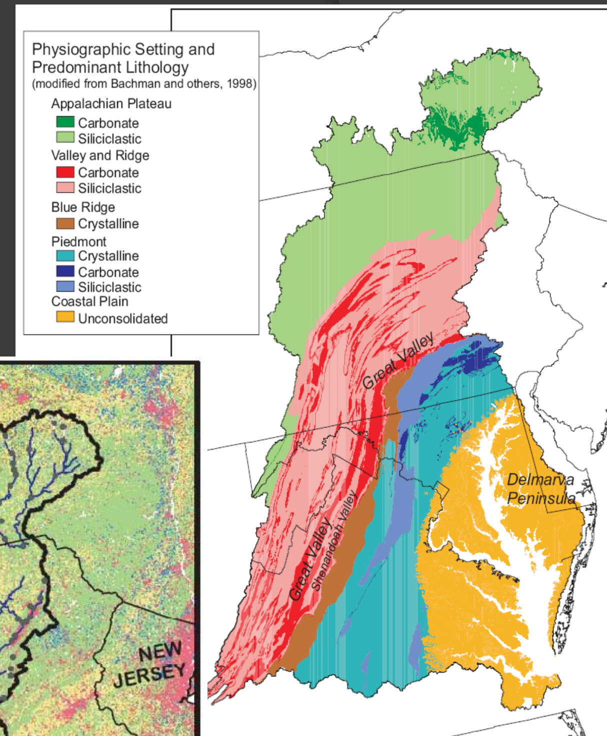
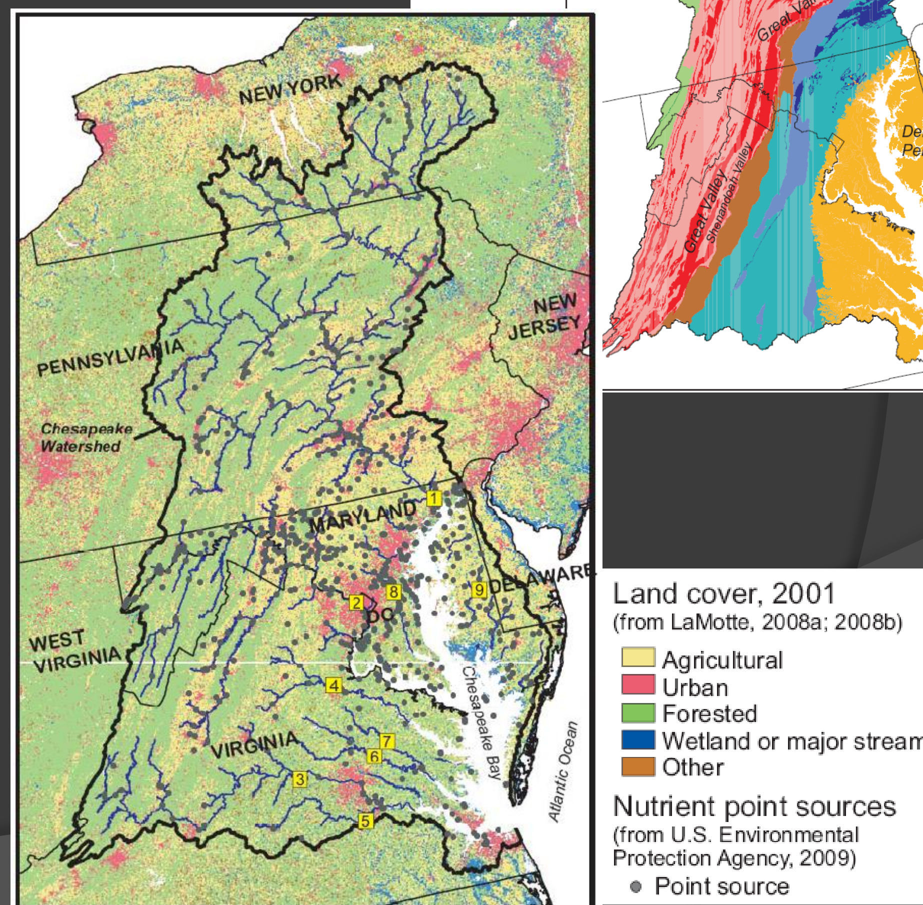
Chesapeake Bay Watershed

- Drains the largest estuary in North America
- Stresses led to the Bay and its tidal rivers being listed as "impaired waters" under the Clean Water Act
  - Largely because of low dissolved oxygen levels and other problems related to pollution like excessive nutrients and sediment
  - Imposed TMDL throughout watershed
- Restoration efforts have been ongoing for several decades.
- Challenges:
  - Diverse and changing land uses
  - Variety of contaminant sources
  - Diverse natural conditions relevant to contaminant fate and transport
- Restoration efforts have been designed and supported using numerical models:
  - Chesapeake Bay Program HSPF watershed model
    - TMDL's implemented and managed
  - USGS SPARROW
    - Help gain a comprehensive understanding of where nutrients and sediment originate
    - How they move throughout the watershed
    - Assist management actions

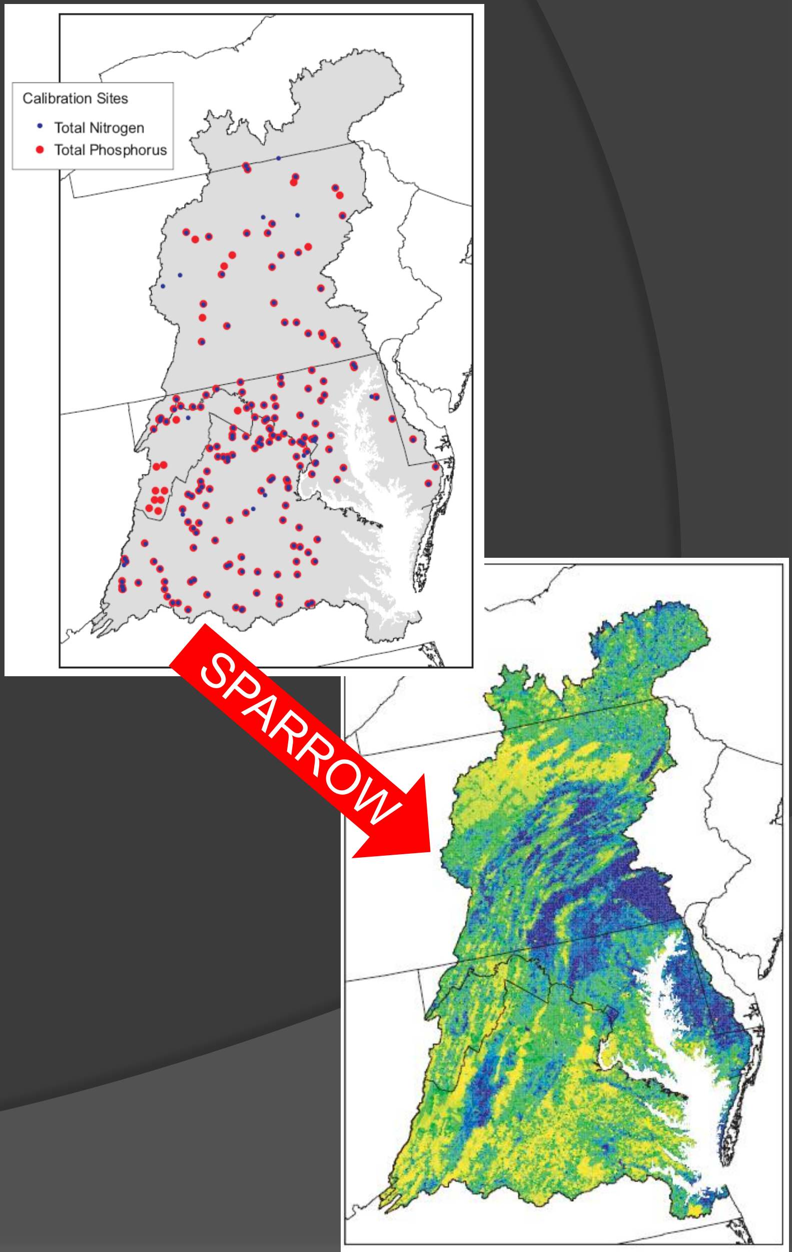




SPARROW

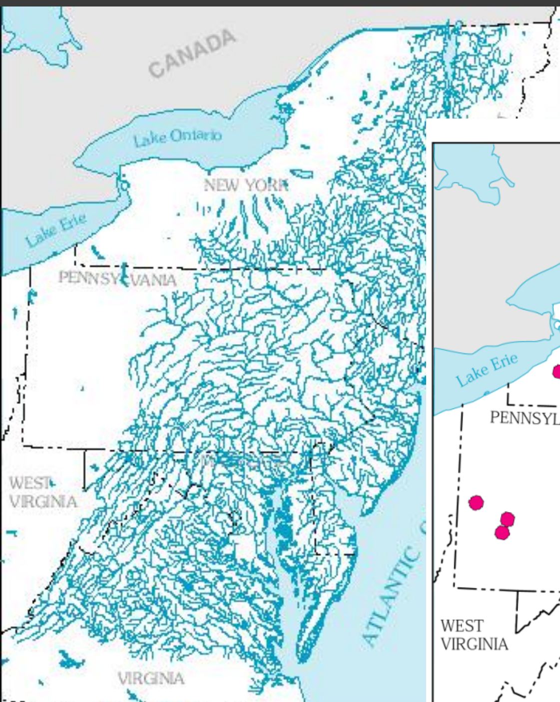
SPatially Referenced Regressions On Watershed Attributes

