Lateral Transfers of Carbon from Terrestrial Watersheds to the Oceans From Rivers & Groundwaters

Beth Boyer (PSU), **Richard Alexander** (USGS), **Joe Needoba** (OHSU), and **Richard Smith** (USGS)

with contributions many others to be acknowledged herein.

quantifying lateral fluxes & coastal carbon

- Overview (Beth Boyer)
- Insights From the West Coast synthesis (Joe Needoba)
- Insights From the Gulf of Mexico Synthesis (Beth Boyer)
- Advances in Understanding Lateral Carbon Fluxes: Continued Development of SPARROW models (Rich Alexander)
- Advances in Understanding Lateral Carbon Fluxes: Insights from the USGS LandCarbon Program (Dick Smith)
- Toward Understanding Groundwater as a Vector for Delivery of Carbon to (& from) Coastal Waters (Beth Boyer)

Quantifying Lateral Carbon Fluxes & Future Needs: Insights From the West Coast synthesis

Joe Needoba, with contributions from Miguel Goni

Terrestrial Carbon Fluxes (West Coast)

- POC, DOC, DIC in rivers
- Pacific Northwest and Northern California – Fraser, Columbia, small mountainous rivers
- Central California –Sacramento, San Joaquin river (San Francisco Bay), Salinas (Monterey Bay), Small mountainous rivers

Data Sources/Access

- Published papers
- Environment Canada/Department of Fisheries and Oceans
- United States Geological Survey (NAWQA and NASQAN)
- Global Carbon Project
- Observation Networks (NANOOS)

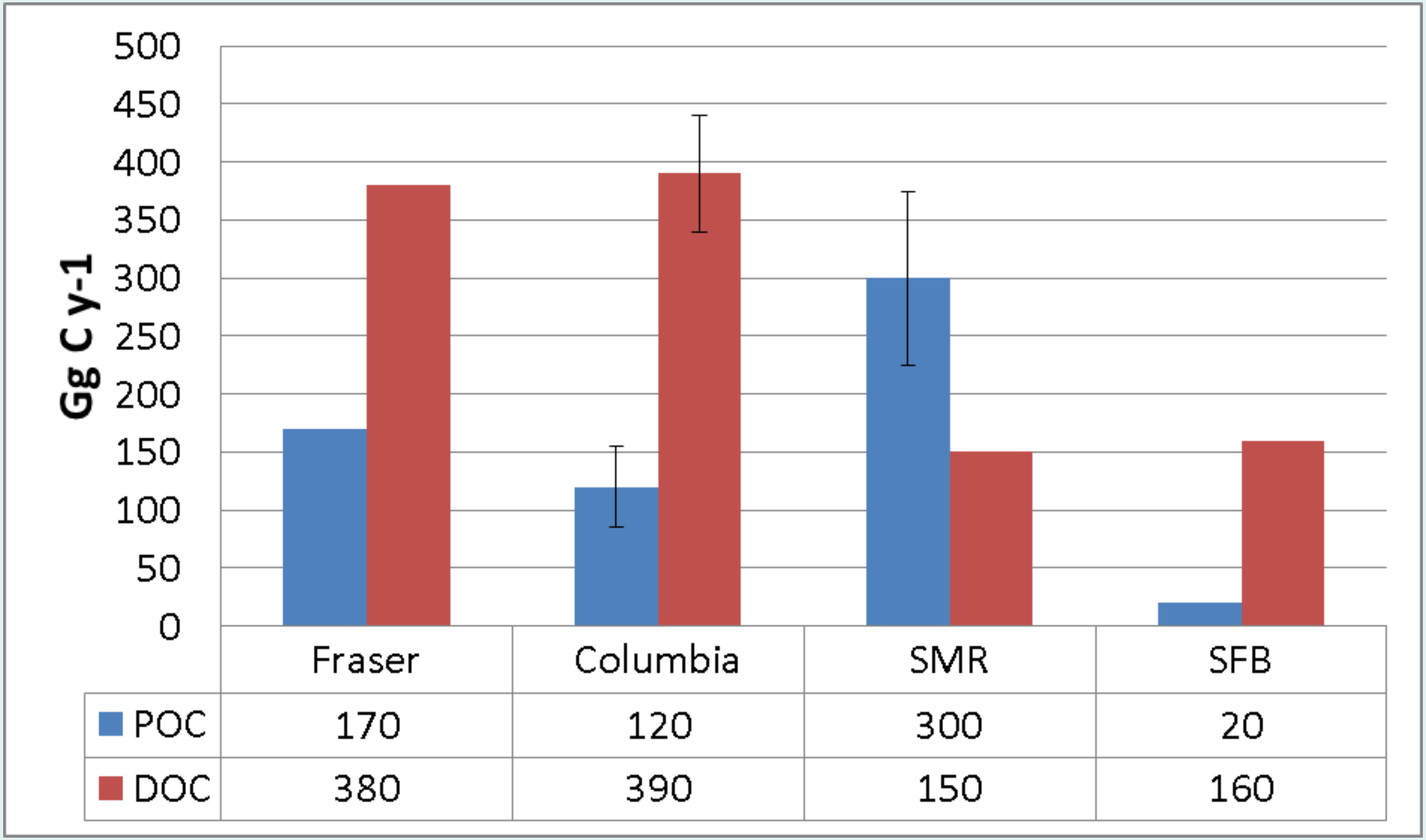
POC Flux

- Fraser: 170 x 10^9 g C y^{-1}
- SoG SMR: 50 x 10^9 g C y^{-1}
- SoG anthropogenic: 34 x 10^9 g C y^{-1}
- Puget Sound: ?
- Columbia: 120 x 10^9 g C y^{-1}
- US SMR: 100 - 400 x 10^9 g C y^{-1}
- Sacramento/San Joaquin: 20 x 10^9 g C y^{-1}

DOC Flux

- Fraser: 380 x 10^9 g C y^{-1}.
- SoG SMR: 150 x 10^9 g C y^{-1}.
- SoG anthropogenic: 80 x 10^9 g C y^{-1}.
- Puget Sound: ?
- Columbia: 390 x 10^9 g C y^{-1}
- US SMR: ?
- Sacramento/San Joaquin 160 X 10^9 g C y^{-1}

Organic Fluxes



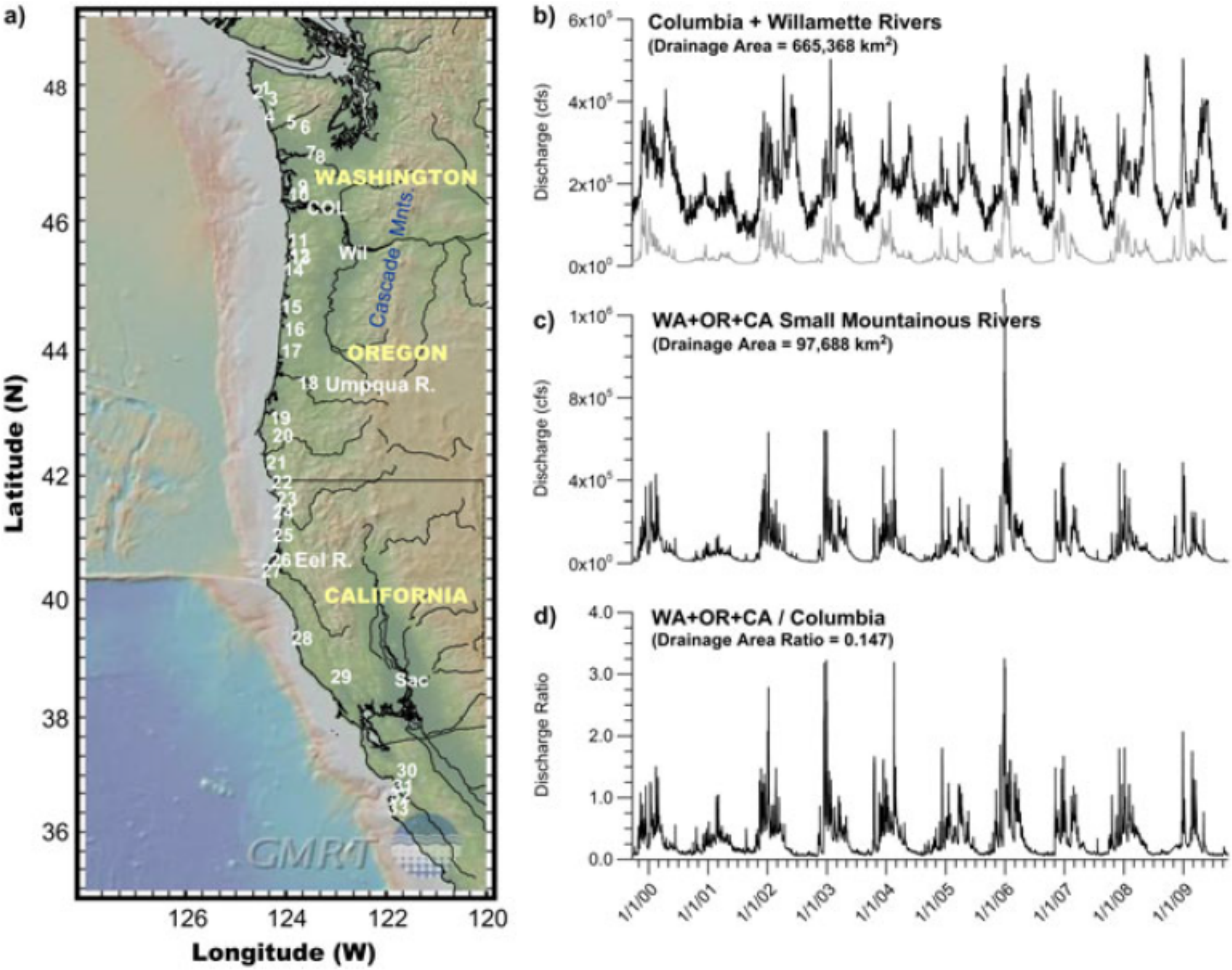
Discussion points

- SMRs transport a majority of POC during episodic storm events. Fluxes are rarely measured during events. Inter-annual variability can be large.

- Fluxes are relatively easy to estimate, but the fate at the coastal zone is much more difficult to quantify

- DOC may be preferentially transported to the coastal zone

- Sensor networks are beginning to collect long term records of relevant parameters


a)
Latitude (N)
Longitude (W)
WASHINGTON
OREGON
CALIFORNIA
Cascade Mnts.
COL
Wil
Umpqua R.
Eel R.
Sac
GMRT
b)
Columbia + Willamette Rivers
(Drainage Area = 665,368 km²)
Discharge (cfs)
c)
WA+OR+CA Small Mountainous Rivers
(Drainage Area = 97,688 km²)
d)
WA+OR+CA / Columbia
(Drainage Area Ratio = 0.147)
Discharge Ratio
1/1/00
1/1/01
1/1/02
1/1/03
1/1/04
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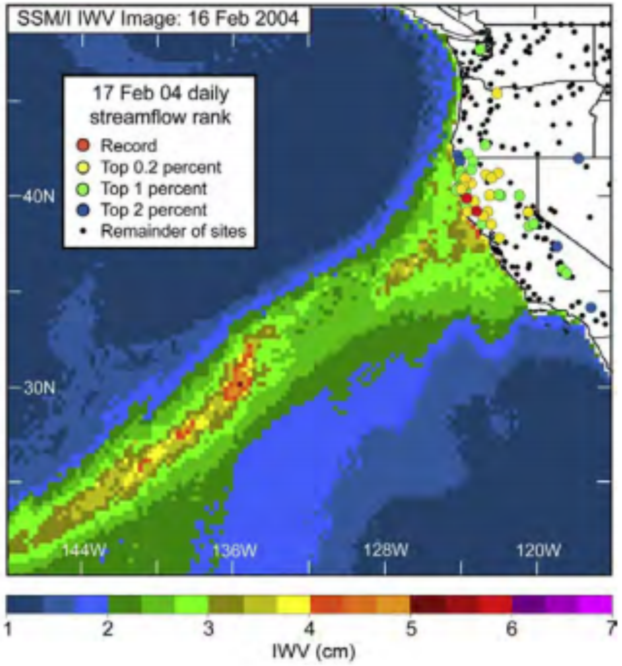
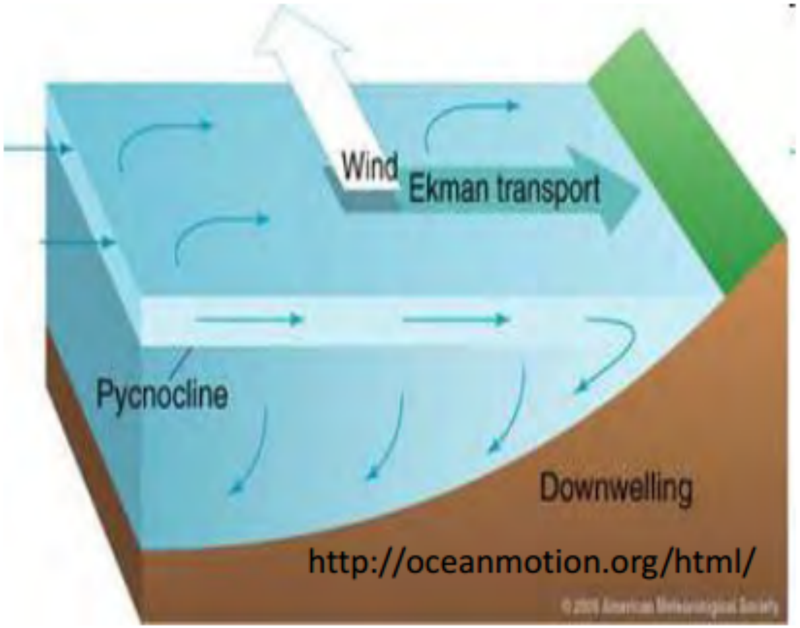
1/1/06
1/1/07
1/1/08
1/1/09



Less-Studied Wintertime Conditions:

- Prevailing southerly winds
- Storms systems from the southwest
- Interaction with coastal topography results in high precipitation and flooding by coastal rivers

*"**Atmospheric rivers**": narrow bands of enhanced water vapor and low-level winds*



