Fluxes of carbon from the land to the ocean

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Jhih-Shyang Shih, Resources for the Future
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
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 by the inherent variability of this data type.
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

- Diffuse Sources
- Industrial / Municipal Point Sources
- Landscape Transport
- Aquatic Transport
  - Streams
  - Reservoirs
- In-Stream Load Prediction
  - Calibration minimizes differences between predicted and calculated mean-annual loads at the monitoring stations
- Water-Quality and Flow Data
  - Periodic measurements at monitoring stations
- Rating Curve Model of Pollutant Loads
  - Station calibration to monitoring data
- Continuous Flow Data
- Mean-Annual Pollutant Load Calculation
- Evaluation of Model Parameters and Predictions

Alexander et al. 2002
SPARROW model components

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!
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:

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
<th>Number of Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insufficient flow record</td>
<td>23%</td>
<td>794</td>
</tr>
<tr>
<td>Nutrient load estimated</td>
<td>23%</td>
<td>782</td>
</tr>
<tr>
<td>No gage nearby</td>
<td>54%</td>
<td>1824</td>
</tr>
</tbody>
</table>

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

- 1125 sites (of about 5000 sites with TOC data) met criteria and were used:
SPARROW model components

- Diffuse Sources
- Industrial Point Sources
- Municipal Sources
- Landscape Transport
- Aquatic Transport: Streams, Reservoirs
- Water-Quality and Flow Data: Periodic measurements at monitoring stations
- Rating Curve Model of Pollutant Loads: Station calibration to monitoring data
- Continuous Flow Data
- Mean-Annual Pollutant Load Calculation
- Evaluation of Model Parameters and Predictions

In-Stream Load Prediction: Calibration minimizes differences between predicted and calculated mean-annual loads at the monitoring stations

Alexander et al. 2002
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: A Spatially-Explicit Mass-Balance Watershed Model
Quantifies nutrient sources and sinks for annual time periods

SPARROW model components: example sources, diffuse & point

- WET & DRY DEPOSITION
  - Impervious area
  - Developed land area
  - Septic systems

- URBAN WASTEWATER
  - Human population
  - EPA permit data

- URBAN RUNOFF

- FARM LIVESTOCK
  - Livestock population, nutrient content of wastes for confined and unconfined operations

- CULTIVATION
  - Commercial fertilizer
  - Manure fertilizer
  - Biological N fixation
  - Crop type
  - Crop harvesting

- WQ & FLOW MONITORING
Example SPARROW significant point & diffuse sources (N model)

Atmospheric Deposition

Fertilizer Application

Animal Waste

Point Sources
SPARROW: A Spatially-Explicit Mass-Balance Watershed Model

Quantifies nutrient sources and sinks for annual time periods

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

WET & DRY DEPOSITION

Impervious area
Developed land area
Septic systems

URBAN WASTEWATER

Human population
EPA permit data

URBAN RUNOFF

COMMERCIAL FERTILIZER
Manure fertilizer
Biological N fixation
Crop type
Crop harvesting

FARM LIVESTOCK

Precipitation
Temperature
Soil permeability
Clay/sand content
Slope
Surface/subsurface flow
Geology
Hydrologic landscape or physiographic region
Drainage density
Wetlands
Artificial drainage

LAND-TO-WATER TRANSPORT

WQ & FLOW MONITORING

Livestock population, nutrient content of wastes for confined and unconfined operations
Example SPARROW significant land-to-water delivery variables (N model)

- **Soil Permeability**
- **Artificial Drainage**
- **Mean Air Temperature**
- **Drainage Density**
SPARROW: A Spatially-Explicit Mass-Balance Watershed Model
Quantifies nutrient sources and sinks for annual time periods

SPARROW model components: example aquatic transport factors

- Impervious area
- Developed land area
- Septic systems
- Human population
- EPA permit data
- Commercial fertilizer
- Manure fertilizer
- Biological N fixation
- Crop type
- Crop harvesting
- Livestock population, nutrient content of wastes for confined and unconfined operations
- Precipitation
- Temperature
- Soil permeability
- Clay/sand content
- Slope
- Surface/subsurface flow
- Geology
- Hydrologic landscape or physiographic region
- Drainage density
- Wetlands
- Artificial drainage