- Spatial Statistical Approach that Empirically Relates Contaminant Sources and Transport Factors to Measured Stream Flux
  - Identify the spatial variability and magnitude of contaminant supply
  - Quantify the contributions at various locations
  - Identify the factors affecting transport
- Tool Provides Spatially Detailed Predictions:
  - Map individual contaminant sources in unmonitored locations
  - Statistical importance and quantification of contaminant sources
  - Provides measures of uncertainty
- Spatial Framework
  - Explicit for evaluating geographic distribution of sources and the factors affecting flux
  - Potential Geographic Targeting for intensive study, increased monitoring, or management practice evaluation/implementation (BMP)

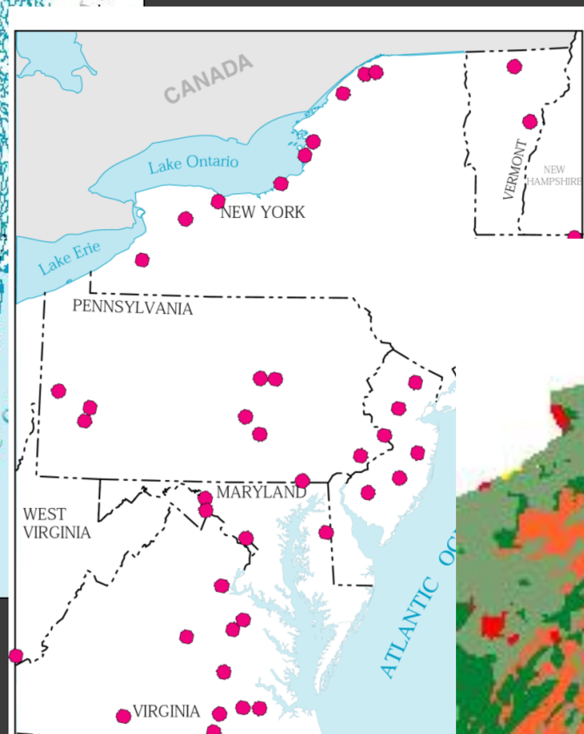


SPARROW Spatially Designed

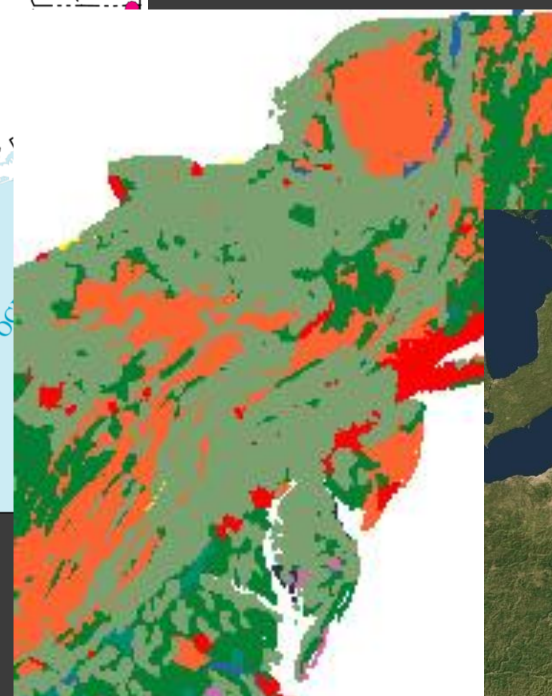
Integrates spatial data over multiple scales to predict origin & fate of contaminants



Network of connected and attributed streams and watersheds

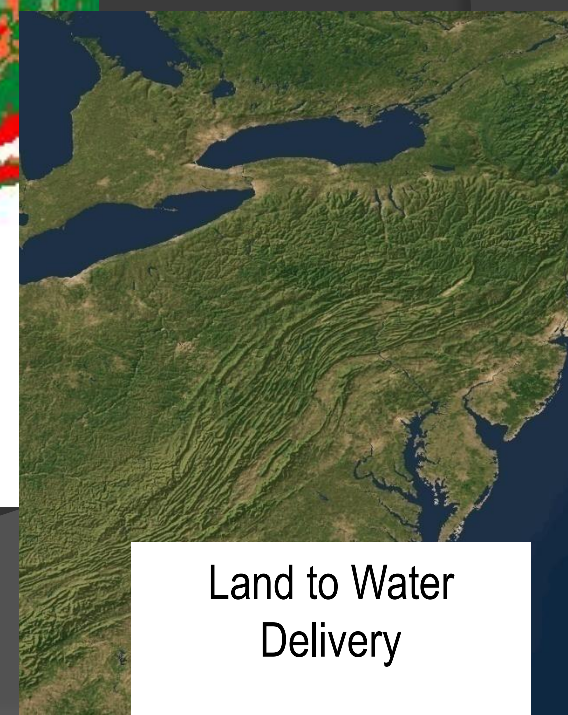


Monitoring Data (Dependent Variable)



Source data

Slope, Physiography, Soil Characteristics, Reservoir Systems



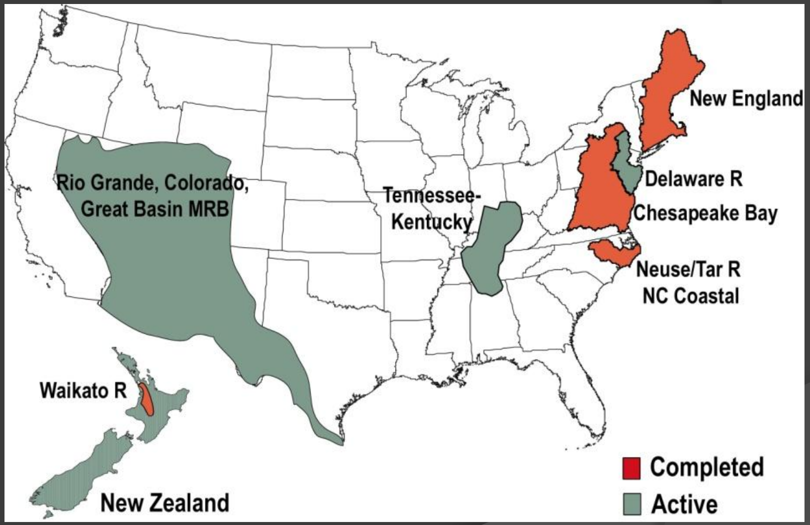
Land to Water Delivery

SPARROW

National and Regional Modeling

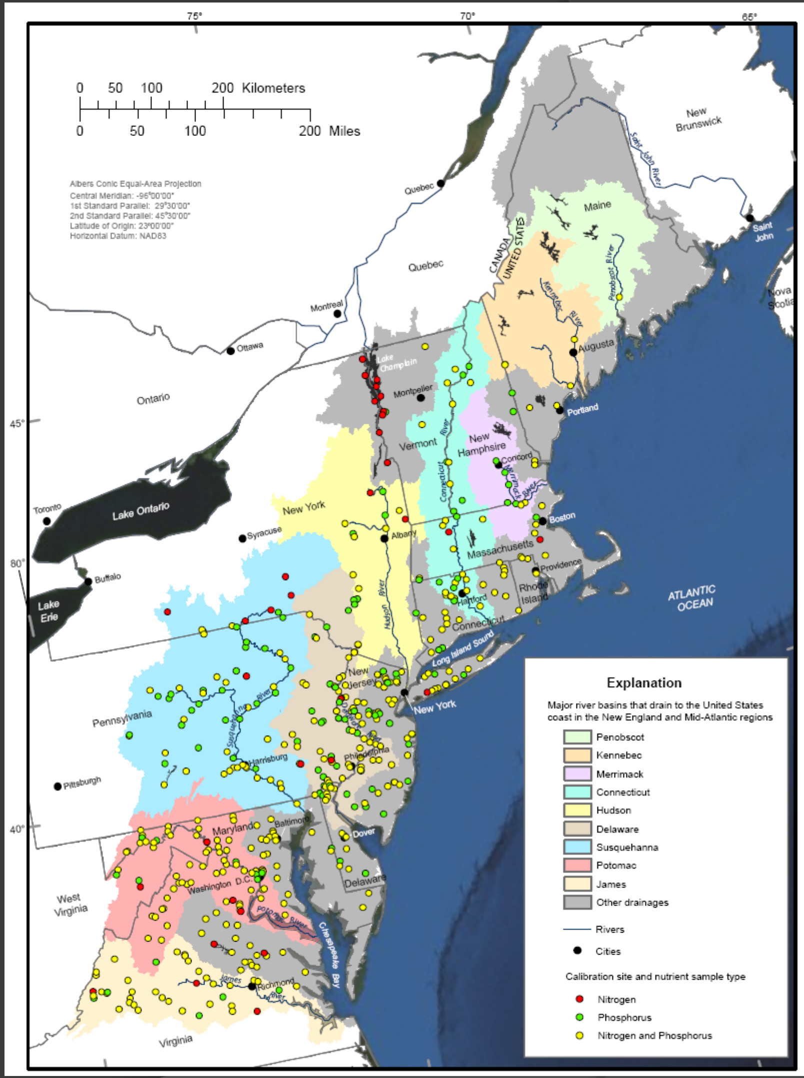
1) Contiguous U.S.
2) Upper and Lower Mississippi River Basin
3) USGS NAWQA Major River Basin Studies