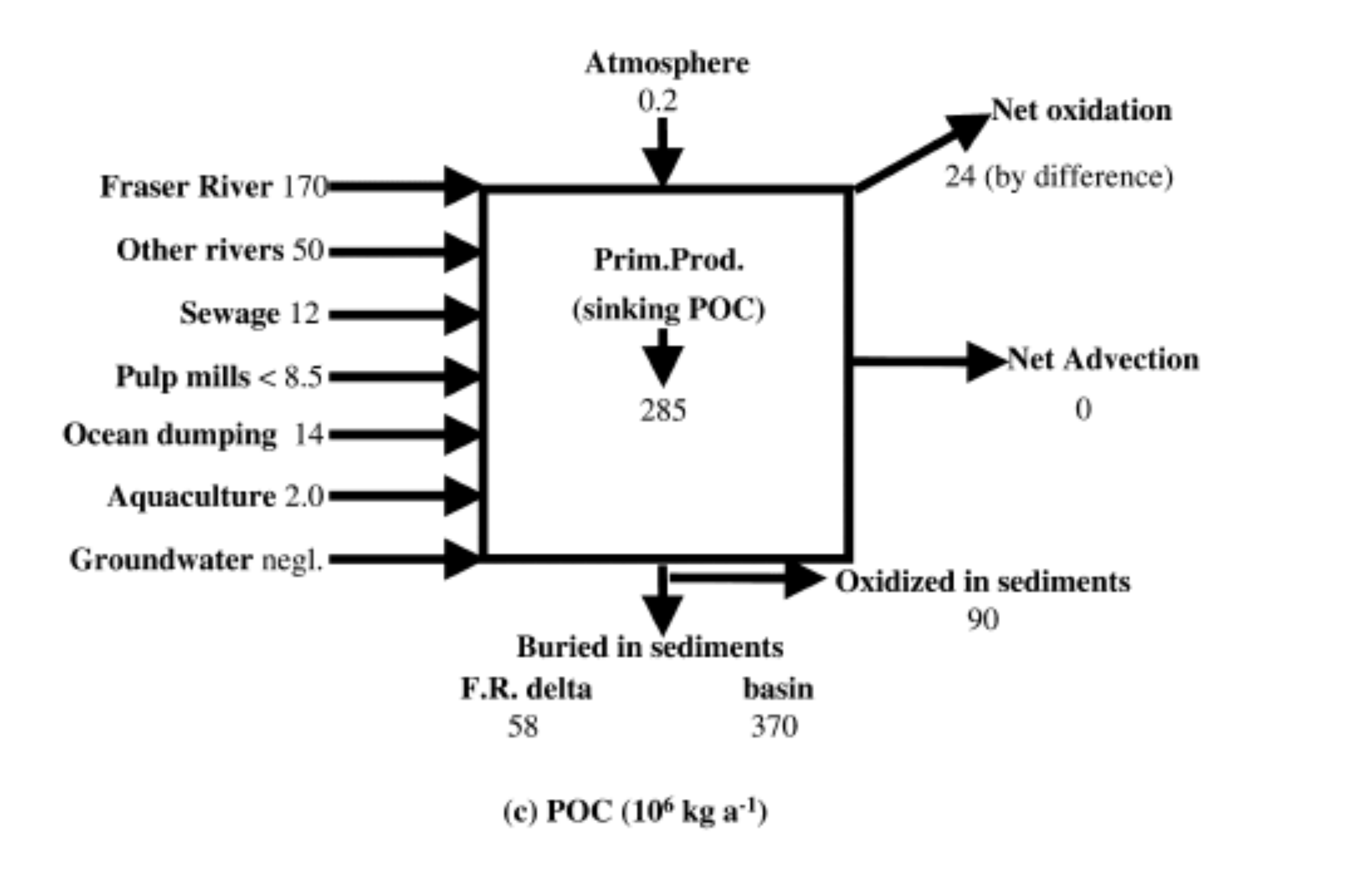
Downwelling-favorable winds and high waves facilitate

- trapping of freshwater inshore and
- offshore particle transport along benthic boundary layer

http://damp.coas.oregonstate.edu/coast/summary.shtml

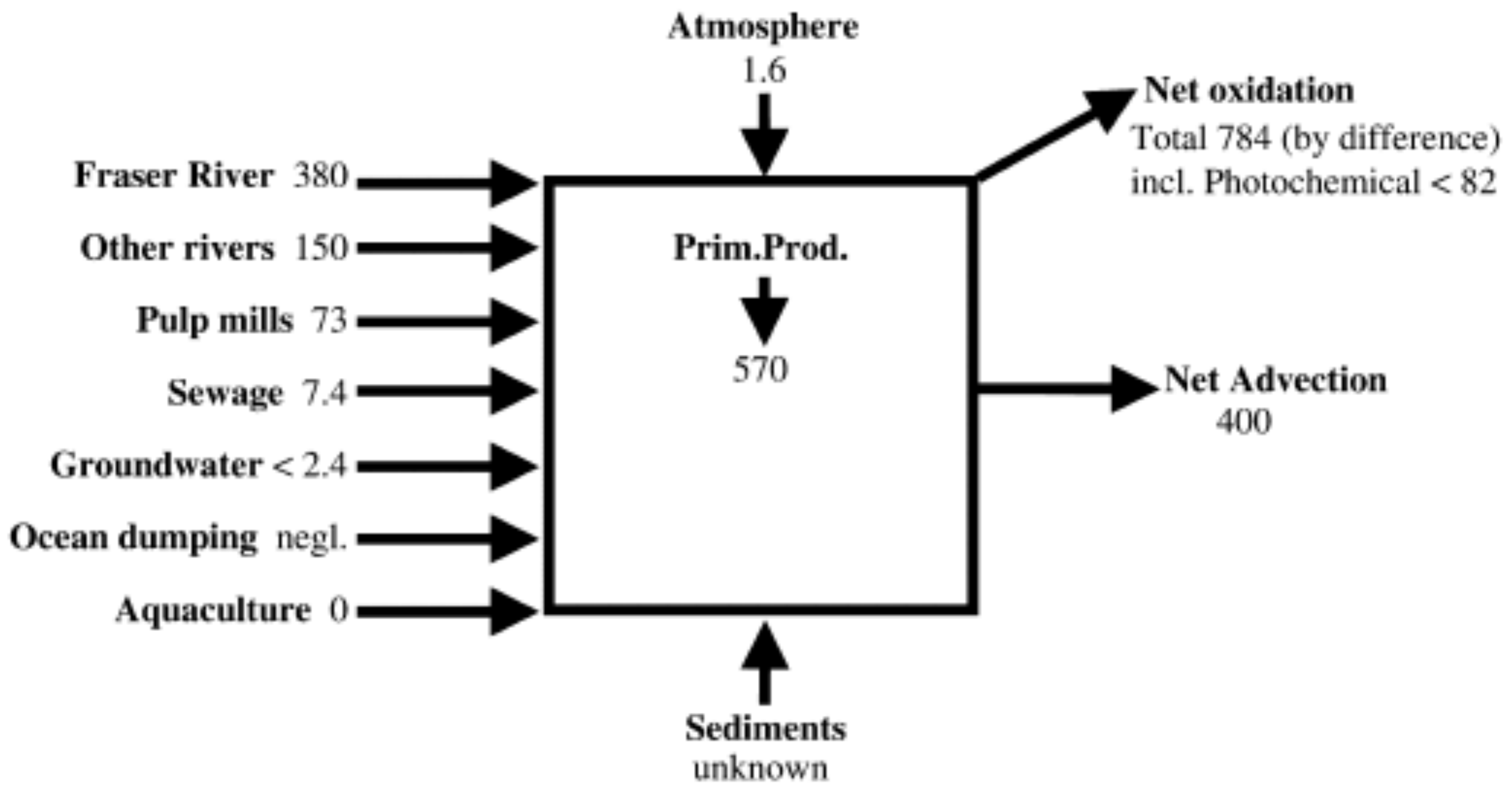
https://www.pices.int/publications/presentations/PICES-2013/2013-S4/S4-Day1-0905-Goni.pdf

Fate of POC in Strait of Georgia



Johannessen et al 2003

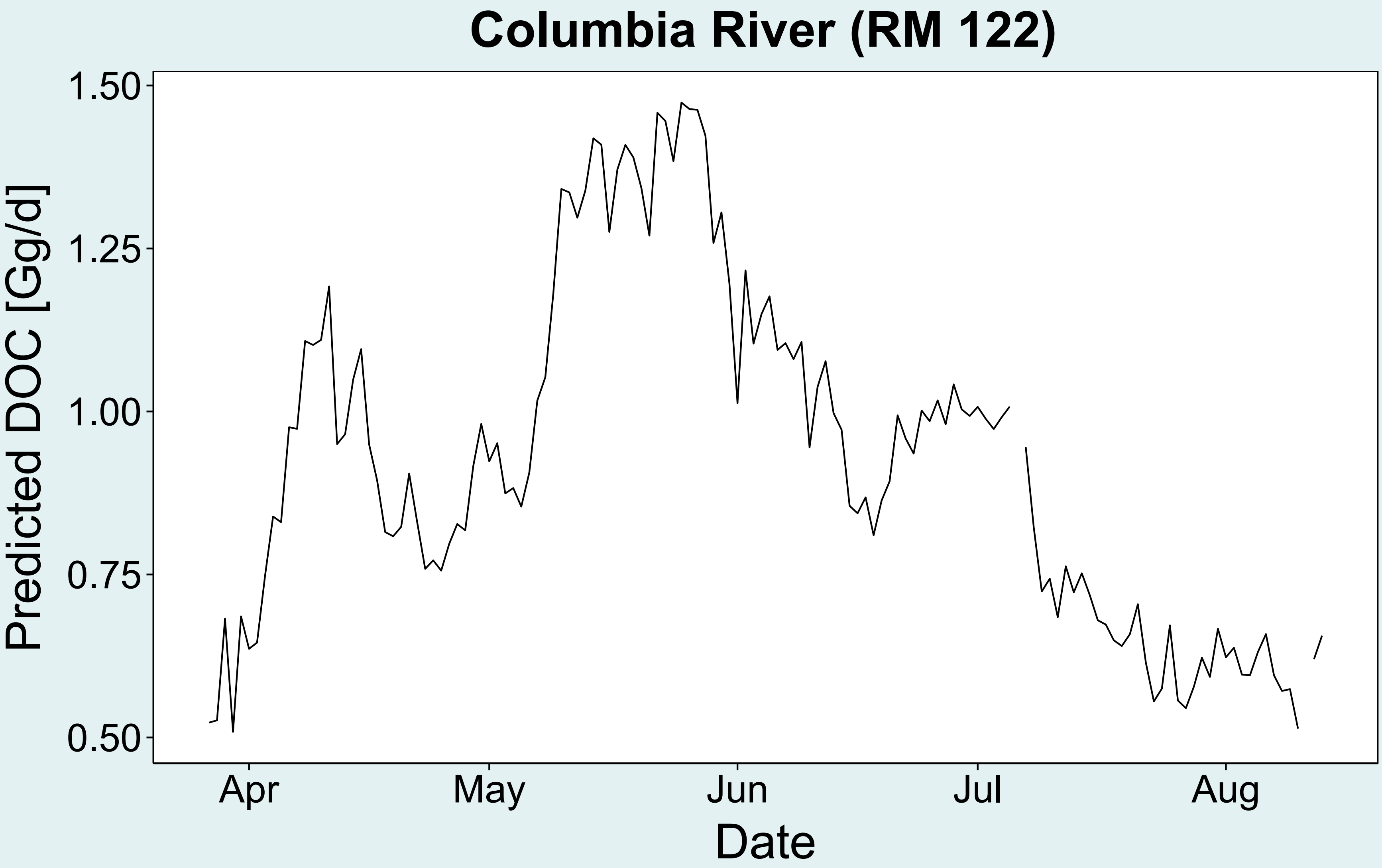
Fate of POC in Strait of Georgia



(d) DOC (10^6 kg a^{-1})

Johannessen et al 2003

Sensors are important for future studies of DOC fluxes



Urban J. Wünsch, Boris P. Koch, Mattihas Witt, Joseph A. Needoba, (in prep)

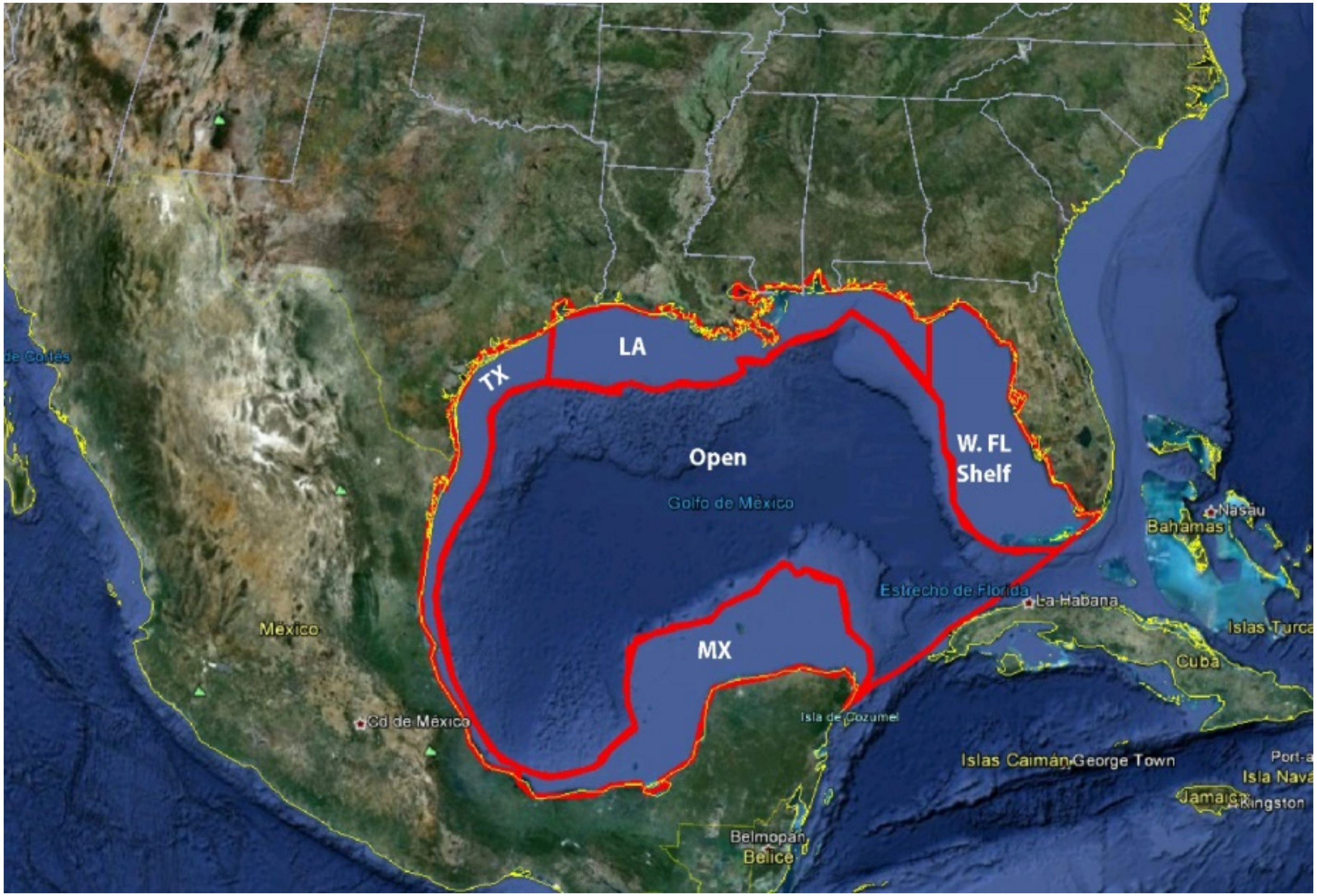
References

- Dahm, C.N., S.V. Gregory, P. Kilho Park (1983). Organic Carbon Transport in the Columbia River. Est. Coast. Shelf Sci. 13, 645-658
- Goni, M. A., J. A. Hatten, R. A. Wheatcroft, and J. C Borgeld (2013), Particulate organic matter export by two contrasting small mountainous rivers from the Pacific Northwest, U.S.A., J. Geophys. Res. Biogeosci., 118, 112–134, doi:10.1002/jgrg.20024.
- Jassby, A.D., J.E. Cloern, T.M. Powell. (1993). Organic carbon sources and sinks in San Francisco Bay: variability induced by river flow. Marine Ecology Progress Series. 95: 39-54
- Johannessen, S.C., R.W. Macdonald, D.W. Paton (2003) A sediment and organic carbon budget for the greater Strait of Georgia. Estuary Coastal and Shelf Science. 56: 845–860