- WET & DRY DEPOSITION
  - WQ & FLOW MONITORING
- URBAN WASTEWATER
- URBAN RUNOFF
- LAND-TO-WATER TRANSPORT
- IN-STREAM TRANSPORT
- FARM LIVESTOCK
- LAND-TO-WATER TRANSPORT
- DOWNSTREAM TRANSPORT & COASTAL DELIVERY

First-order decay reflects denitrification and multi-year storage
Example SPARROW significant aquatic transport factors (N model)

Stream Velocity

Reservoir Hydraulic Load
SPARROW model components

- Diffuse Sources
- Industrial / Municipal Point Sources
- Landscape Transport
- Aquatic Transport
  - Streams
  - Reservoirs
- In-Stream Load Prediction
  - Calibration minimizes differences between predicted and calculated mean-annual loads at the monitoring stations

Monitoring Station Load Calculation
- Water-Quality and Flow Data
  - Periodic measurements at monitoring stations
- Rating Curve Model of Pollutant Loads
  - Station calibration to monitoring data
- Continuous Flow Data

Mean-Annual Pollutant Load Calculation

Evaluation of Model Parameters and Predictions

Alexander et al. 2002
**SPARROW mathematical form**
reach-scale mass balance; relate watershed data to monitored loads

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

- 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
Spatial referencing is accomplished by linking all data to a geographically defined stream-reach data set.
SPARROW nutrient model calibration observed versus predicted riverine yields of N & P

**Total Nitrogen**
(N=425 monitoring sites)

- R² = 0.87
- RMSE = 55%

**Total Phosphorus**
(N=425 monitoring sites)

- R² = 0.68
- RMSE = 76%

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
• 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?
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)
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.

1125 sites (of about 5000 sites with TOC data) met criteria and were used:

Calibration sites currently included in TOC model
## Terrestrial C sources: proxies by land area

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

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

In contrast, the net removal rate for reservoirs was estimated to be zero and was not statistically significant. This suggests that production and loss processes 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.

**Aquatic C sources: in-stream C losses**

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient units¹</th>
<th>Estimate</th>
<th>Standard Error</th>
<th>t value</th>
<th>Level of Statistical Significance, p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>kg km⁻² yr⁻¹</td>
<td>1454</td>
<td>167</td>
<td>8.65</td>
<td>0.000</td>
</tr>
<tr>
<td>Forest, deciduous</td>
<td>kg km⁻² yr⁻¹</td>
<td>1061</td>
<td>191</td>
<td>5.54</td>
<td>0.002</td>
</tr>
<tr>
<td>Forest, evergreen</td>
<td>kg km⁻² yr⁻¹</td>
<td>1378</td>
<td>167</td>
<td>8.21</td>
<td>0.000</td>
</tr>
<tr>
<td>Forest, mixed</td>
<td>kg km⁻² yr⁻¹</td>
<td>2568</td>
<td>627</td>
<td>4.09</td>
<td>0.001</td>
</tr>
<tr>
<td>Urban</td>
<td>kg km⁻² yr⁻¹</td>
<td>4777</td>
<td>778</td>
<td>6.14</td>
<td>0.000</td>
</tr>
<tr>
<td>Wetlands</td>
<td>kg km⁻² yr⁻¹</td>
<td>25,008</td>
<td>2529</td>
<td>9.89</td>
<td>0.000</td>
</tr>
<tr>
<td>In-stream photosynthesis</td>
<td>dimensionless</td>
<td>1.10</td>
<td>0.13</td>
<td>8.67</td>
<td>0.000</td>
</tr>
<tr>
<td>Soil permeability</td>
<td>log (cm hr⁻¹)</td>
<td>-0.1407</td>
<td>0.0368</td>
<td>-3.82</td>
<td>0.000</td>
</tr>
<tr>
<td>Precipitation</td>
<td>cm</td>
<td>0.0047</td>
<td>0.0006</td>
<td>7.51</td>
<td>0.000</td>
</tr>
<tr>
<td>Artificial drainage</td>
<td>percent area</td>
<td>0.0116</td>
<td>0.0031</td>
<td>3.82</td>
<td>0.001</td>
</tr>
<tr>
<td>Drainage density</td>
<td>log (km⁻³)</td>
<td>0.4407</td>
<td>0.0545</td>
<td>8.08</td>
<td>0.000</td>
</tr>
<tr>
<td>Land slope</td>
<td>log (percent)</td>
<td>-0.0023</td>
<td>0.0040</td>
<td>-0.58</td>
<td>0.5620</td>
</tr>
<tr>
<td>In-stream carbon removal</td>
<td>per day</td>
<td>0.0338</td>
<td>0.0036</td>
<td>9.31</td>
<td>0.000</td>
</tr>
<tr>
<td>Log root mean square error</td>
<td></td>
<td>0.540</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of observations</td>
<td></td>
<td>1125</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted R-squared Yield</td>
<td></td>
<td>0.928</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-squared Yield</td>
<td></td>
<td>0.77</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Watershed land-cover type</th>
<th>No. of watersheds</th>
<th>10th</th>
<th>25th</th>
<th>50th</th>
<th>75th</th>
<th>90th</th>
<th>Range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>1,841</td>
<td>15.1</td>
<td>19.1</td>
<td>24.5</td>
<td>34.7</td>
<td>59.9</td>
<td>14.1–19.5²</td>
</tr>
<tr>
<td>Forest</td>
<td>70</td>
<td>12.1</td>
<td>14.0</td>
<td>16.2</td>
<td>21.4</td>
<td>34.0</td>
<td>4–80⁴</td>
</tr>
<tr>
<td>Deciduous</td>
<td>248</td>
<td>13.6</td>
<td>16.1</td>
<td>20.3</td>
<td>28.6</td>
<td>56.0</td>
<td>14–500⁴</td>
</tr>
<tr>
<td>Evergreen</td>
<td>3,203</td>
<td>0.1</td>
<td>0.3</td>
<td>0.8</td>
<td>2.3</td>
<td>8.2</td>
<td>4–13⁴</td>
</tr>
<tr>
<td>Range</td>
<td>143</td>
<td>36.3</td>
<td>48.3</td>
<td>73.3</td>
<td>108.6</td>
<td>329.3</td>
<td>19–146⁴</td>
</tr>
<tr>
<td>Urban</td>
<td>191</td>
<td>160.3</td>
<td>276.4</td>
<td>476.3</td>
<td>801.6</td>
<td>2180.0</td>
<td>50–220⁵</td>
</tr>
</tbody>
</table>