USGS State Science Center Projects



Northeastern US SPARROW

- Provides broader context of how Chesapeake compares to wider region
- Similar calibration to Chesapeake models:
  - TN and TP
  - Early 2000s
  - 1:100,000 scale
  - Slightly different source and transport specification
- September release
  - Online tool for customized mapping and reporting of SPARROW results and scenario testing

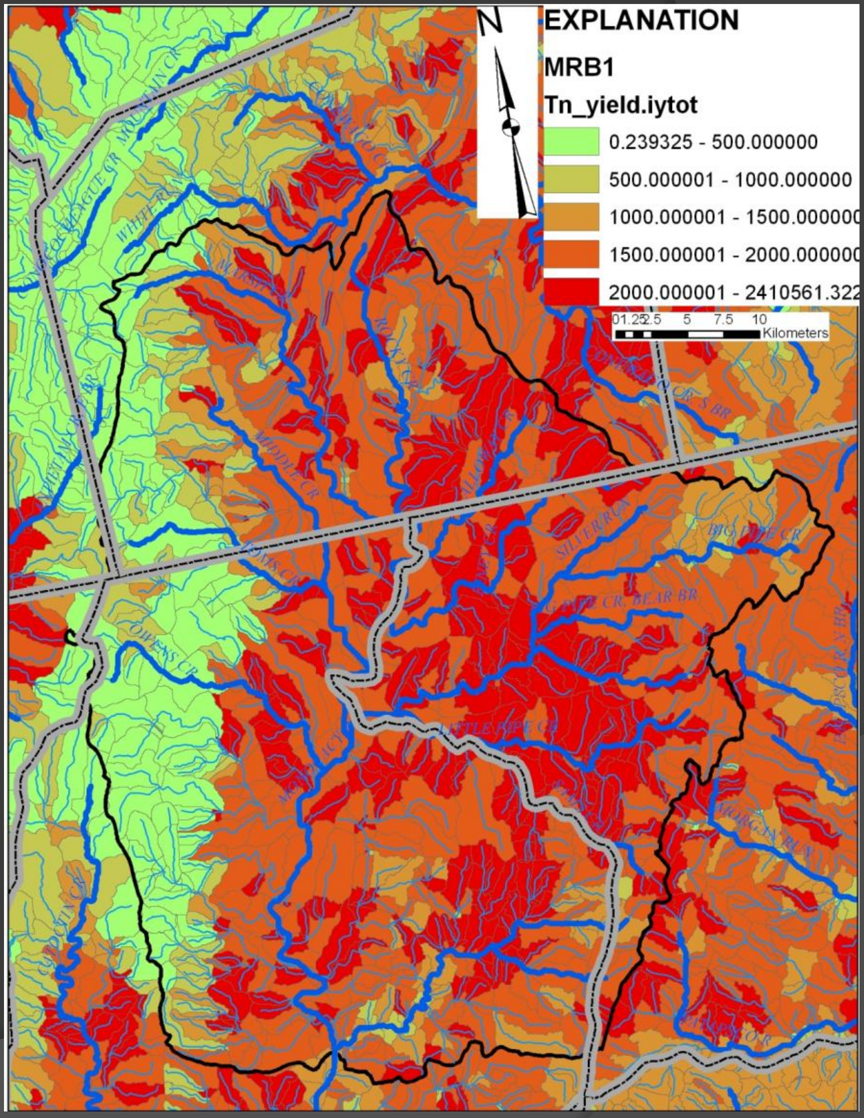


Moore et al., in press JAWRA

Chesapeake Bay SPARROW Models

- Previous models:
  - Late 1980s (TN, TP)
  - Early 1990s (TN, TP)
  - Late 1990s (TN, TP)
  - Early 2000s (sediment)
- Updated models:
  - Early 2000s (TN,TP)
  - Finer spatial resolution
  - More calibration stations
  - Updated sources and expanded transport specification

Scale	Water-sheds	Mean Size (km^2)
1:500,000	2,734	75
1:100,000	80,579	2.1



Nitrogen SPARROW

RMSE=0.2892, R^2=0.9784, yieldR^2=0.8580
N = 181

- Sources: On average:
  - 1,090 kg/km² of N from Urban areas reach the stream
  - 24% of N from fertilizer and fixation reaches streams
  - Only 6% of N in manure reaches streams
  - 27% of N from atmospheric deposition reaches streams

Nitrogen Model	Estimate	p
Sources		
Point sources (kg/yr)	0.774	0.0008
Urban land (km²)	1090	<0.0001
Fertilizer/fixation (kg/yr)	0.237	<0.0001
Manure (kg/yr)	0.058	0.0157
Wet atmospheric (kg/yr)	0.267	<0.0001
Land to Water Transport		
Ln(mean evi)	-1.70	0.0039
Ln(mean soil AWC)	-0.829	0.0016
Ln(GW recharge (mm))	0.707	<0.0001
Ln (% Piedmont carb)	0.158	0.0018
Aquatic Decay		
Small streams (<122 cfs)	0.339	0.0118
Lg Streams, T > 18.5 C	0.153	0.0030
Lg Streams, T< 15.0 C	0.013	0.431
Impoundments	5.93	0.0424

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Nitrogen SPARROW

RMSE=0.2892, R^2=0.9784, yieldR^2=0.8580
N = 181

- Fate and transport:
  - Delivery to streams is greater in areas of greater groundwater flow, particularly in the Piedmont carbonate
  - Delivery to streams is less in areas with reducing conditions or greater plant uptake
  - In-stream losses are greater in smaller streams
  - In-stream losses in larger streams are greater in warmer areas
  - Losses in impoundments are likely due mainly to denitrification

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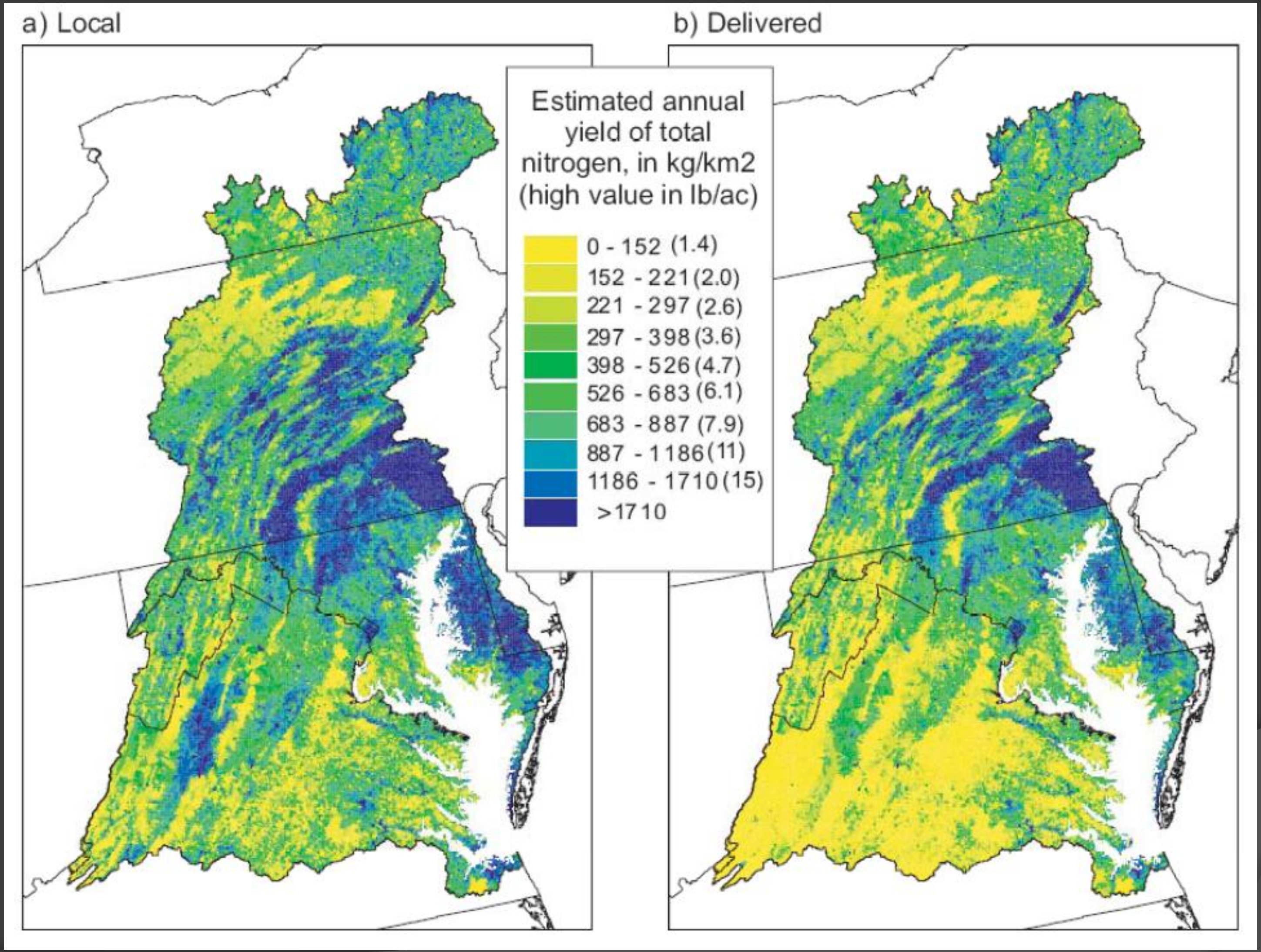
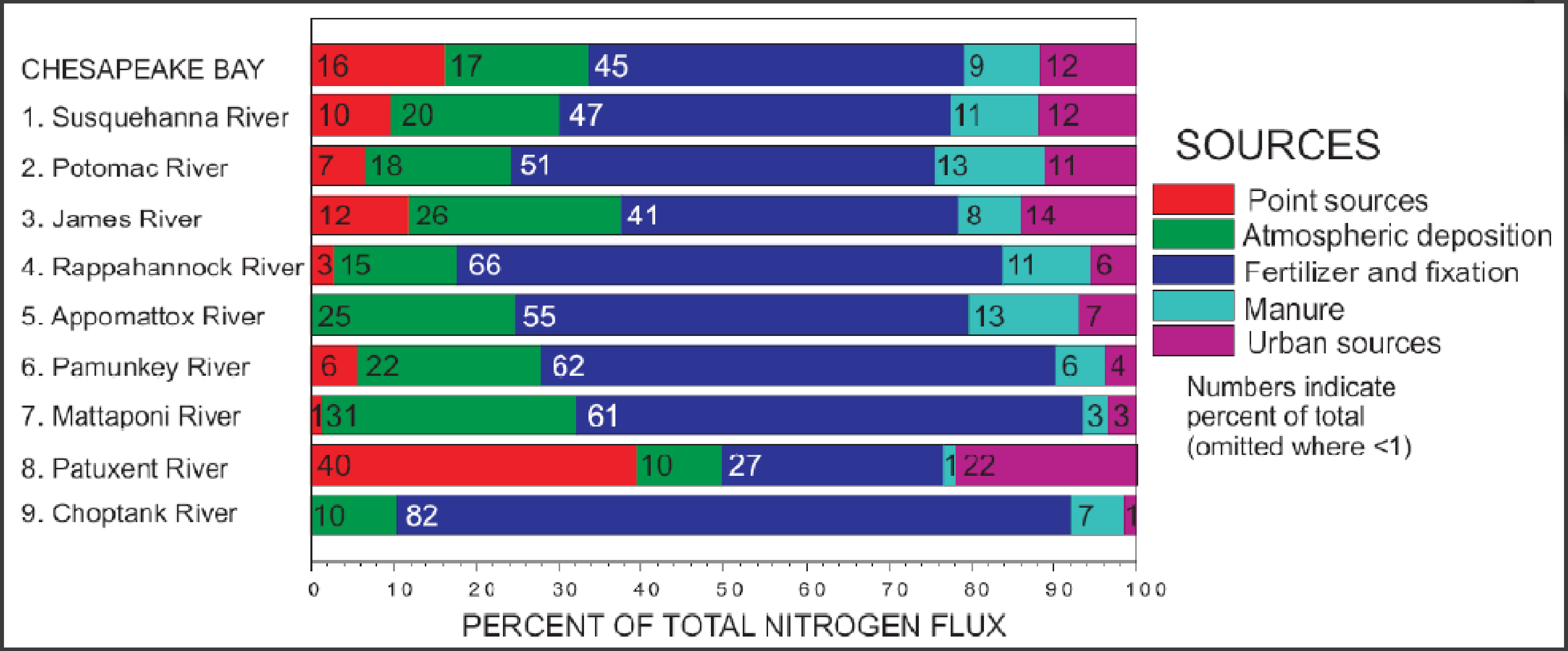
Spatial Distribution of TN