Quantifying Lateral Carbon Fluxes & Future Needs: Insights From the Gulf of Mexico Synthesis

Beth Boyer, with contributions from Richard Alexander, David Butman, Paula Coble, Maria Hermann, Emilio Mayorga, Ray Najjar, Richard Smith, Ted Stets, Rob Striegel, Hanquin Tian, Others

Toward reliable terrestrial carbon flux estimates from rivers to GOM region



Observational Data – Load Estimation

- Stets, Striegel, et al. -- simulations of carbon at USGS gaging stations; *International Society of Limnology 2012*
- In GOM region, 38 stations have DIC data, and 30 have DOC data

Carbon export by rivers draining the conterminous United States

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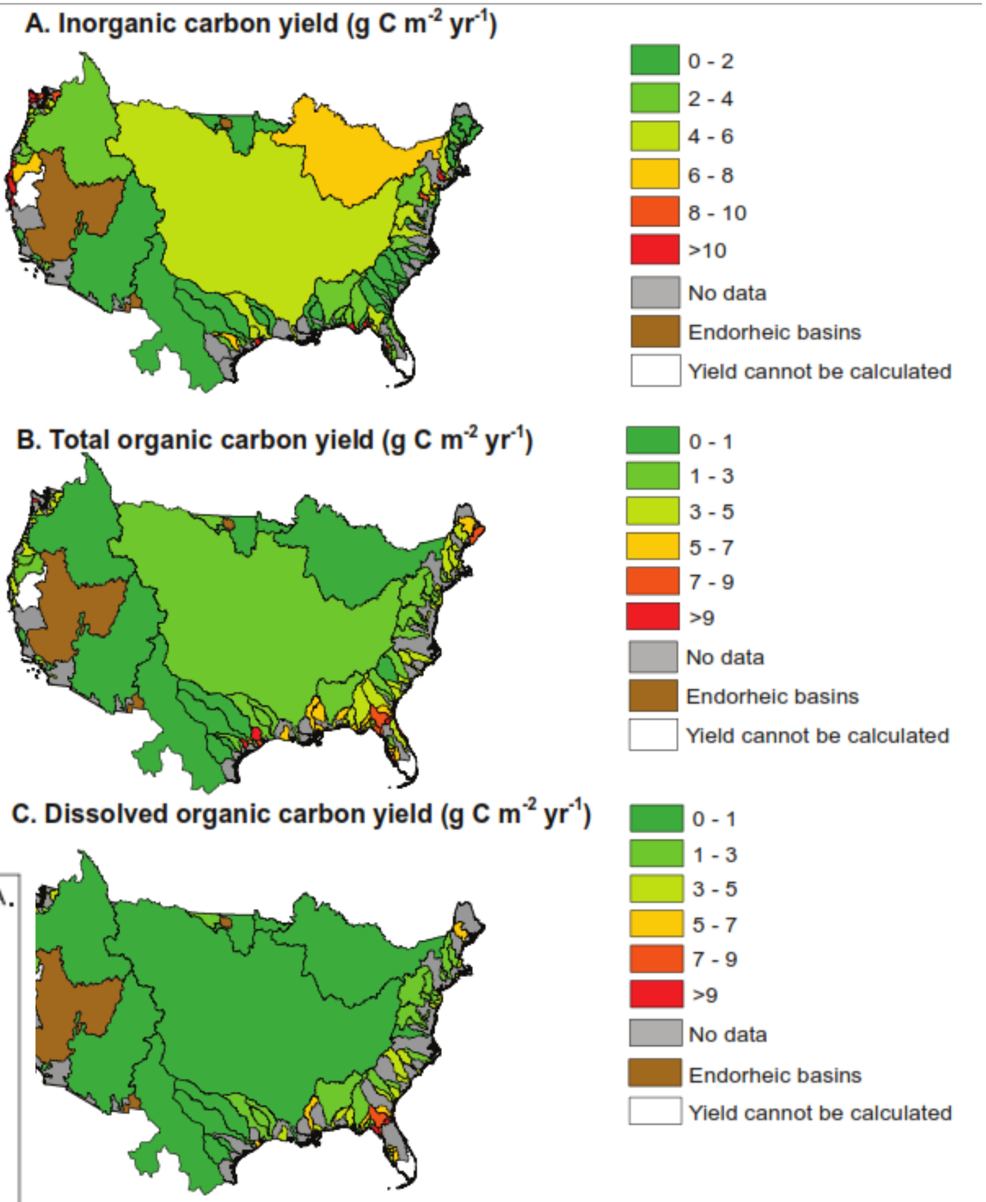
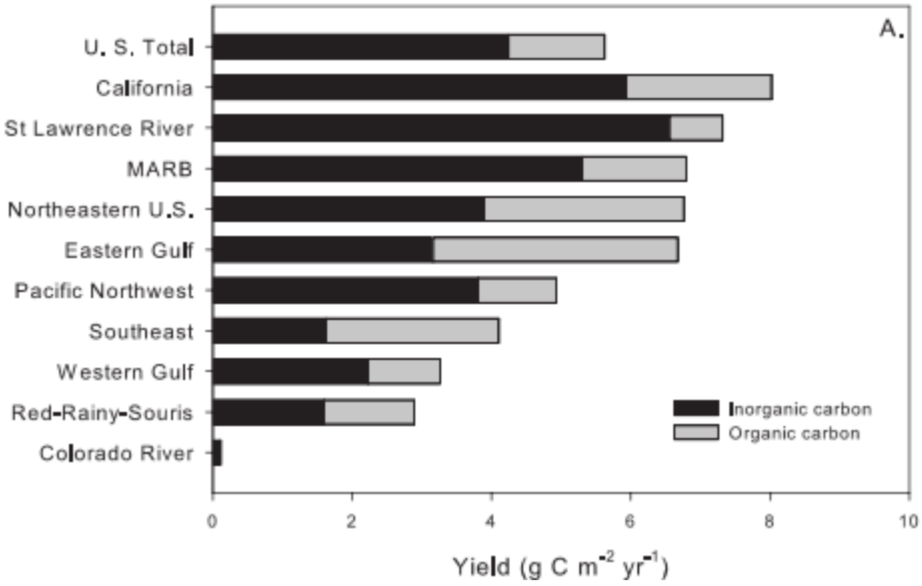
Abstract

Material exports by rivers, particularly carbon exports, provide insight to basin geology, weathering, and ecological processes within the basin. Accurate accounting of those exports is valuable to understanding present, past, and projected basin-wide changes in those processes. We calculated lateral export c
OC) from rivers draining the conterminous United States using stream gaging
100 rivers. Approximately 90% of land area and 80% of water export were incl
estimate using minor extrapolation. Total carbon export was 41–49 Tg C yr^{-1}.
OC export in every region except the southeastern Atlantic seaboard. The 10 la
66% of water export and carried 74 and 62% of IC and OC export, respectively
minous United States was 4.2 and 1.3 g C m^{-2} yr^{-1} for IC and OC, respecti
unexpected but is consistent with geologic models suggesting high weathering r
to the prevalence of easily weathered sedimentary rock.

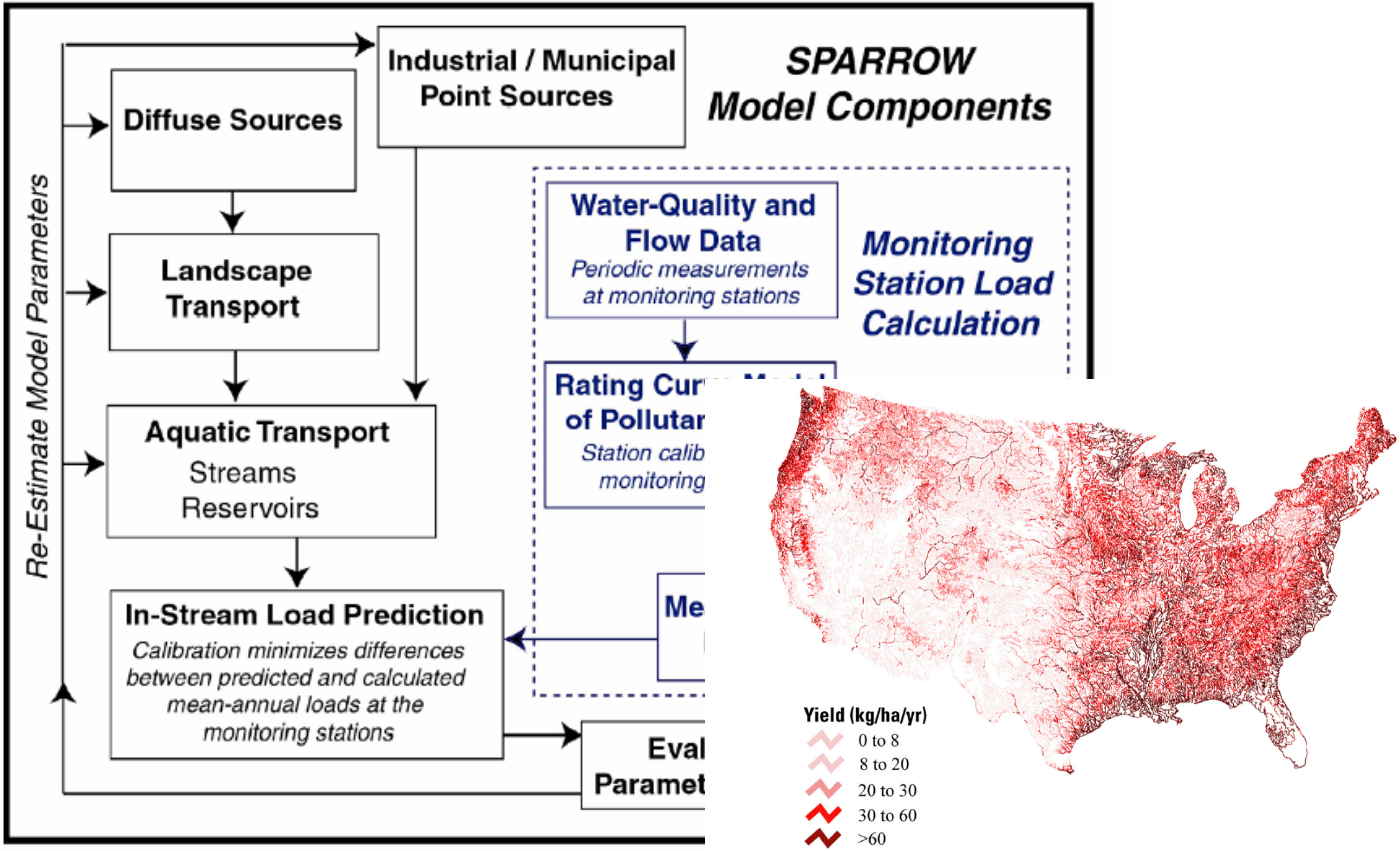
Key words: biogeochemistry, carbon cycle, inorganic carbon, load estima