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%). bDalzell et al. 2007. cHope et al. 1994; North America, New Zealand, Russia (total organic carbon). dMulholland 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

[Map of the United States with TOC simulations, showing percentage distribution of TOC with color codes: 0 to 20, 20 to 40, 40 to 60, 60 to 80, 80 to 100]
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

![Map of the United States with regional boundaries highlighting coastal areas.]

| Region                | Drainage area (km²)
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delivered yield (kg/ha/yr)</td>
</tr>
<tr>
<td>North Atlantic</td>
<td>446,500</td>
</tr>
<tr>
<td>South Atlantic - Gulf</td>
<td>730,000</td>
</tr>
<tr>
<td>Mississippi - Atchafalaya - Red</td>
<td>3,248,700</td>
</tr>
<tr>
<td>Texas - Gulf</td>
<td>925,400</td>
</tr>
<tr>
<td>Pacific Northwest</td>
<td>713,700</td>
</tr>
<tr>
<td>California</td>
<td>234,200</td>
</tr>
<tr>
<td>Great Lakes</td>
<td>313,100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>Source share percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Agriculture</td>
</tr>
<tr>
<td>North Atlantic</td>
<td>29</td>
</tr>
<tr>
<td>South Atlantic - Gulf</td>
<td>13</td>
</tr>
<tr>
<td>Mississippi - Atchafalaya - Red</td>
<td>7</td>
</tr>
<tr>
<td>Texas - Gulf</td>
<td>12</td>
</tr>
<tr>
<td>Pacific Northwest</td>
<td>39</td>
</tr>
<tr>
<td>California</td>
<td>39</td>
</tr>
<tr>
<td>Great Lakes</td>
<td>11</td>
</tr>
</tbody>
</table>

1Square kilometer.
## Relation between TOC and DOC in water regions

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

Boyер et al., in prep.
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.
SPARROW MODEL

Home page: http://water.usgs.gov/nawqa/sparrow
Software: http://water.usgs.gov/nawqa/sparrow/sparrow-mod.html