Nitrogen Source Shares



- Agriculture is widespread, and a dominant sources of N to the Bay and most tributaries

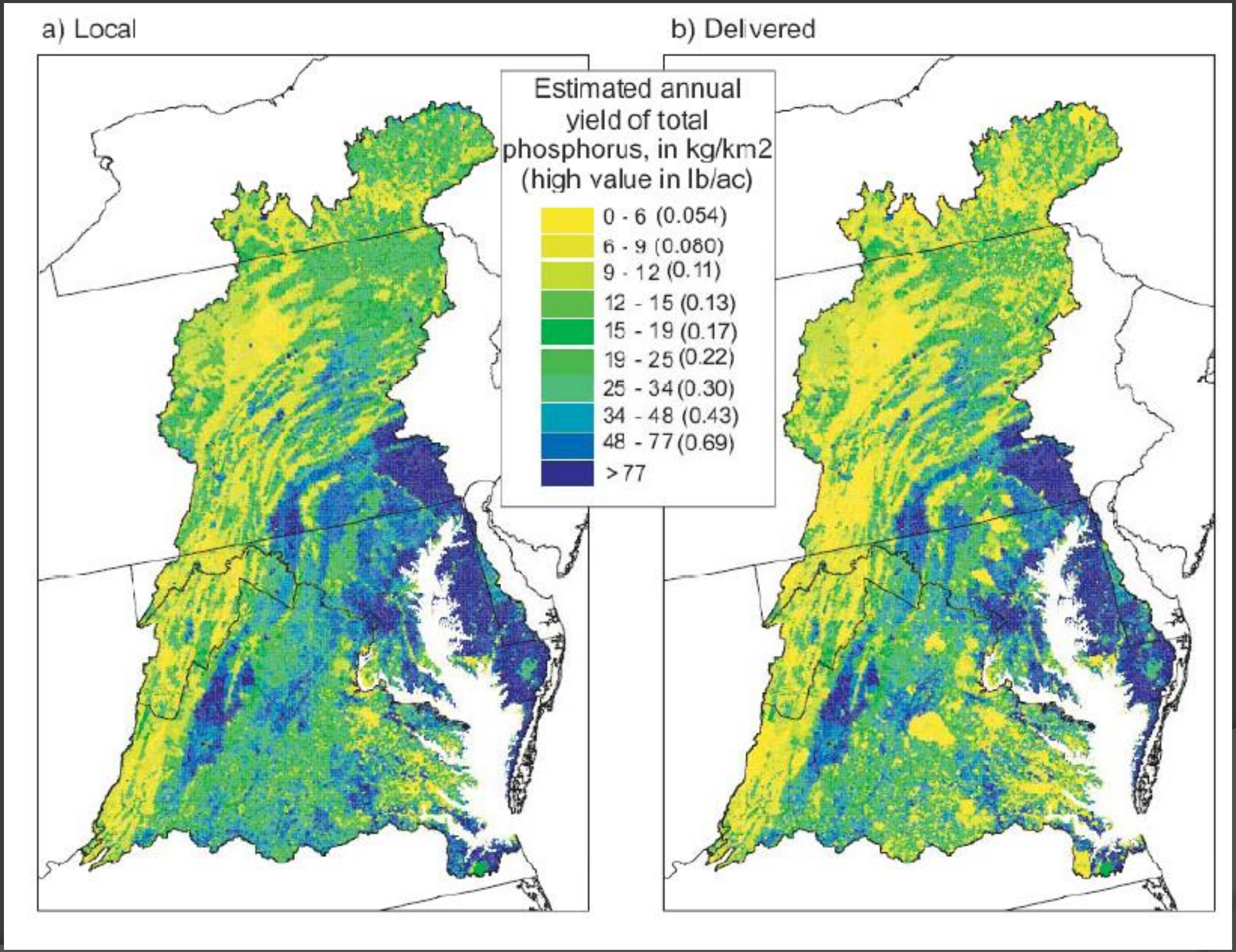
Phosphorus SPARROW

RMSE=0.4741
R^2=0.9510
yieldR^2=0.7300
N = 184

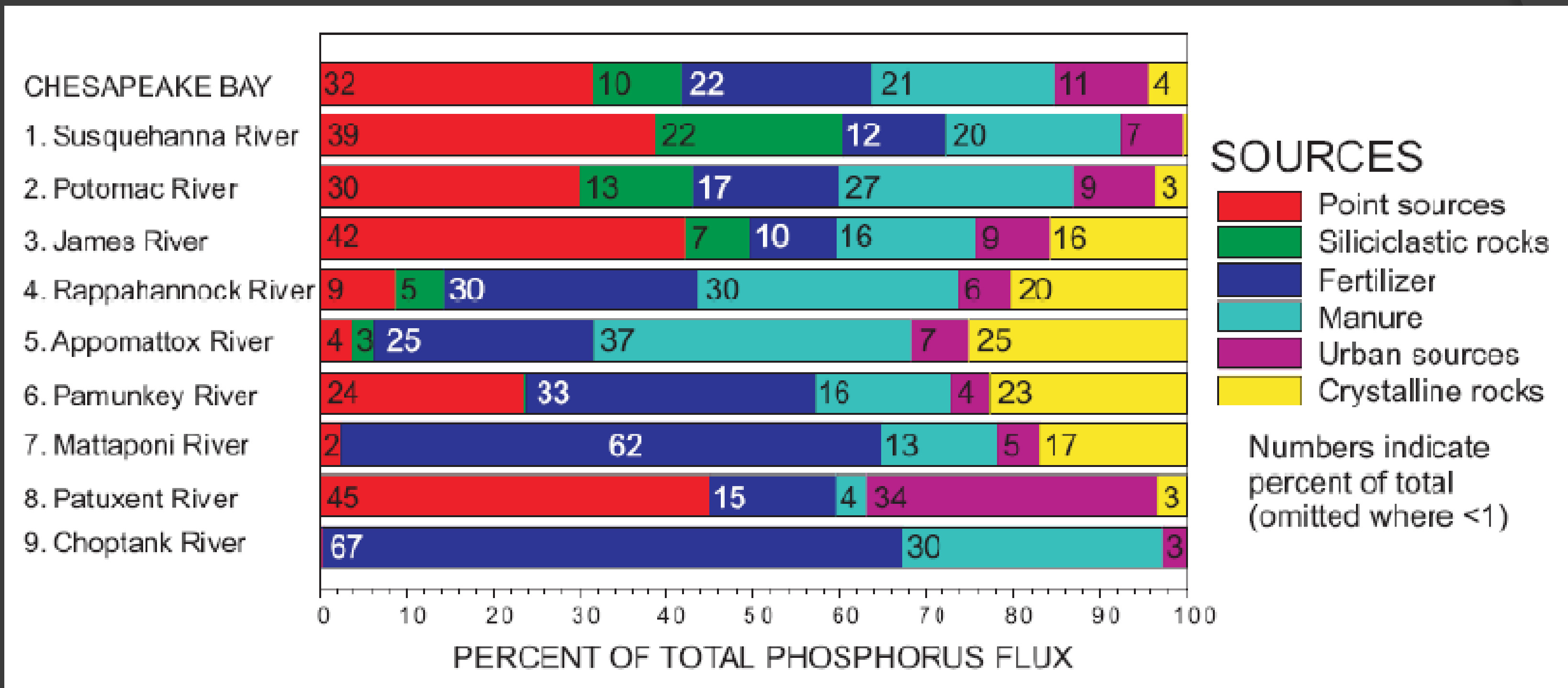
- On average, less than 5% of applied P in fertilizer and manure reaches streams
- Urban areas yield 49 kg/km^2
- Natural mineral sources are significant
- Delivery to streams is greater where runoff is more likely and in the Coastal Plain, possibly due to legacy applications or saturation
- Significant losses occur in impoundments