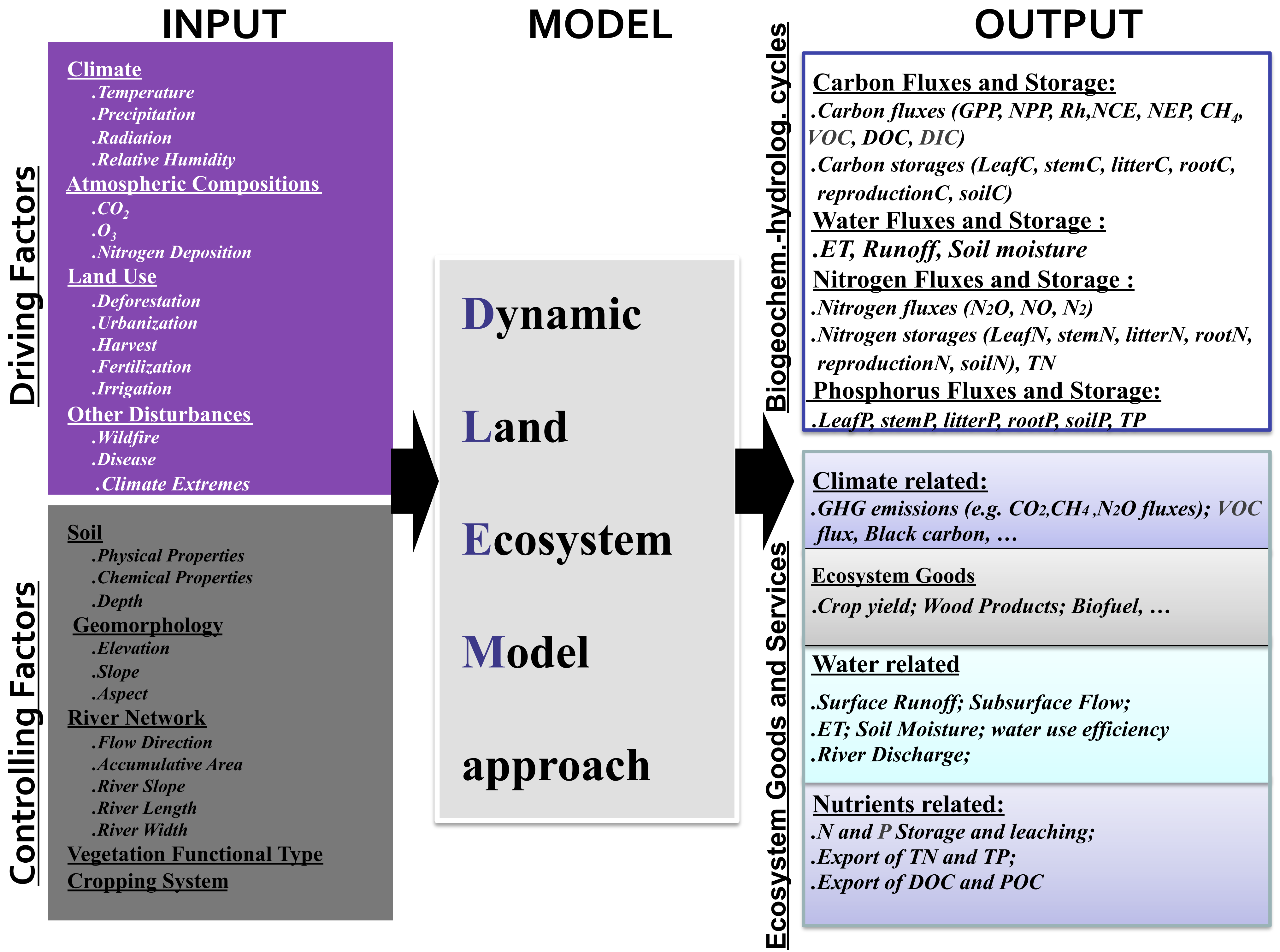
Stets et al. 2012



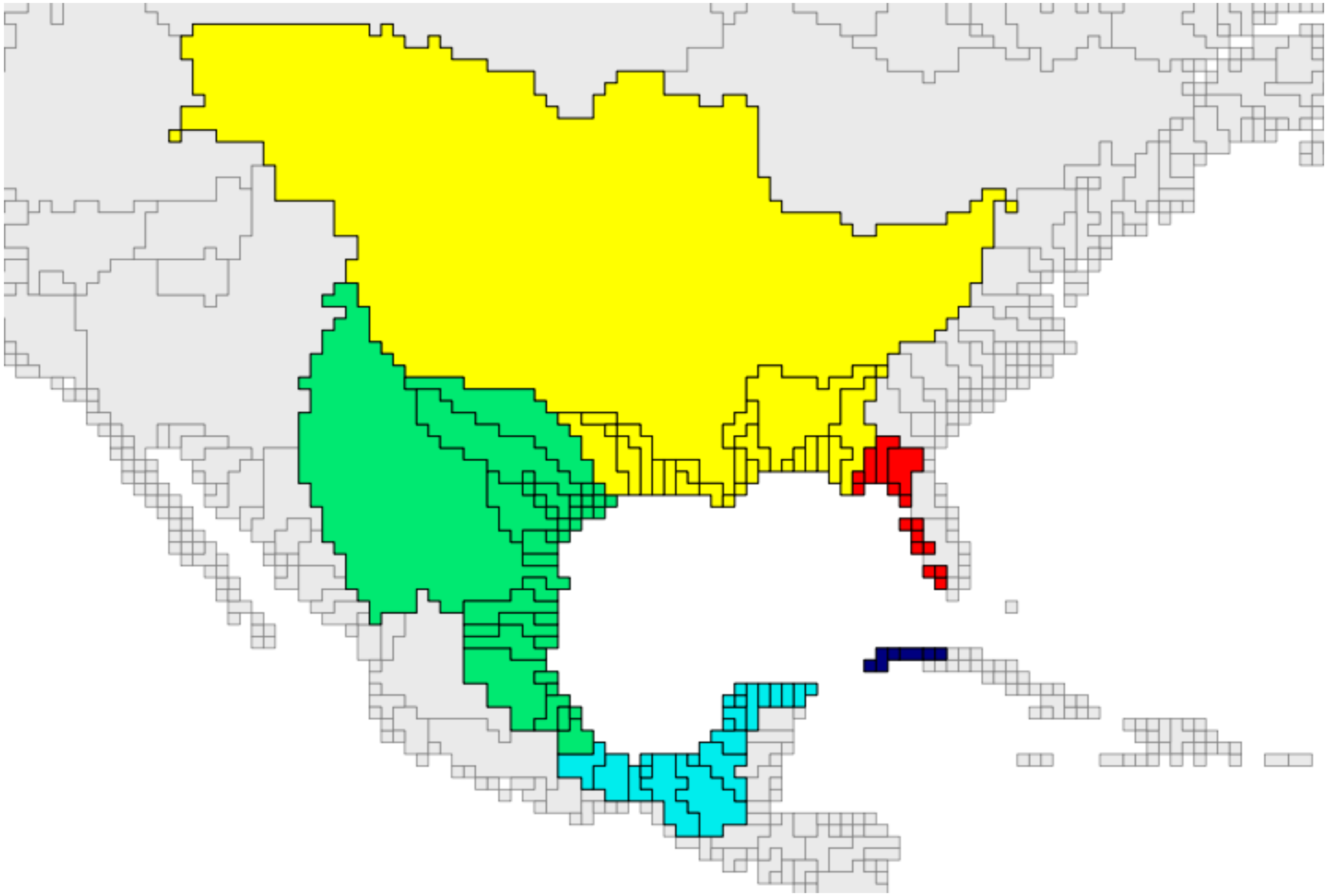


SPARROW modelling approach: Spatially referenced regression on watershed attributes




INPUT
MODEL
OUTPUT
Driving Factors
Climate
.Temperature
.Precipitation
.Radiation
.Relative Humidity
Atmospheric Compositions
.CO_2
.O_3
.Nitrogen Deposition
Land Use
.Deforestation
.Urbanization
.Harvest
.Fertilization
.Irrigation
Other Disturbances
.Wildfire
.Disease
.Climate Extremes
Controlling Factors
Soil
.Physical Properties
.Chemical Properties
.Depth
Geomorphology
.Elevation
.Slope
.Aspect
River Network
.Flow Direction
.Accumulative Area
.River Slope
.River Length
.River Width
Vegetation Functional Type
Cropping System
Dynamic
Land
Ecosystem
Model
approach
Biogeochem.-hydrolog. cycles
Carbon Fluxes and Storage:
.Carbon fluxes (GPP, NPP, Rh,NCE, NEP, CH_4, VOC, DOC, DIC)
.Carbon storages (LeafC, stemC, litterC, rootC, reproductionC, soilC)
Water Fluxes and Storage :
.ET, Runoff, Soil moisture
Nitrogen Fluxes and Storage :
.Nitrogen fluxes (N_2O, NO, N_2)
.Nitrogen storages (LeafN, stemN, litterN, rootN, reproductionN, soilN), TN
Phosphorus Fluxes and Storage:
.LeafP, stemP, litterP, rootP, soilP, TP
Ecosystem Goods and Services
Climate related:
.GHG emissions (e.g. CO_2,CH_4,N_2O fluxes); VOC flux, Black carbon, …
Ecosystem Goods
.Crop yield; Wood Products; Biofuel, …
Water related
.Surface Runoff; Subsurface Flow;
.ET; Soil Moisture; water use efficiency
.River Discharge;
Nutrients related:
.N and P Storage and leaching;
.Export of TN and TP;
.Export of DOC and POC

Global NEWS modeling approach
Global Nutrient Export from Watersheds



State-of-the GOM riverine exports

- Preliminary data for C exports to the GOM regions were shown from each approach (draft; do not cite).

- Will be discussed with coauthors at this meeting; refinements and decisions on which values to use in GOM report will be made.

State-of-the GOM riverine exports

- 1st estimates from load estimation methods are varying at monitoring locations
  - Different time series and regression calibration-estimation approaches used
  - Extrapolate watercourse fluxes to areal estimates
- 1st estimates from SPARROW, DLEM, NEWS2 approaches are limited
  - Wildly varying approaches.
  - Only some C-constituents and GOM regions have available simulation data to compare.

Preliminary data in prep., do not cite

Advances in Quantifying Lateral Carbon Fluxes: Continued Development of SPARROW models

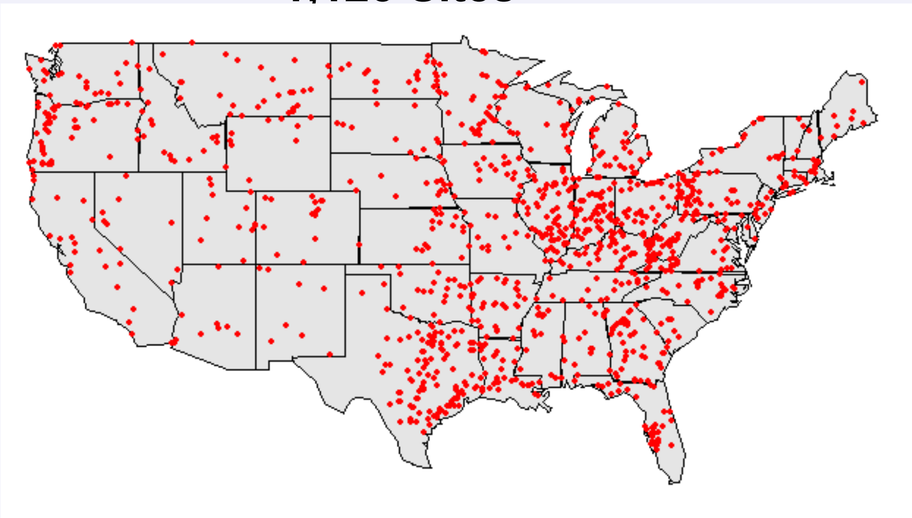
Richard Alexander, with contributions from Beth Boyer, Greg Schwarz, Jhih-Shyang Shih, Dick Smith

Terrestrial Fluxes: SPARROW Watershed Carbon Modeling Needs and Next Steps

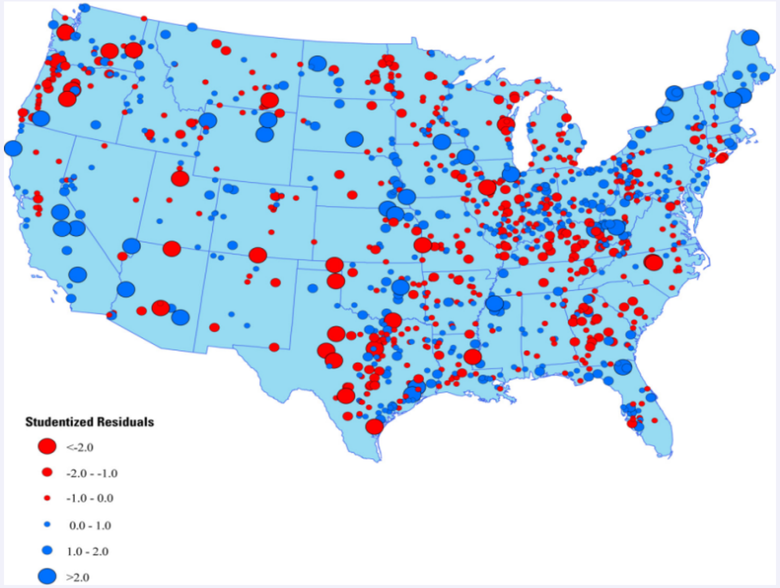
- TOC model (long-term mean conditions):
  - Existing model for conterminous USA: Shih et al. 2010
  - Extend river monitoring data retrievals beyond 2007
  - Eliminate sites operated prior to 1990s to reduce model prediction biases

National SPARROW TOC MODEL*

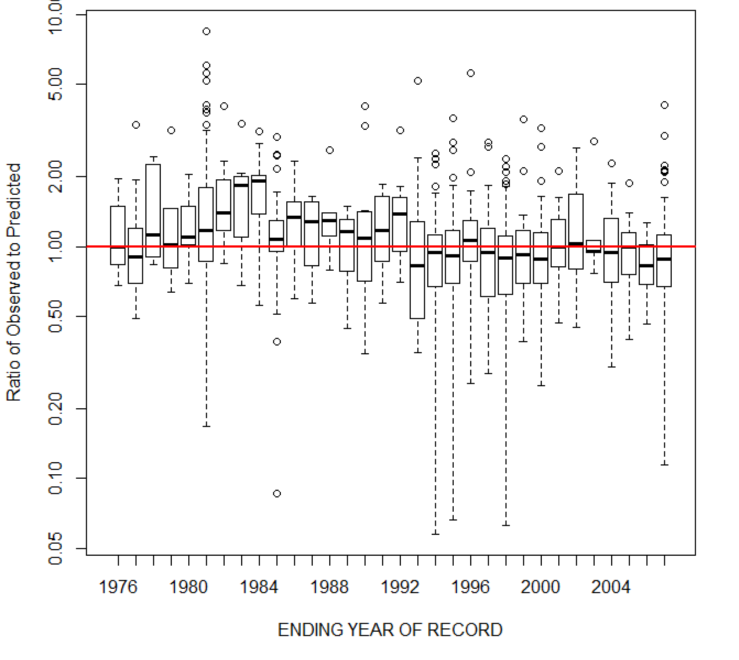
CALIBRATION SITES
1,125 Sites



MODEL ERRORS



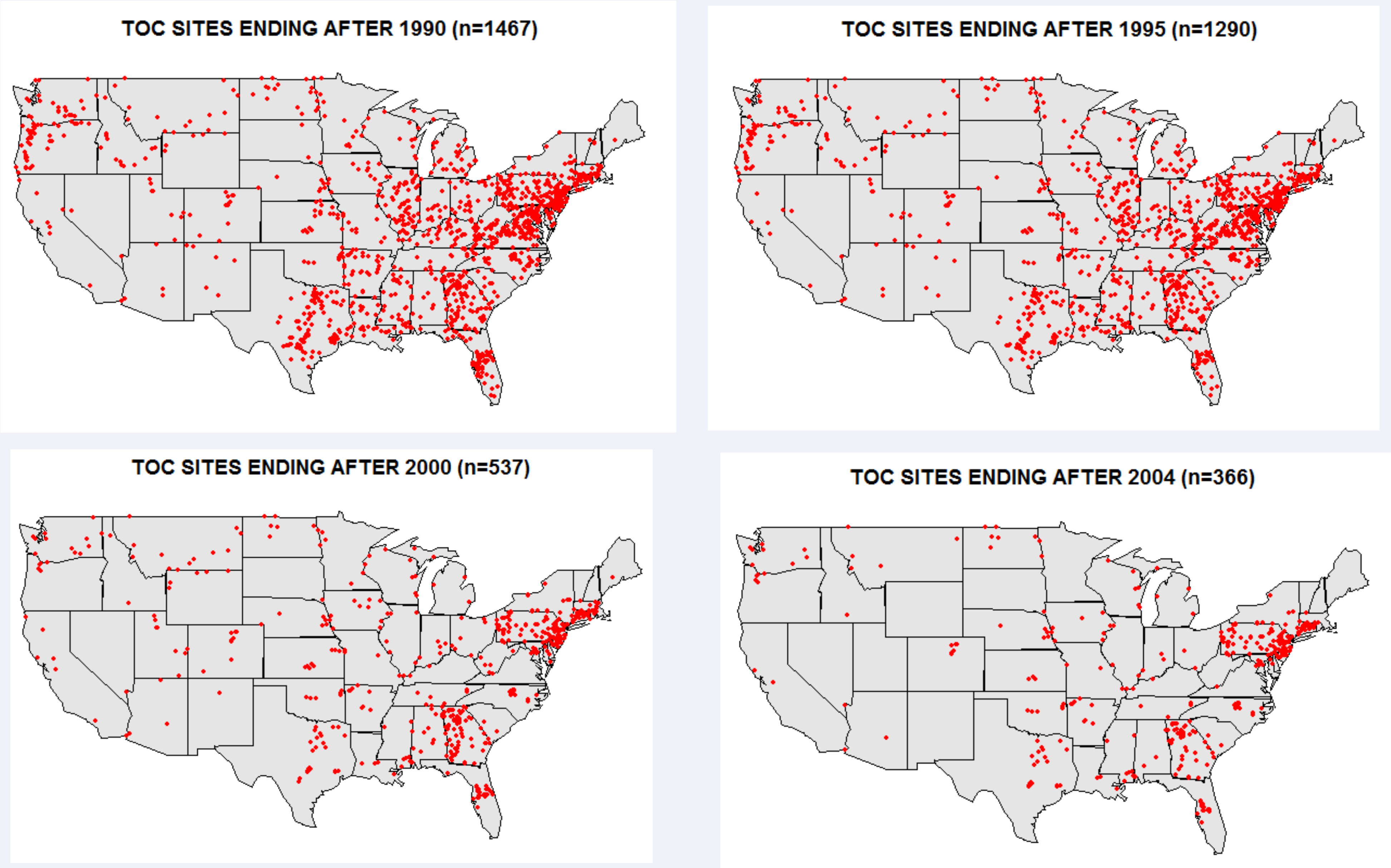
MODEL ERRORS



- Original model calibrated to 1,125 sites
- Under predictions (blue) commonly associated with sites with records ending before 1992
- An updated model will use sites with records beginning after ~1992
- TOC sites with sufficient record for loads have declined over time, with increased Eastern bias

* *Shih et al. 2010*

Decrease in River Monitoring Sites with Sufficient TOC Records for Load Estimation



Terrestrial Fluxes: SPARROW Watershed Carbon Modeling Needs and Next Steps

- TOC model (long-term mean conditions):
  - Extend river monitoring data retrievals beyond 2007
  - Eliminate sites operated prior to 1990s to reduce model prediction biases
  - Evaluate additional explanatory variables (e.g., NPP, soil organic C) and update land use data
  - Separate tidal and non-tidal wetlands (tidal 7x larger)
  - Improve model accuracy and interpretability using Bayesian estimation techniques
    - Supports spatially variable model parameters (e.g., wetlands, forests, streams); Process error estimation reduces prediction biases
- DOC model: river monitoring data limited; extrapolate TOC predictions from DOC/TOC ratios based on available records
- DIC model: not currently planned but needed

Development of Dynamic SPARROW TOC Model

Advantages:

1. Could model seasonal storage and lags in TOC (SPARROW TN models have done this.)
2. Could be driven by satellite GPP, linking terrestrial photosynthesis to aquatic TOC.
3. Aquatic photosynthesis would vary seasonally, driven by seasonal light and temperature.

Disadvantages:

1. More time and resources required (30%?) for data assembly and calibration.

Terrestrial Fluxes: SPARROW Watershed Modeling Needs and Next Steps

<u>Nutrients</u>

- River monitoring data – temporal and geographic coverage generally ok
- USGS river load estimation procedures being revised (of most importance for nitrate and TP)
- Regionally specific TN and TP models now exist (2002 base year); being updated to 2012
- National TN model (2002 base year) under development using Bayesian estimation

- nitrogen for seasonal conditions in selected watersheds (Potomac, Dynamic
- models developed South Carolina, Long Island Sound); developing linkages to ground water inputs (Potomac, Chesapeake)

<u>New Modeling Techniques and Constituents</u>

- Bayesian estimation: provides improved accuracy and interpretability
- Streamflow and water balance modeling: long-term mean and monthly conditions

Advances in Understanding Futures of Coastal Carbon Fluxes and Storages: Insights from the USGS LandCarbon Program

Dick Smith, with contributions from Brian Bergamaschi, Michael Sauer, Jhih-Shyang Shih

Chapter 6. Terrestrial Fluxes of Nutrients and Sediment to Coastal Waters and Their Effects on Coastal Carbon Storage in the Eastern United States

Brian A. Bergamaschi[1], Richard A. Smith[1], Michael J. Sauer[1], Jhih-Shyang Shih[2], and Lei Ji[1]

[1] USGS

[2] Resources for the Future

In *Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of the Eastern United States*, 2014, Zhiliang Zhu and Bradley Reed Eds, USGS Professional Paper 1804.

http://www.usgs.gov/climate_landuse/land_carbon/Publications.asp

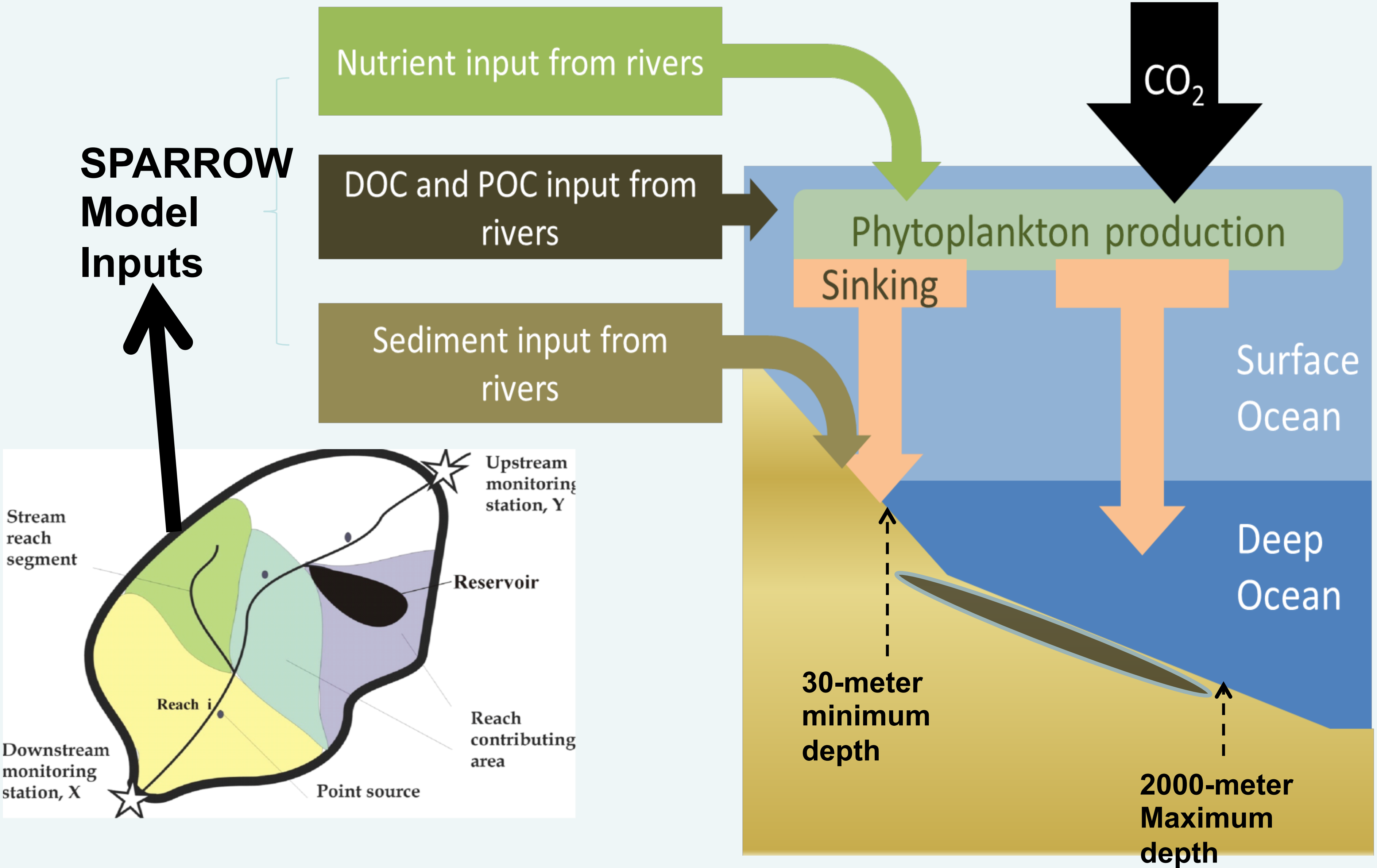
Objectives of USGS Land Carbon Assessment of Coastal Carbon Storage

1. Quantify lateral transport of TOC, sediment, nutrients from specific terrestrial sources to US coastal waters.

2. Estimate coastal carbon storage resulting from this transport.

3. Project the above for 2050 based on three IPCC scenarios for land use and population changes.

Integrated Modeling Procedure



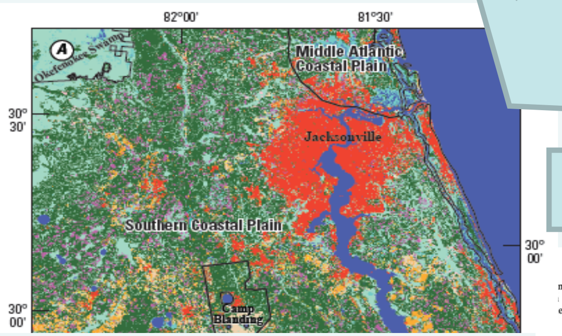
USGS LandCarbon Project

IPCC Scenarios – *DIFFER PRINCIPALLY IN MANAGEMENT OF NATURAL SYSTEMS*

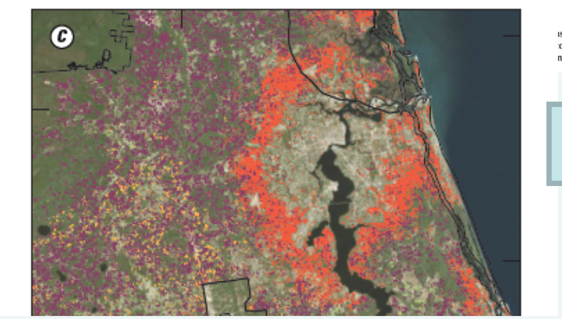
Table 2–1. Assumptions about the primary driving forces affecting land-use and land-cover change.

Driving forces	Scenario A1B	Scenario B1
Population growth (global and United States)	Medium; 8.7 billion by 2050, then declining; in the United States, 385 million by 2050	Medium; 8.7 billion by 2050, then declining; in the United States, 385 million by 2050
Economic growth in the United States	Very high; per capita income $72,531 by 2050	High; per capita income $59,880 by 2050
Regional or global orientation	Global	Global
Technological innovation	Rapid	Rapid
Energy sector	Balanced use	Smooth transition to renewable
Environmental protection	Active management	Protection of biodiversity

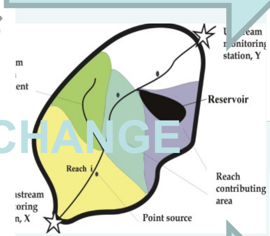
CURRENT LAND USE



PROJECTED LAND USE CHANGE

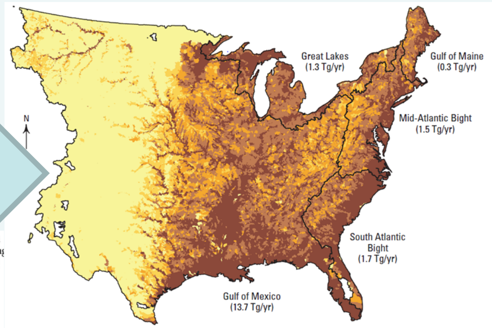


SPARROW

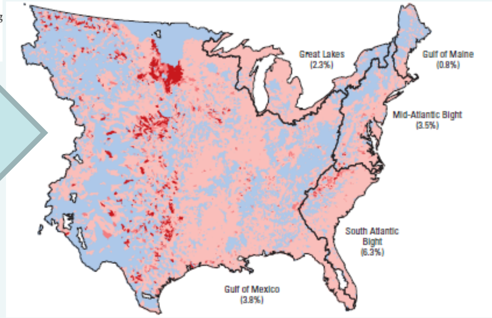


SPARROW

CURRENT YIELDS



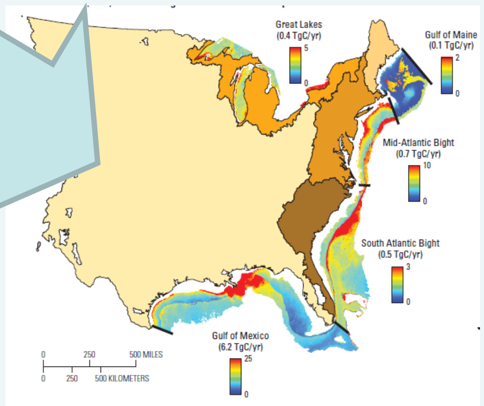
CHANGE IN YIELDS



MODELED CONSTITUENTS:

1) TOC
2) TN
3) TP
4) TSS

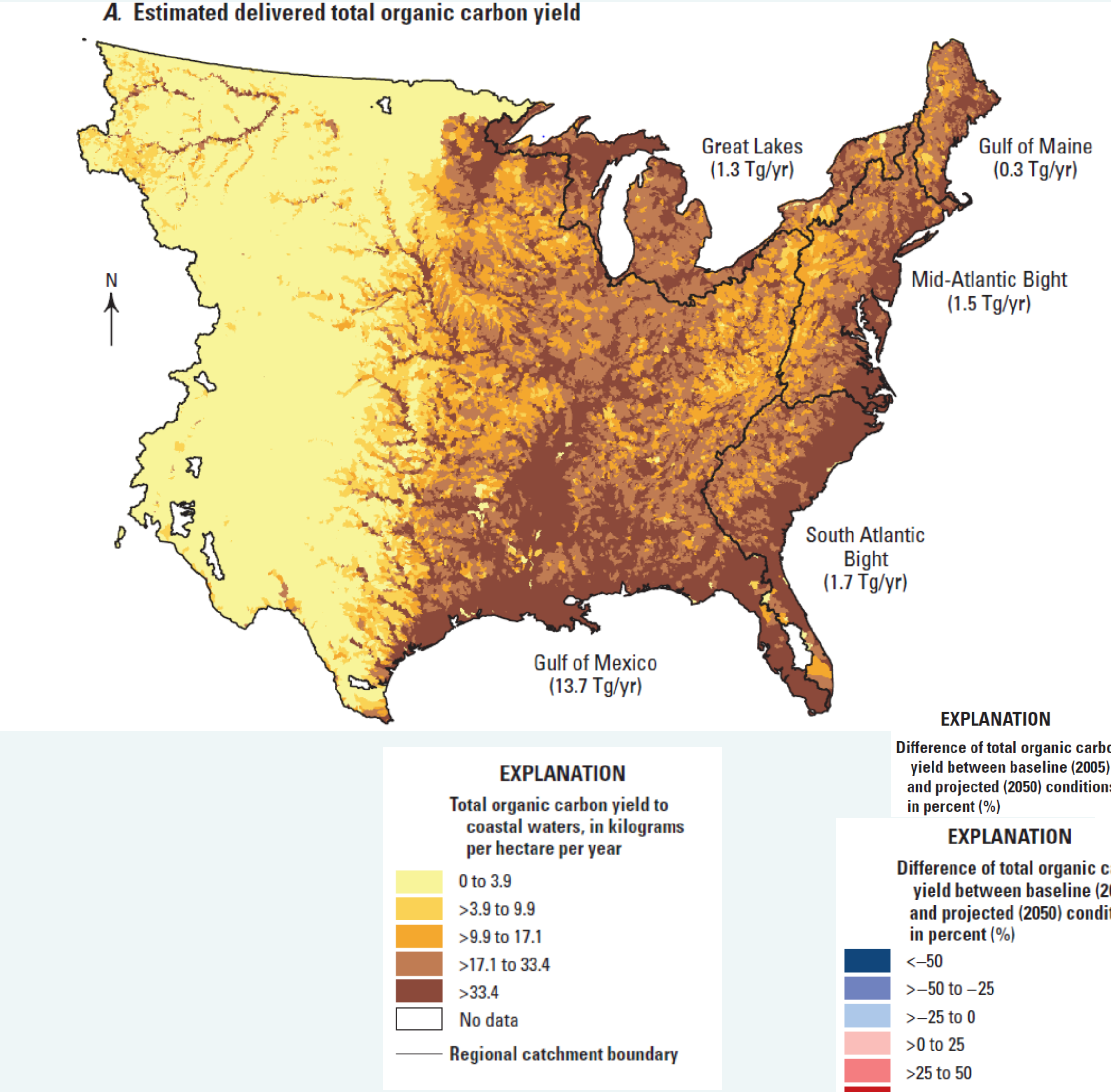
POTENTIAL EFFECTS ON COASTAL C PROCESSES