Phosphorus Model	Estimate	p
Sources		
Point sources (kg/yr)	0.877	<0.0001
Urban land (km^2)	49	<0.0001
Fertilizer (kg/yr)	0.0377	0.0014
Manure (kg/yr)	0.0253	0.0002
Siliclastic rocks (km^2)	8.52	<0.0001
Crystalline rocks (km^2)	6.75	0.0009
Land to Water Transport		
Soil erodibility (k factor)	6.25	0.0002
Ln(% well drained soils)	-0.100	0.0019
Ln(precipitation (mm))	2.06	<0.0237
Coastal Plain (% of area)	1.02	<0.0001
Aquatic Decay		
Impoundments	54.3	0.0174

Spatial Distribution of TP



Phosphorus Source Shares



- TP from urban (including point sources) and agricultural sources are roughly equivalent
- Natural mineral sources represent about 14 percent of TP sources

Suspended Sediment SPARROW

RMSE=0.96
R^2=0.83
yieldR^2=0.57
N = 129

- Sediment yields *(export coefficient)* are greatest from areas of urban development *(represented by an increase in impervious surface)* ~4,000 kg/km^2
- Agriculture contributes less by unit area, but is widespread and a significant source of sediment to local streams and Chesapeake Bay
- In-stream sources *(bank, bed, or flood plain erosion)* are also significant in small streams above the Fall Line
- Upland sediment transport to streams is enhanced in areas with greater slope, fewer reservoirs, less permeable soils, and in the Piedmont
- Significant losses occur in impoundments and large Coastal Plain streams

Sediment Model Variable	Estimate	p
Sources		
Agriculture Area (km^2)	56.96	< 0.001
Forested Area (km^2)	0.98	0.495
Developed lands (km^2)	3,928.41	0.004
Stream Channel < 35 ft^3/sec	.029	0.030
Land to Water Transport		
Watershed Slope	0.01	0.083
Soil Permeability	-1.19	0.022
Piedmont Province	0.96	0.002
Off Reach Impoundment density	-22.96	0.021
Aquatic Decay		
Impoundments (m/yr)	234.91	0.034
CP Streams (120 – 250 ft^3/sec) Day^{-1}	2.54	0.007
CP Streams (> 250 ft^3/sec) Day^{-1}	1.92	0.14

Published in Brakebill et al., 2010, JAWRA, 1:500,000 stream network

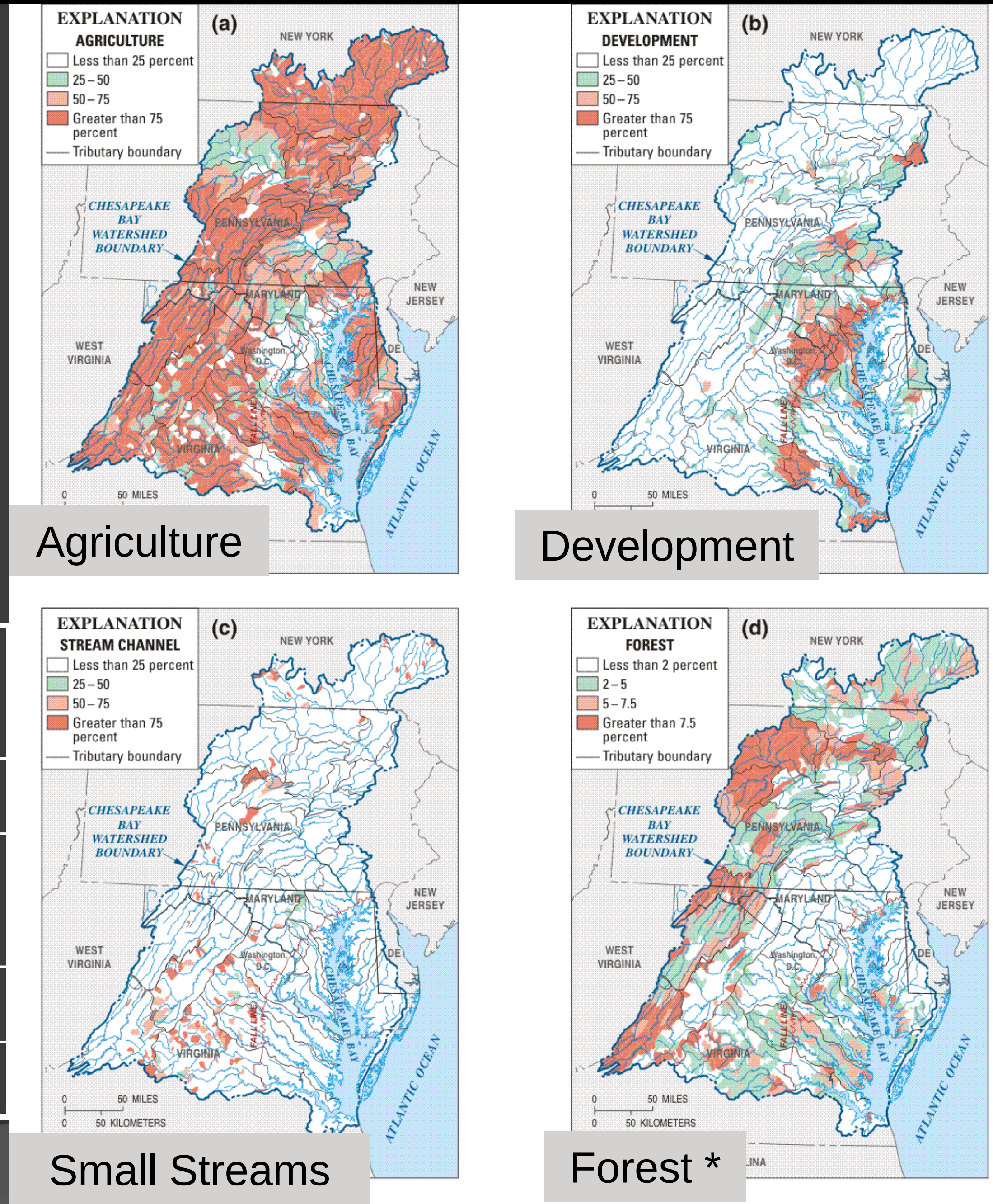
Applications – Individual sediment source contributions

Sediment Source Shares

- Incremental (local) sources
  - how much sediment is generated in each catchment?