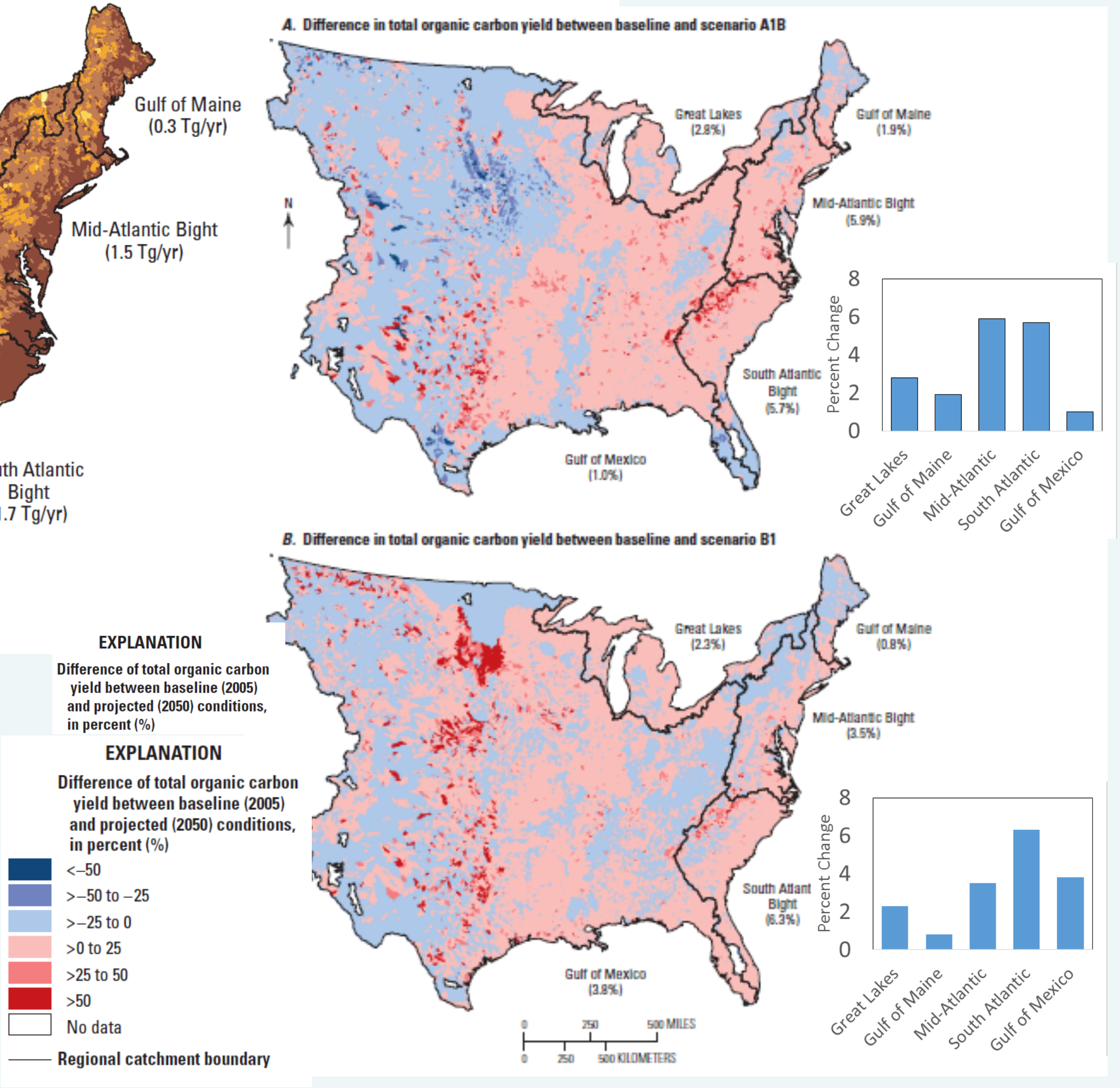


Significant difference between scenarios in changes to lateral flux

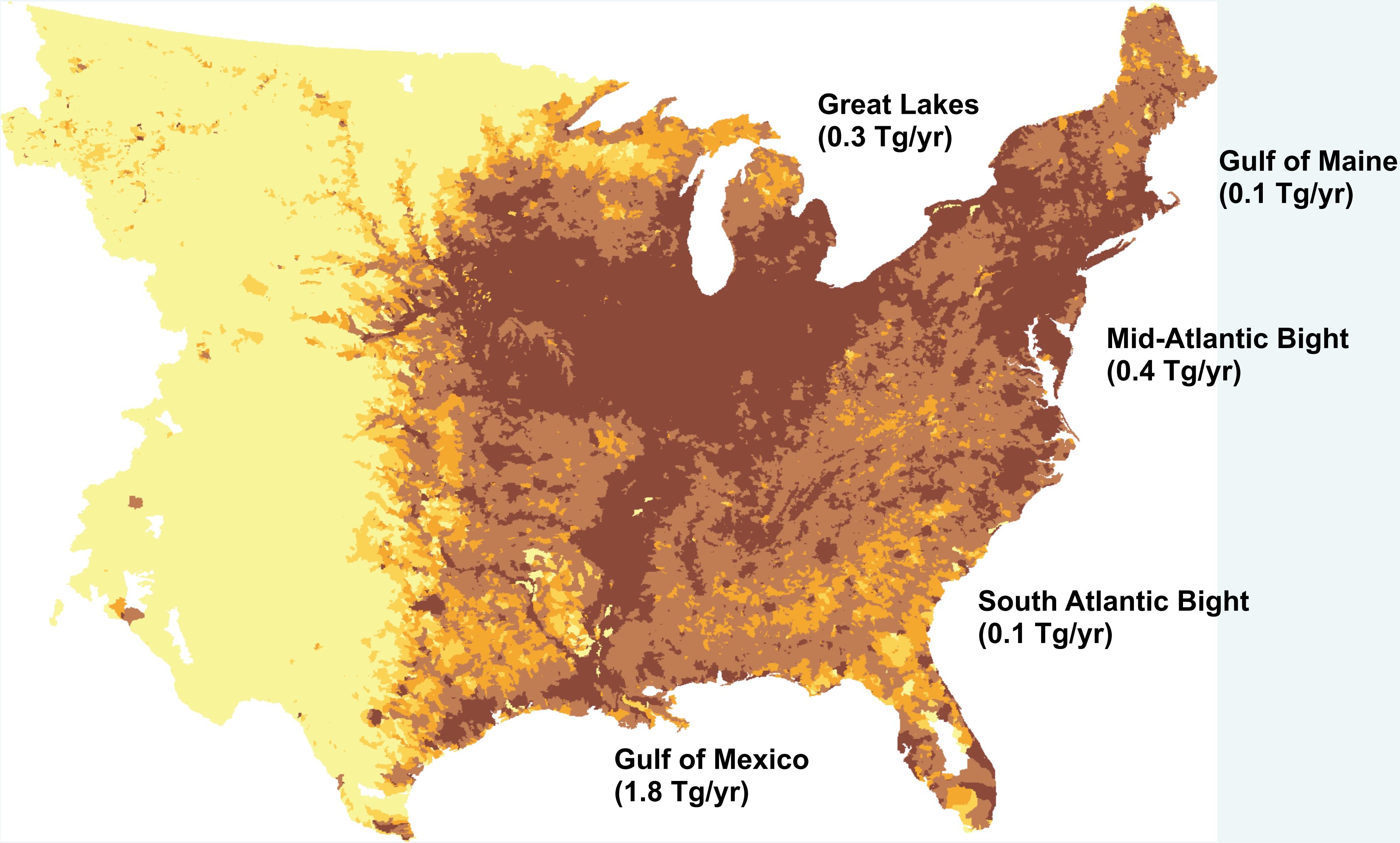
DELIVERED YIELD OF TOC

DIFFERENCE BETWEEN BASELINE (2005) AND PROJECTED (2050) FOR SCENARIO A1B and B1

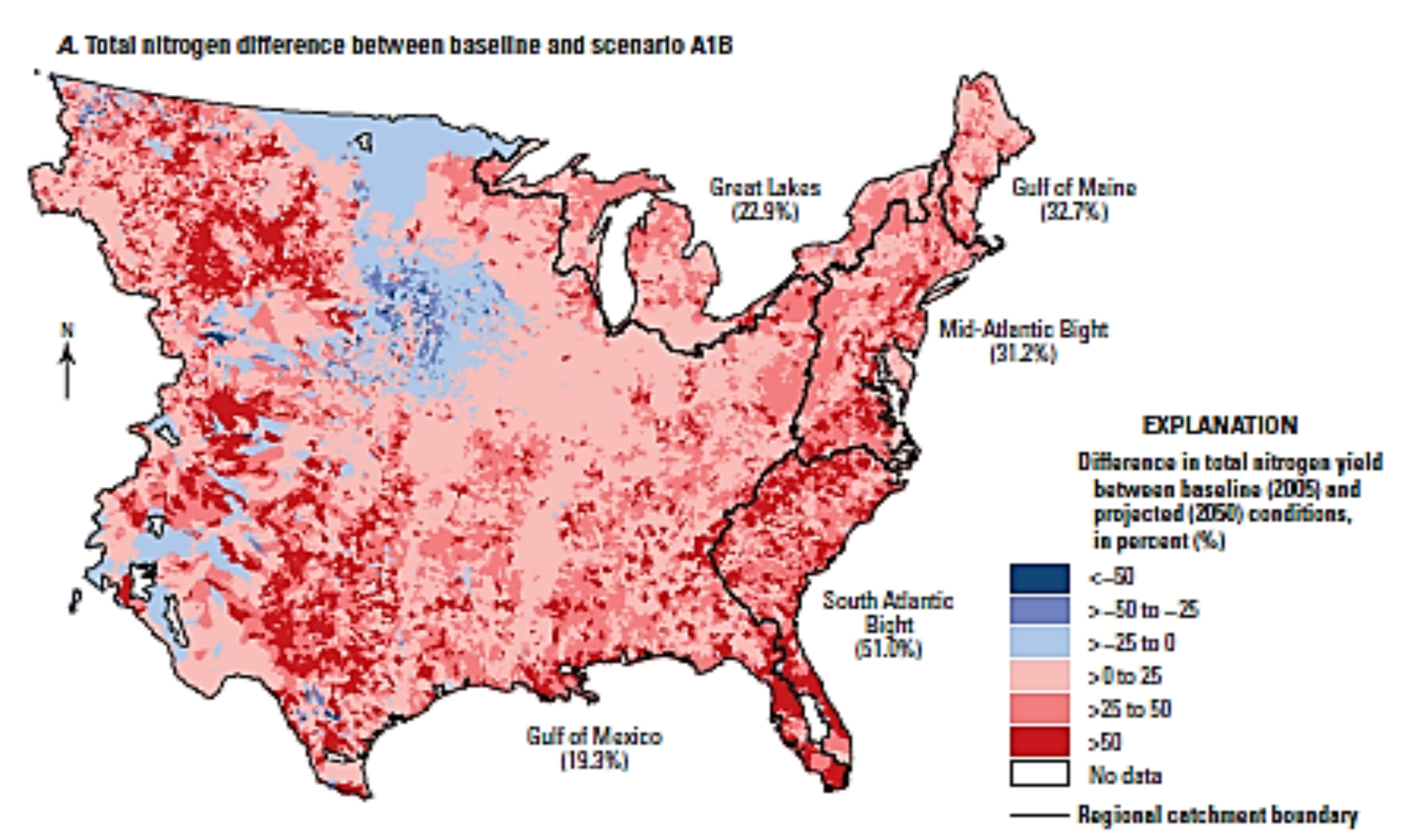




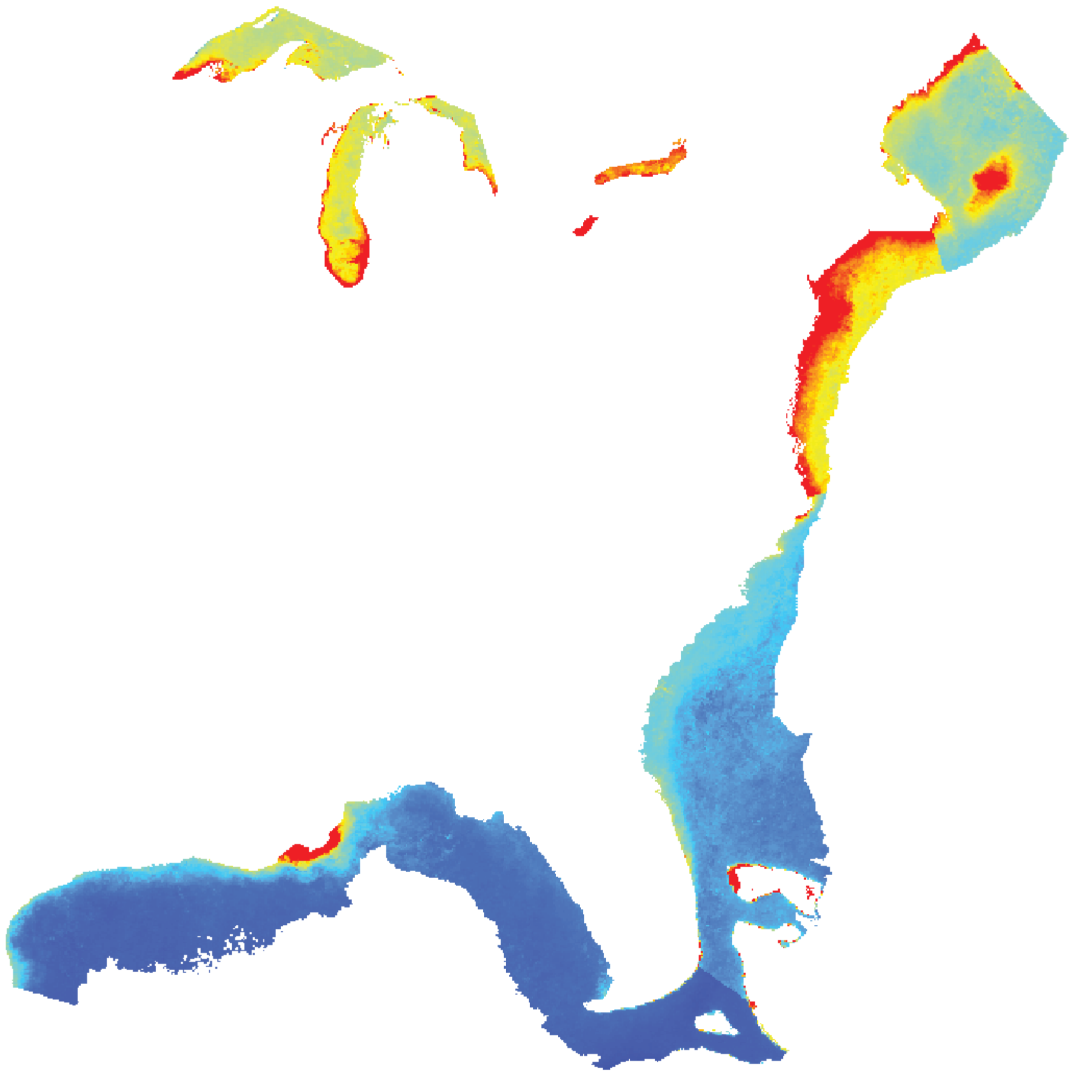
Estimated Delivered Total Nitrogen Yield and Regional Flux