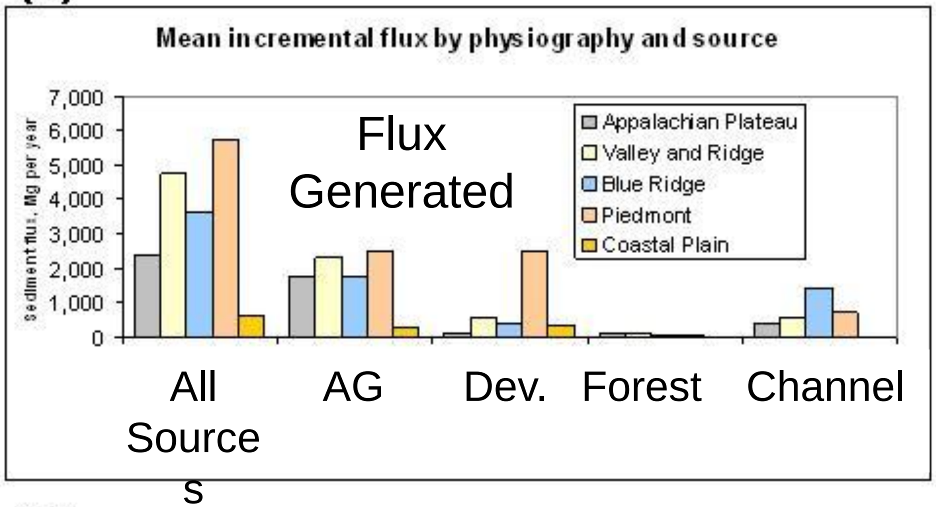
Source Share (%)	Mean	Median
Agriculture	62	74
Urban Development	26	14
Forest	5	3
Small streams	7	0

* Forest mapped 1 order of magnitude less than other sources

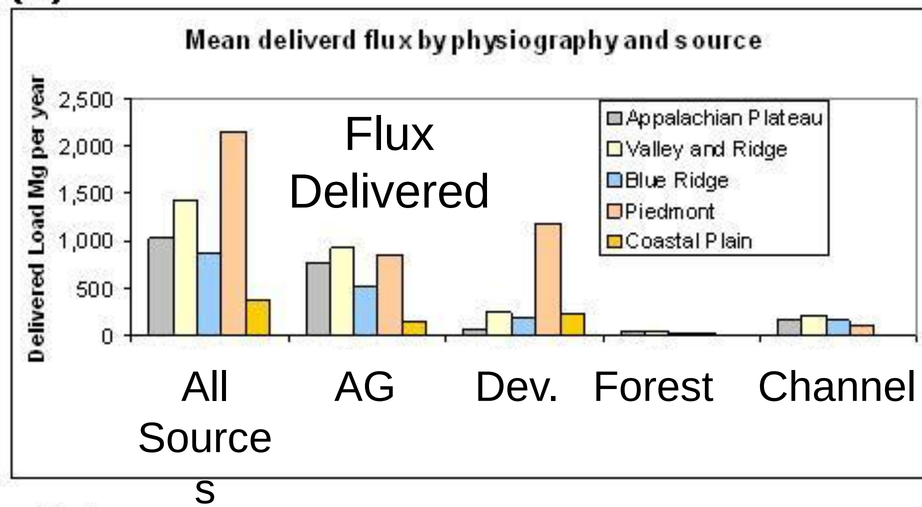


Sediment Source Distribution *By Physiography*

(a)



(a)



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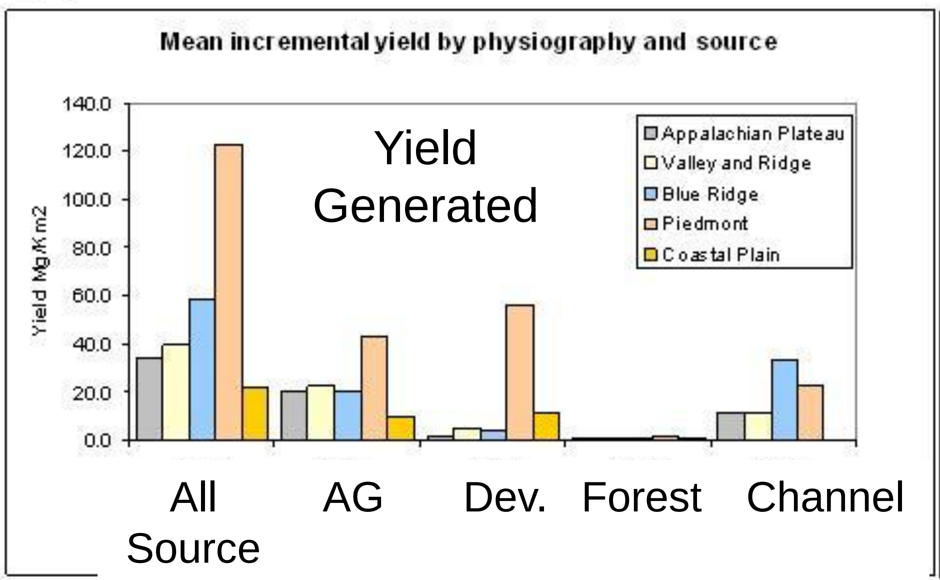

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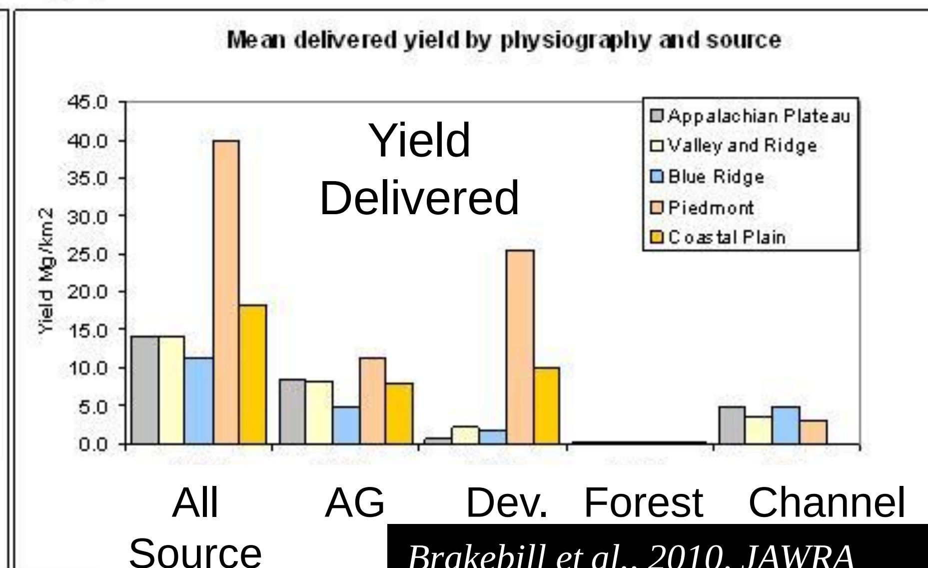


Brakebill et al., 2010, JAWRA

Delivery to the Bay

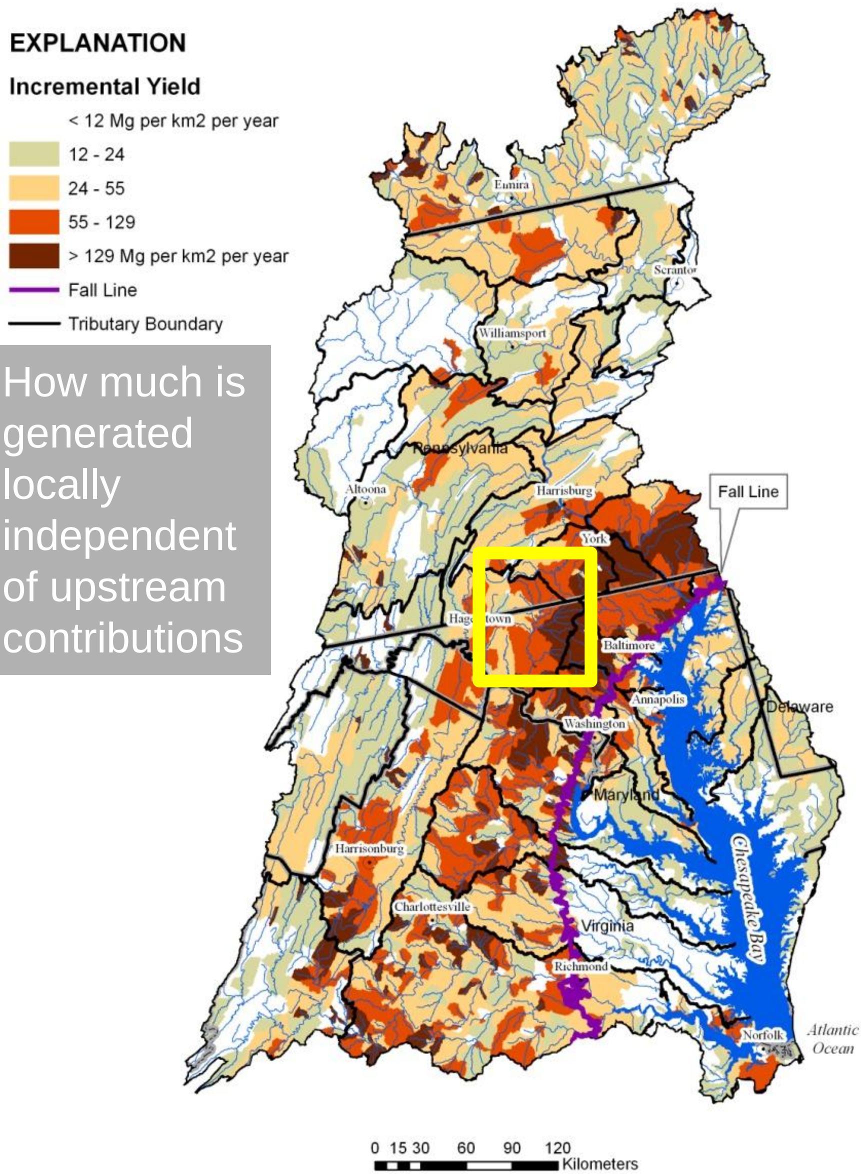
Sediment Source Distribution

- Quantified amounts of each sediment source transported to the Bay
- Can be quantified and mapped at any location on the network

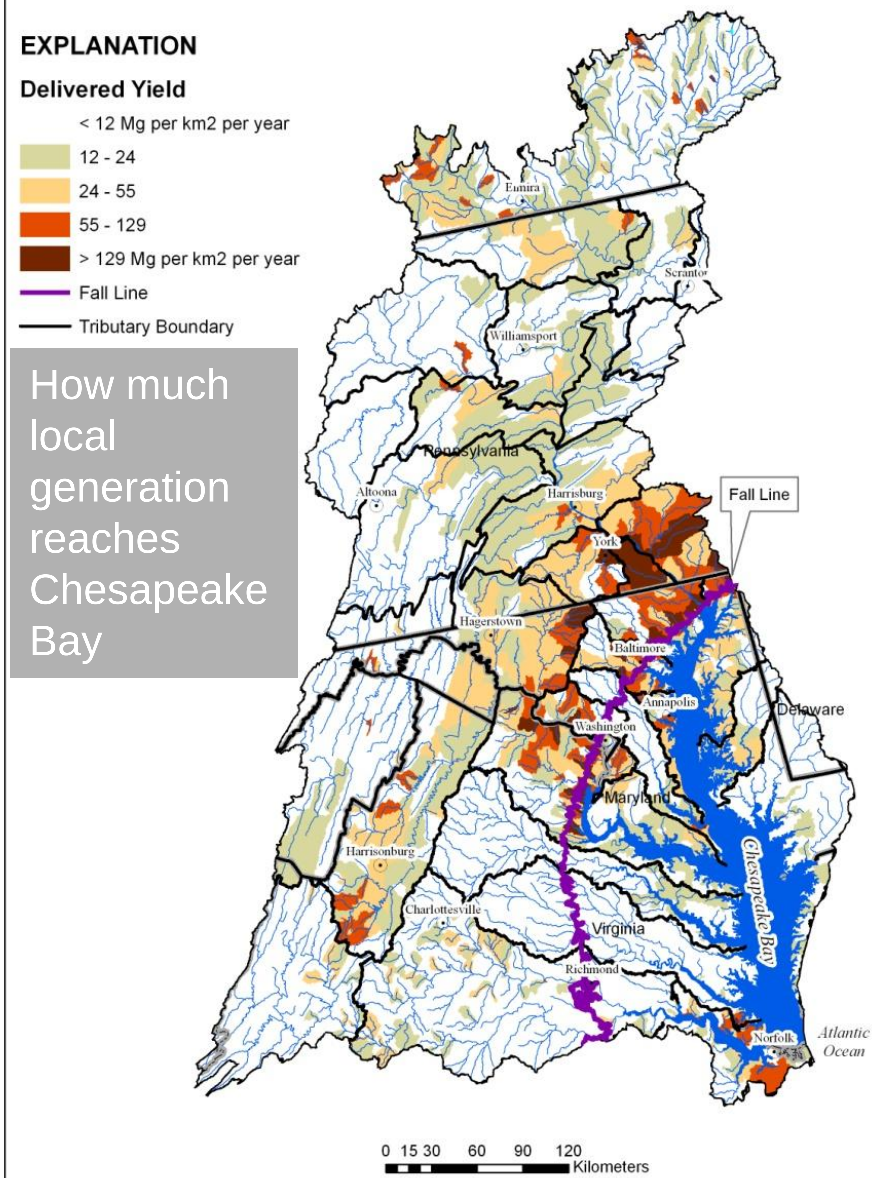
Source	Flux (10^6 Mg/year)	
Agriculture	51%	1.50
Urban Development	39%	1.16
Forest	08%	0.25
Small Streams	02%	0.05
TOTAL		2.96

Brakebill et al., 2010, JAWRA

Applications – Geographic targeting



How much is generated locally independent of upstream contributions



How much local generation reaches Chesapeake Bay

Incremental Yield

Modified from Brakebill et al., 2010, JAWRA

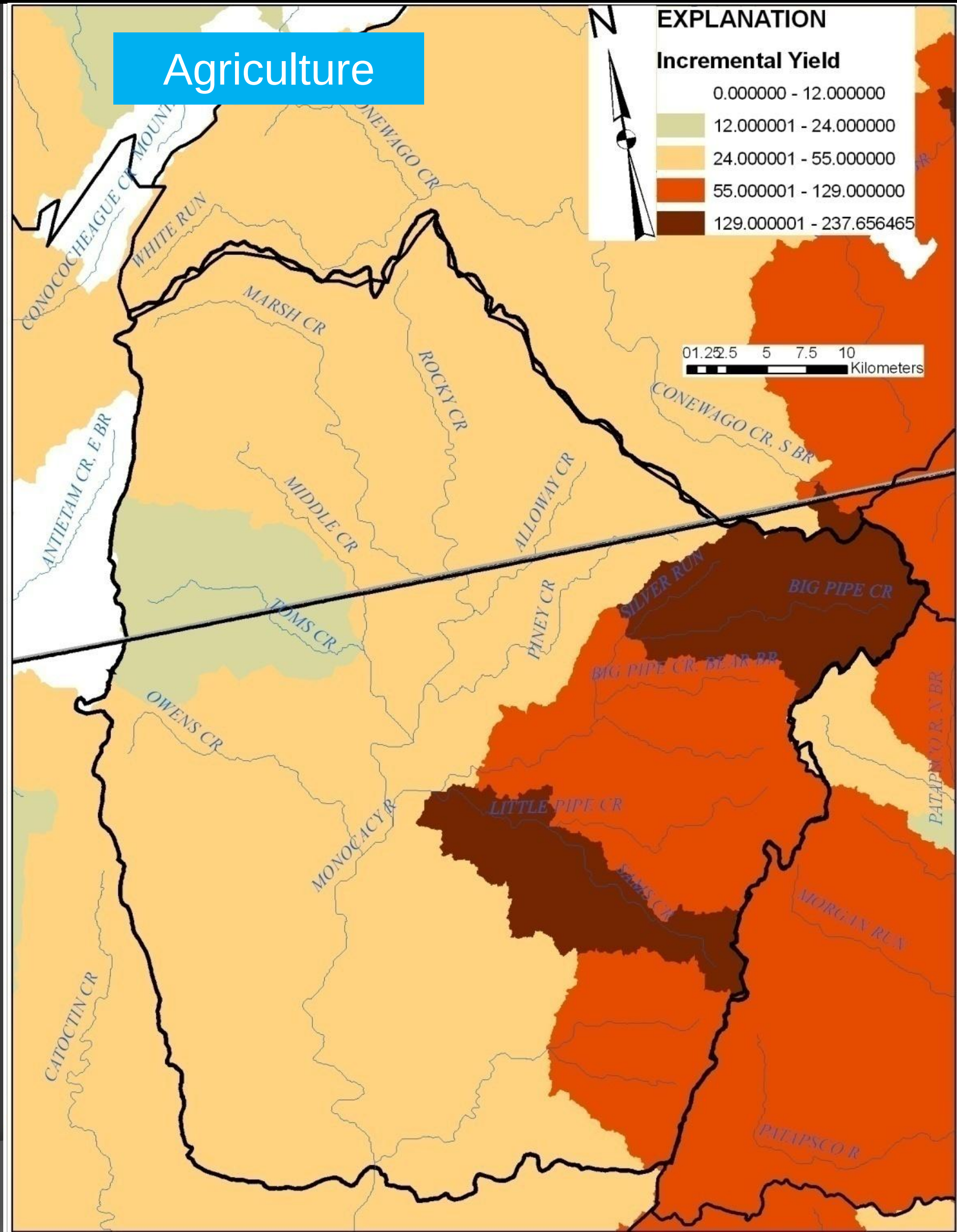
Delivered Yield

Applications – Geographic targeting

Additional information required?

- Ability to look at each source individually
  - Is sediment yield related to urbanization?
  - Is sediment yield related to agriculture?
- Other sources?
- Other factors?

Upper Monocacy River Basin



Applications

- Applying the SPARROW model provides the ability to gain a regional understanding of contaminant supply, fate, and transport within the Chesapeake Bay watershed
  - The SPARROW model demonstrates reasonable relations between the response variable (long-term water-quality conditions) and selected exploratory data representing supply, transport, and storage (Model diagnostics).
- Model evaluations and predictions are directly applicable to nutrient and sediment management in watersheds of estuaries like Chesapeake Bay:
  - Identifying individual source contributions and their relative importance
  - Identifying important transport factors and their relative importance
  - Quantifying relative amounts of sediment generated and transported to Chesapeake Bay
  - Enhanced geographic targeting tool for further study, additional monitoring, or prioritizing management actions for a variety of sources and settings
- Seeking out and working with State and Local agencies to better provide information suited for their needs

Information

- 2002 North East Nitrogen and Phosphorus SPARROW models
  - September. 2011
  - 1:100,000 scale
  - JAWRA
  - Online tool (DSS) for customized mapping and reporting of SPARROW results and scenario testing
- 2002 Chesapeake Bay Nitrogen and Phosphorus SPARROW models
  - Last quarter, 2011
  - 1:100,000 scale
  - USGS SIR Report (including predictions)
  - Also available in DSS (soon after publication) for customized mapping and reporting of SPARROW results and scenario testing
- 2002 Chesapeake Bay Suspended Sediment model – Published
  - 1:500,000 scale
  - JAWRA
  - http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2010.00450.x/abstract