Changes (%) in TN Yield 2005 to 2050 Under Scenario A1B

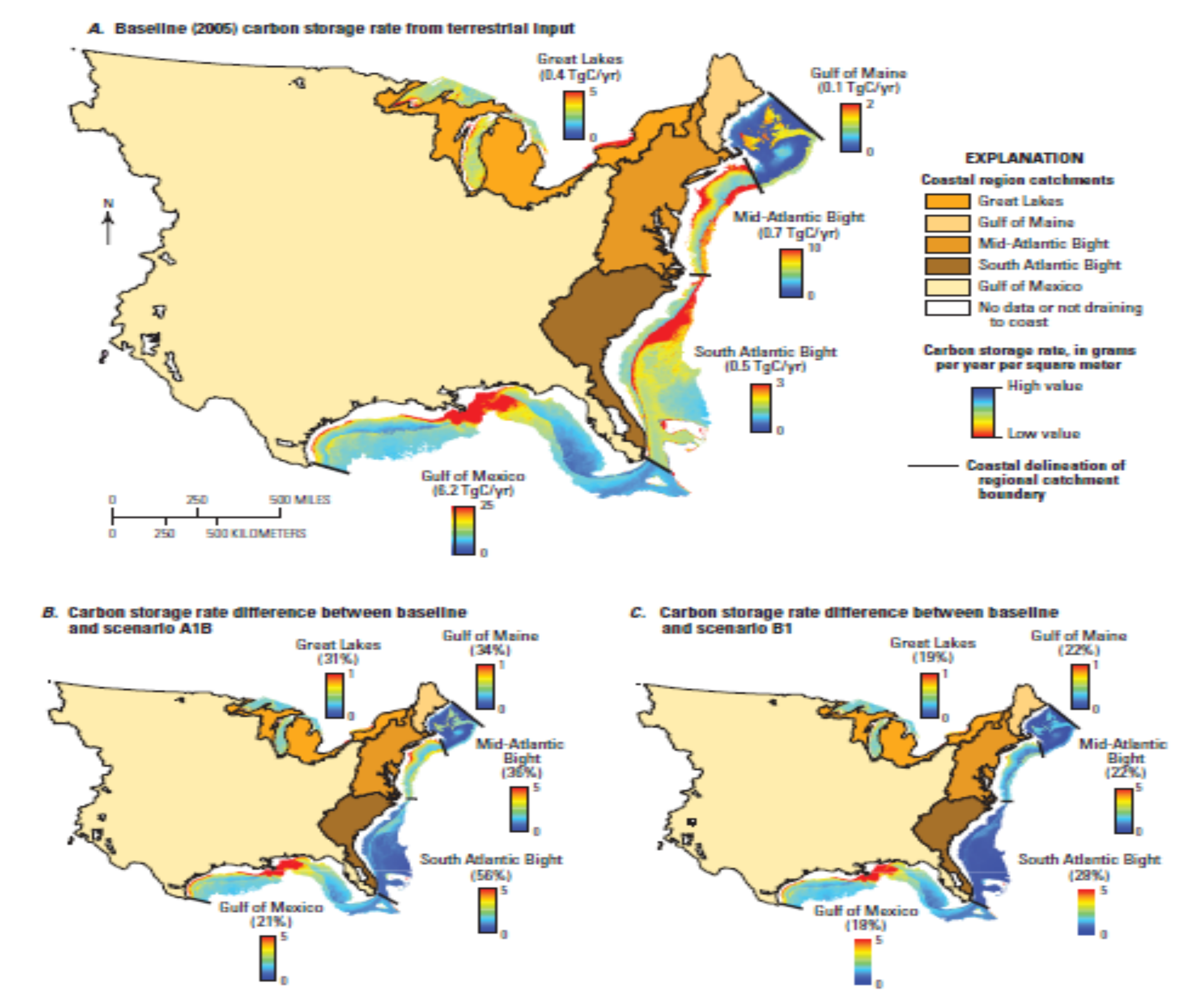


Chlorophyll Dispersion Field Based on 2011 MERIS Data



Sediment Dispersion Field Based on 2011 MERIS Data

Estimated Coastal Carbon Storage Rates, 2005 and 2050 Under Scenario A1B



Hypotheses generated from model re: carbon storage

- Model estimates indicate that nutrient and sediment fluxes from terrestrial environments of the Eastern United States contribute significantly to the uptake and storage of carbon in coastal waters.

- Changes in population and land use are projected to result in significantly greater fluxes of nutrients and sediments to coastal waters by 2050 relative to the baseline years (2001–2005). However, total organic carbon flux to coastal areas is projected to increase only slightly. For example, projected nitrate fluxes for 2050 are 16 to 52 percent higher than the baseline year, depending on the region and LULC scenario modeled. As a consequence, an associated increase in the frequency and duration of coastal and estuarine hypoxia events and harmful algal blooms could be expected.

Hypotheses generated from model re: carbon storage

- The estimated annual coastal carbon storage flux related to continental inputs was 7.9 TgC/yr, or 3 percent of the estimated average annual terrestrial flux based on LULC in 2005.
- ~60 percent of coastal carbon storage related to terrestrial inputs is buried in sediments and 40 percent is stored in deep ocean waters, below the surface ocean mixed layer.
- Annual rates of coastal carbon storage are projected to increase by 18 to 56 percent between 2005 and 2050, based on several modeled LULC scenarios. This is in contrast to terrestrial rates of carbon storage, which are projected to decrease by 20 percent. The differing trends in coastal and terrestrial storage result from projected increases in nutrient and sediment runoff from urban and agricultural lands and from decreases in forest cover.

Toward Understanding **Groundwater** as a Vector for Delivery of Carbon to (& from) Coastal Waters

presented by: **Beth Boyer**, with heavy contributions from:
Jennifer Cherrier (Florida A&M), **Kevin Kroeger** (USGS Woods Hole, MA), **Chris Smith** (USGS St. Petersburg, FL), and **Peter Swarzenski** (USGS Santa Cruz, CA)

Challenge: identifying freshwater/saline GW boundaries and their carbon contents

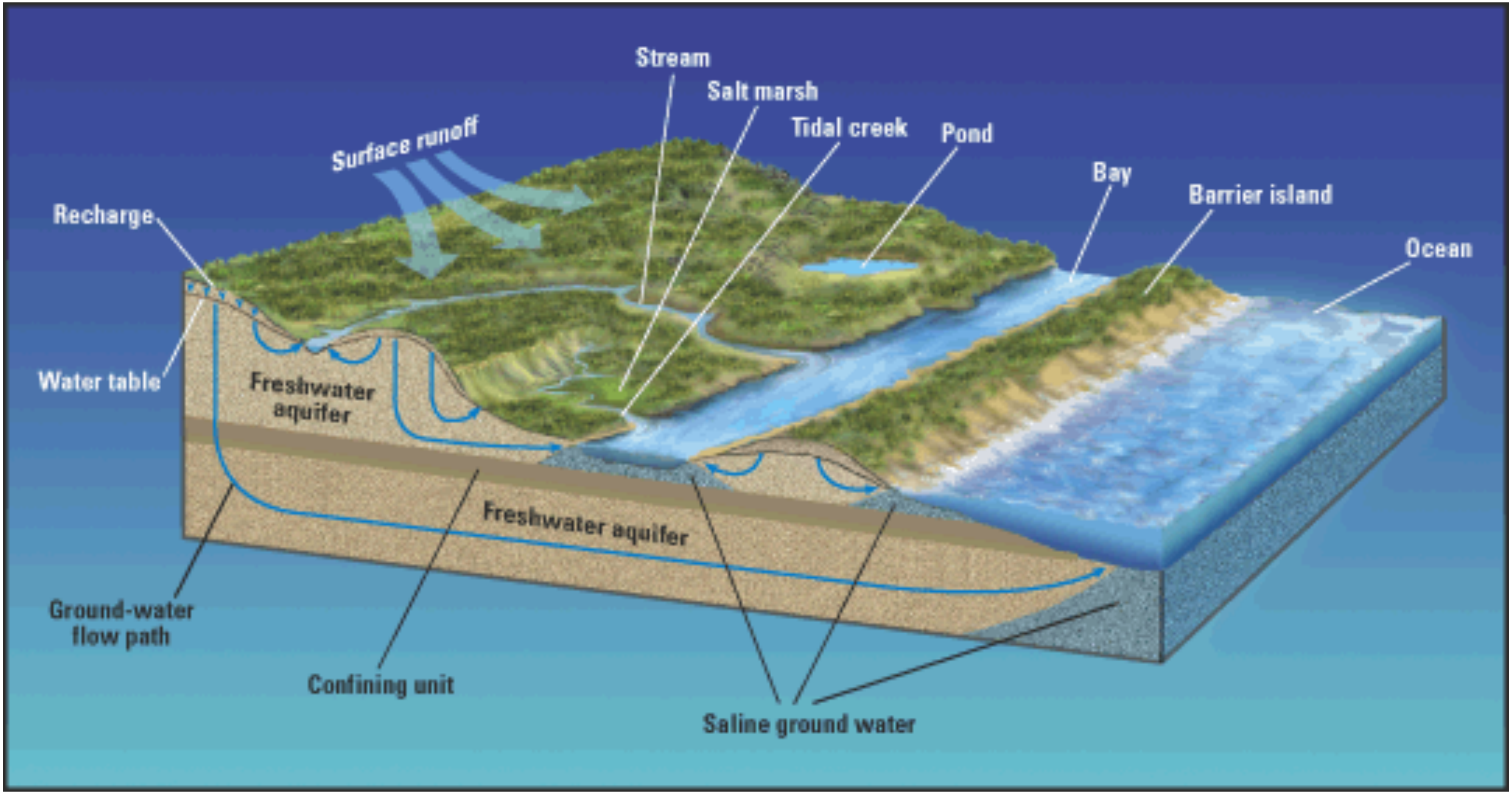
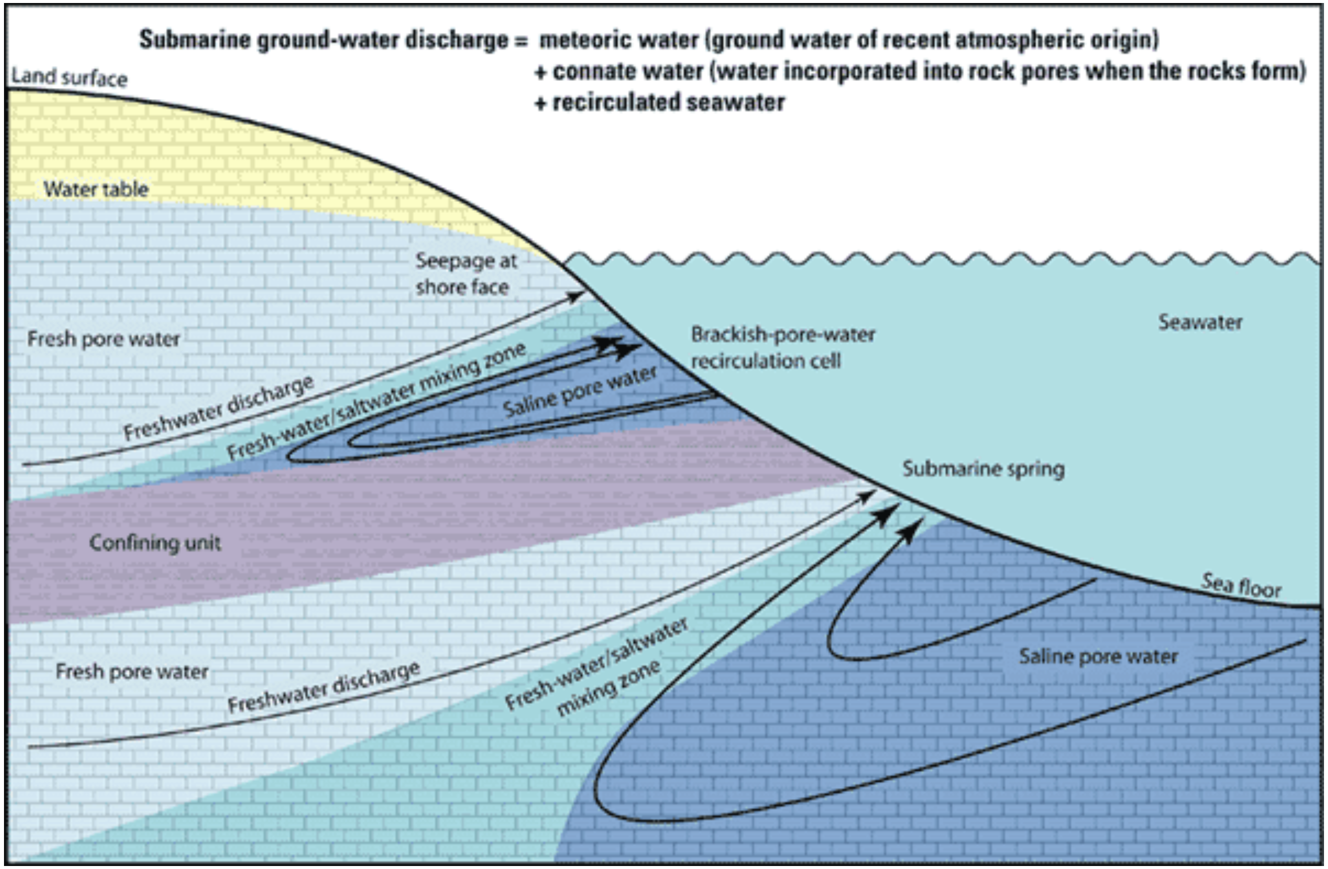


Image from: http://pubs.usgs.gov/circ/2003/circ1262/

Challenge: quantifying submarine groundwater discharges (SGD) in coastal waters

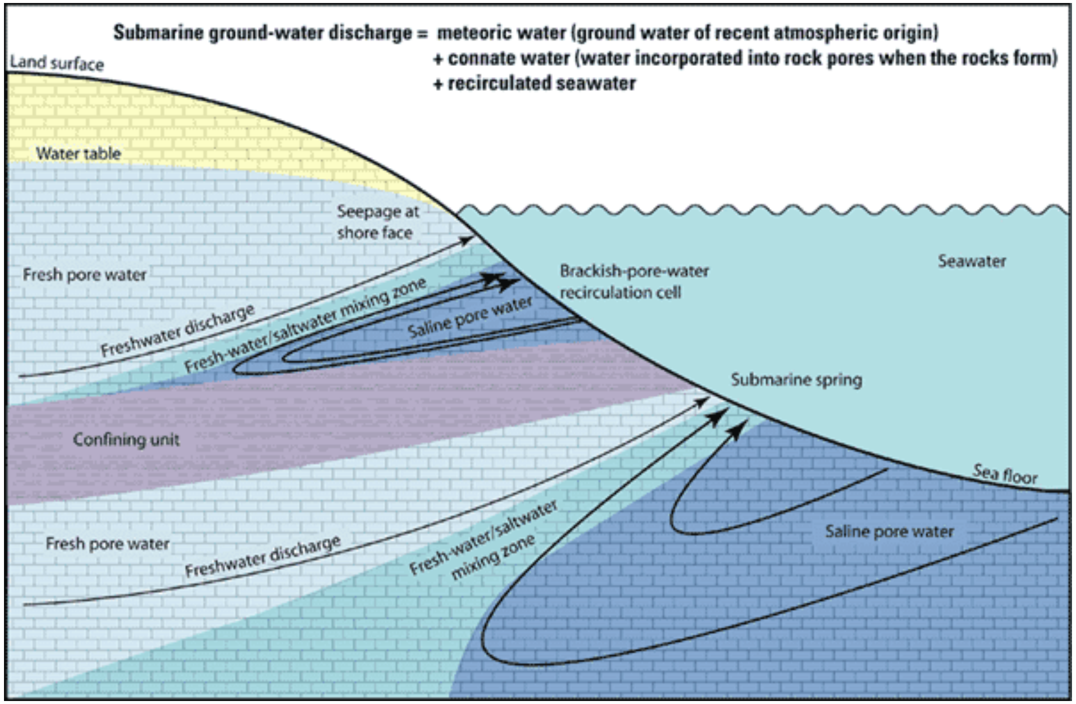


Terrestrial SGD delivers freshwater Q and C laterally to coastal zone.

Marine SGD is predominantly recycled seawater Q yet modified (e.g., in C content and composition).

After Swarzinski

Challenge: quantifying submarine groundwater discharges (SGD) in coastal waters



- Progress has been made at quantifying volumes of SGD and its chemical composition.
- Recent studies separate terrestrial & marine fractions & their relative magnitudes.
- Scaling up site specific studies to regional scales = difficult!

After Smith, Cherrier, Swarzinski

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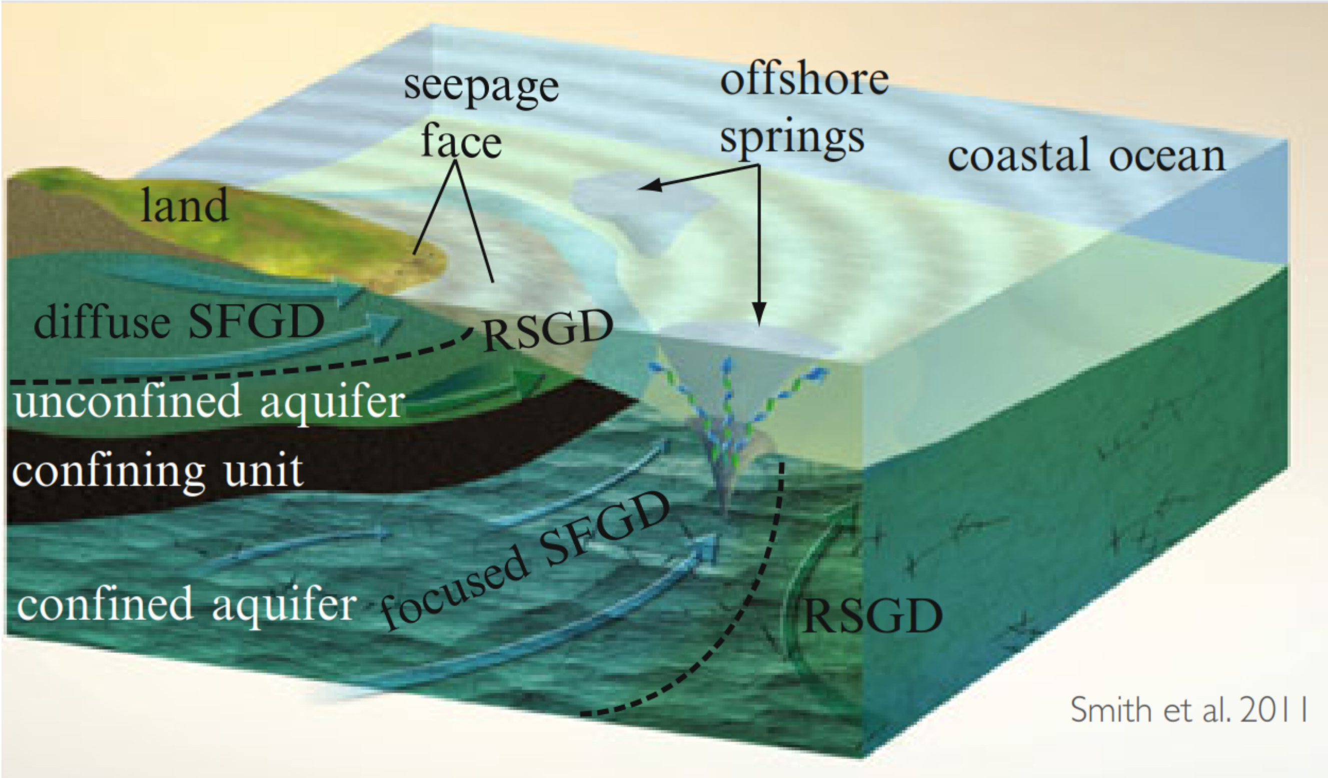


Controls on SGD C fluxes:

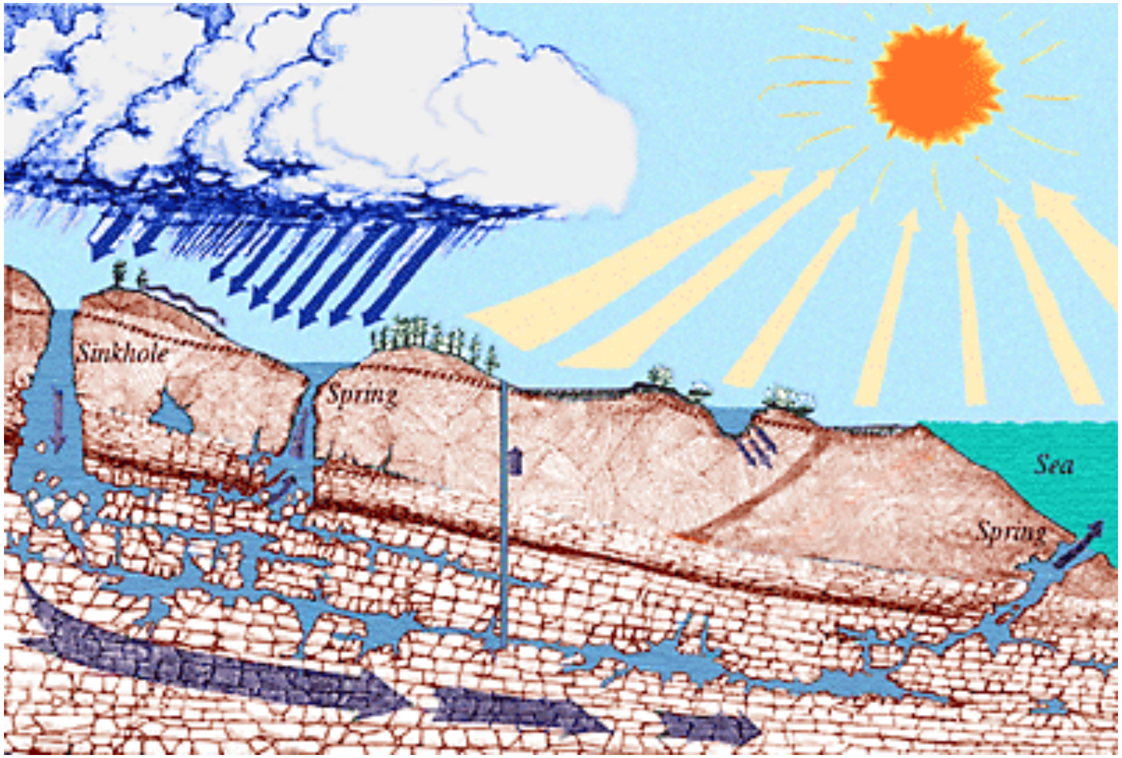
- Climate
- Hydrogeology: aquifer composition, hydraulic gradients, etc.
- Redox gradients & microbial communities
- Mixing, tidal pumping, waves, sea-level differences

→ Progress has been made at developing typologies for SGD; w/ limitations.

After Smith, Cherrier, Swarzinski

Challenge: quantifying submarine GW discharges to coastal waters in karstic terrain

- 12-25% of world's coastal geomorphology is karst
- Submarine springs prevalent
- High permeability results in reduced mixing at interface (greater proportion of fresh submarine groundwater discharge)
- Carbonate lithology supports unique metal and isotope endmembers



After Swarzinski

Challenge: sparse SGD + Carbon studies within from EC & GOM regions

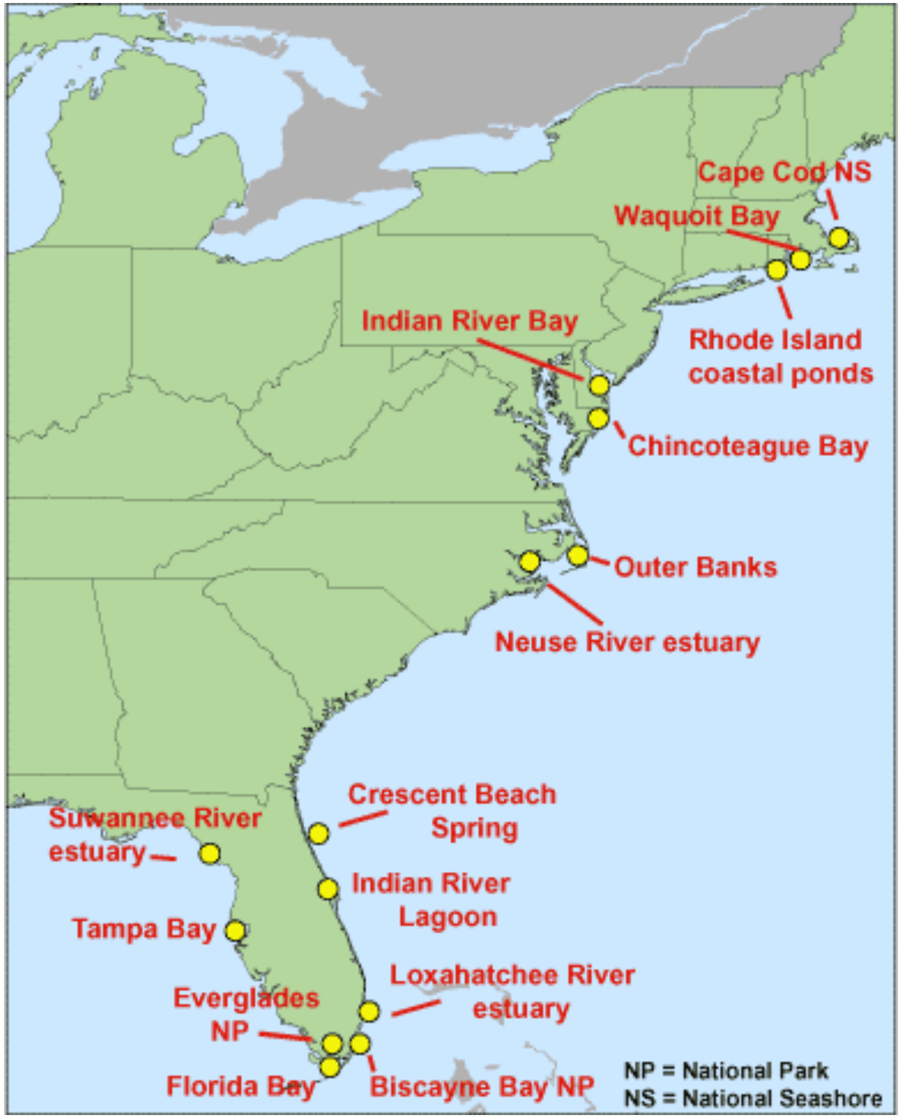


Image from: Peter Swarzenski

Image from: Chris Smith & Jennifer Cherrier

Challenge: steps typically taken to "scale up" to coastal regions are limited by data quality & availability

1. Identify scope: Typical annual fresh groundwater delivery of terrestrial materials on the US east coast. *Regional water budgets defined by hydrogeology & watersheds*

2. Develop a data set of chemical concentrations in discharging groundwater. Must be at appropriate scale and of sufficient resolution. *Carbon monitoring data from USGS, EPA, others*

3. Develop estimates of discharge rates & fluxes

After Kroeger

Challenge: toward a global (and regional) perspective on importance of SGD in C-cycling

Terrestrial SGD

- Global SFGD: 5 - 10% of River Flux
- SFGD total carbon contribution 0.13 - 0.25 Pg C y^{-1} (median 0.19)
    - Largely as DIC
    - That is 27% of the riverine efflux of total dissolved carbon OR
    - 73% of the riverine efflux of dissolved inorganic carbon

SGD data from Burnett et al. 2003;
Carbon data from Cole et al. 2007

After Smith & Cherrier, based on literature review

Needs

- It remains difficult to develop comprehensive GW flow & C budgets in coastal waters & continental margins.
- SGD is a potentially important source of C to coastal waters & remains poorly quantified.

- There are needs for **more observational data** (volumes, concentrations, composition; contrasting ecosystems), **new measurement techniques** (e.g., non-invasive), **more temporal and long-term studies** (e.g. to diagnose mixing between SGD & seawater driven by tides), and **more integrated modeling** (e.g., well-coordinated hydro-bio-geo transport & biogeochemical processes).