Thank You

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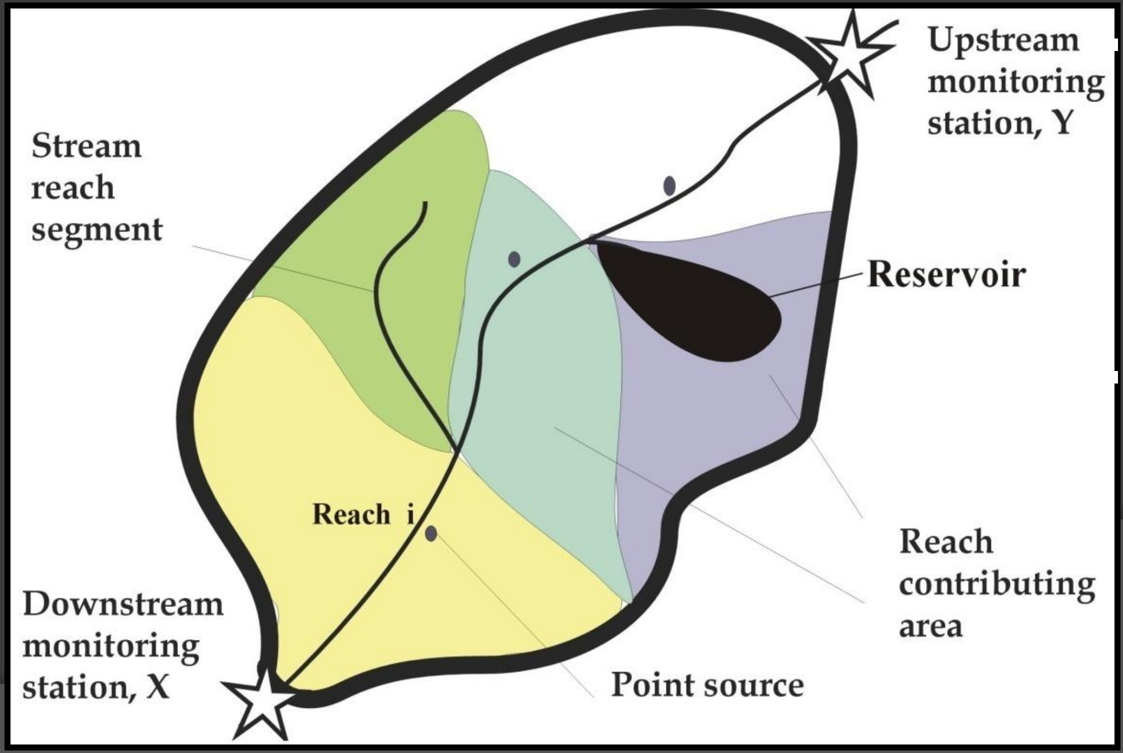
SPARROW Mass-Balance Model

Nonlinear regression

$$\text{Load}_i = \left\{ \sum_{j \in J(i)} \left[\sum_{n=1}^{N} S_{n,j} \underbrace{\beta_n \exp(-\alpha' Z_j)} \right] \underbrace{\exp(-\delta' T_{i,j})} \right\} \underbrace{\exp(\epsilon_i)}$$

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

- Source
- Delivery
- Decay/storage
  - in-stream
  - reservoir
- Monitoring



- Nonlinear model structure includes topography and water routing; provides separation of land and water processes
- Steady-state, mass-balance structure gives improved interpretability of the model coefficients and predictions

Schwarz et al., 2006

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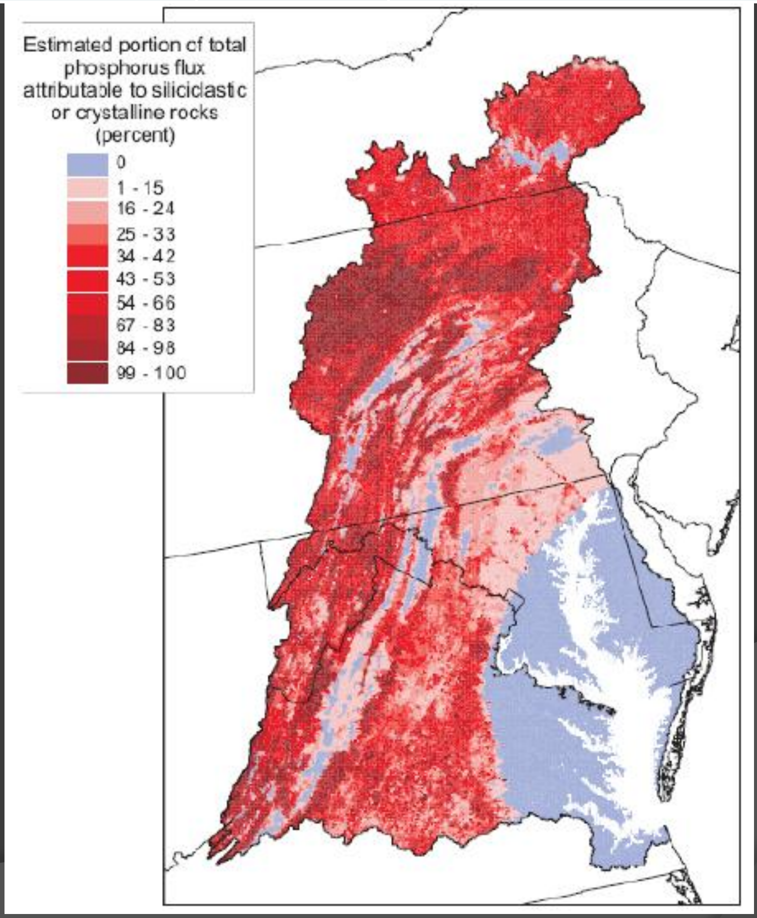
Phosphorus

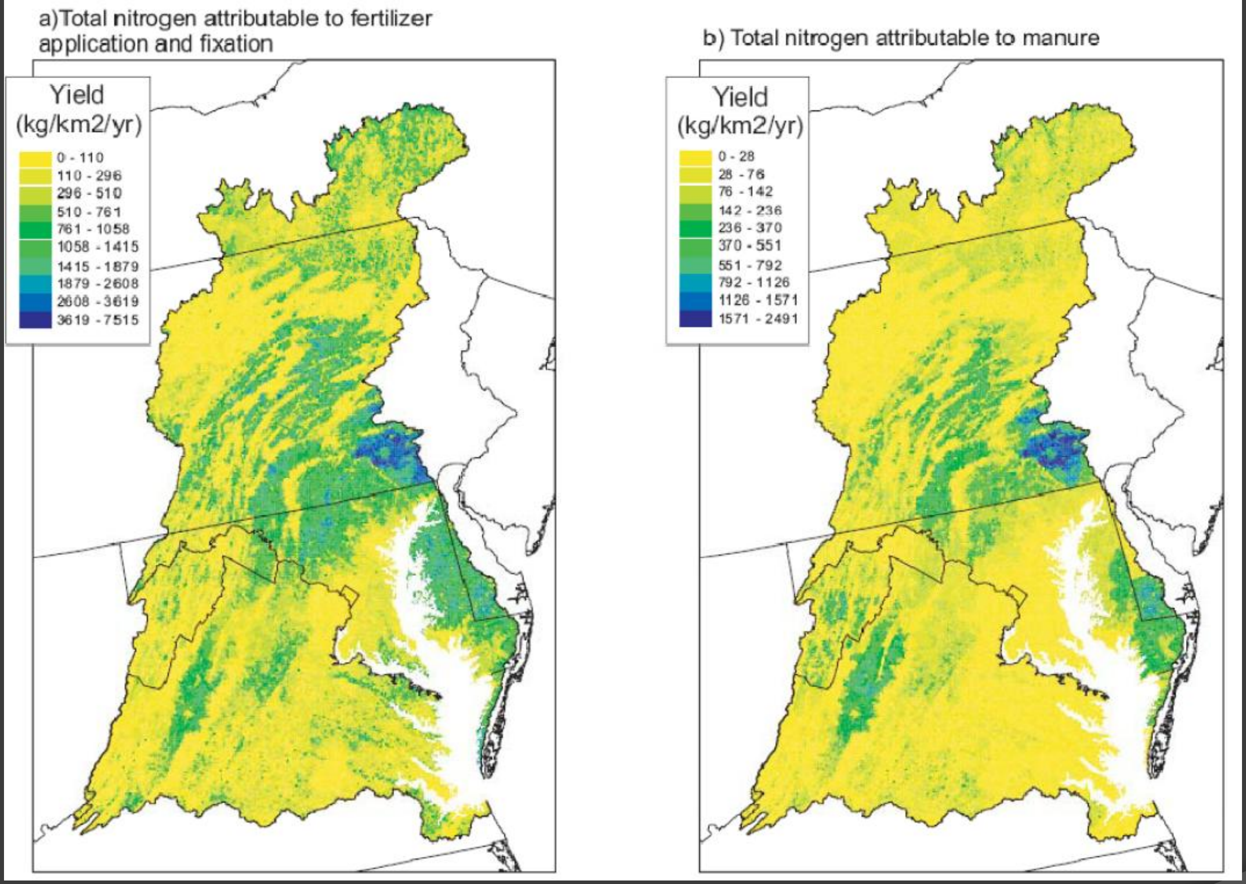
- Denver et al. (2010) suggested crystalline and siliciclastic rocks may represent a natural mineral P source:
  - Alkili-feldpars
  - Fluor-apatite
  - Fe-hydroxides
- Model coefficients generally agree with previous estimates of P yields
- Natural mineral sources dominate TP yields over large areas

Estimated Yield (kg/km^2/yr)

Rock	Bay Model	Ontario (Dillon and Kirchner, 1975)
Crystalline	6.8	4.8
Siliciclastic	8.5	10.7



Nitrogen



- Nitrogen yields from agricultural sources are greatest in the Lancaster, PA area