River Corridors of the Amazon Basin and their Response to Anthropogenic Change: A look back and a glimpse forward.

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LBA Science Plan

- “The Amazon still persists as one of the few remaining basins where the watercourses and nearby land have not yet undergone overwhelming human modification.”
  - Richey et al., 1997

- How do the pathways and fluxes of organic matter, nutrients and associated elements through river corridors (riparian, floodplain, channels, and wetlands) change as a function of land cover?”
River Function

- Interaction of hydrology, floodplains, and the land surface, specifically removing excess water
  - 160,000 m³/sec discharge, 3 month lag from north to south

- Transport of dissolved and particulate materials, fueling biological activity
  - 30 Tg ton C/yr, FPOC long MRT, DOC close to modern

- Trees, macrophytes, phytoplankton, attached algae, vascular vegetation, and annual herbaceous vegetation may all achieve peak production at different stages of the hydrograph

- Organic matter consumption and oxygen depletion drive the relative production of CO₂, CH₄, and N trace gases
  - Floodplains as much as 5-10% of global CH₄ flux
Impacts of Anthropogenic Change

- At small scale upland clearing increases stream runoff
  - lost ET, decreased infiltration, decreased WHC
  - Enhanced sediment and nutrient flow (3-50x for N)
  - Expected response strong for small streams, mitigated by riparian zones, but riparian zones may also change with increased sediment input, water table rise, and vegetation change
Within Floodplains - deforestation, pastures, and agriculture

- Sharper peak flows, higher flow rates
- Trees to grasses or herbs, more light for algae but also more sediment
- Decomposition may lead to enhanced CH$_4$
At the Basin Scale

- Will the Amazon come to resemble many of the world’s large river basins
  - Channelized and cut off from floodplains
  - Agricultural lands “reclaimed” from wetlands
  - Large loads of fertilizers and anthropogenic chemicals
  - Industrial and domestic wastes
  - Dams on all major tributaries
Fundamental Questions for River Corridors during LBA

- What are the changes in the pathways, fluxes and processing of organic matter and nutrients through river corridors?

- How can these changes be described as a function of original landscape characteristics and imposed land use?

- How much change is required to create a signal larger than natural variability at various scales, and how far downstream will disturbance signals persist?
Science Plan

- Rivers should respond with differing magnitudes and lags to perturbations depending on the processes involved and the downstream transfer rates of their characteristic products, as such it is critical to work at multiple scales
  - Small watershed (<10 km²)
    - Paired, process level
  - Mesoscale (~10,000 km²)
    - Regions of intensive study
  - Whole Basin (7x10^6 km²)
    - Remote sensing products, tested against hydrologic outputs from large tributaries

- Nested within each other, and within a background of natural variability,
- Seeking a process-based understanding, with a particular interest in processes of organic matter movement and transformation
Richey, 2004
The Catchment Scale

- Before LBA few experimental sites (Barro Branco, Lake Calado, Roraima)
- During LBA the number of sites increased with each having unique site characteristics

Modified from Tomasella et al., 2010
Hydrologic flow

Figure 1. A conceptual framework of hillslope runoff-generating mechanisms

Anisotropic soil properties
Subsurface stormflow
Microtopography
Slope concavity
Surface saturation
Rainfall > infiltration

Elsenbeer 2001
Saturated Hydraulic Conductivity (Ksat) as a function of depth under forest Eastern Amazon

Number of perched water table observations per class of water column height (cm) from the bottom of 1-m depth wells

Moraes et al 2006
Land Use Impacts at the Catchment Scale

Relative proportion of sources contributing to channel flow for the entire rainy season, Rancho Grande

Modified from Chavez et al., 2009
<table>
<thead>
<tr>
<th>Basin</th>
<th>Area (km²)</th>
<th>Location</th>
<th>Land Cover</th>
<th>Runoff Coef (%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fazenda Vitoria</td>
<td>0.0072</td>
<td>E. Amazon</td>
<td>Pasture</td>
<td>17.3</td>
<td>Moraes et al., 2006</td>
</tr>
<tr>
<td>Cumaru WS3</td>
<td>0.122</td>
<td>E. Amazon</td>
<td>Fallow Veg-Ag</td>
<td>38.0</td>
<td>Wickel et al., 2004, 2008</td>
</tr>
<tr>
<td>Cumaru WS1</td>
<td>0.358</td>
<td>E. Amazon</td>
<td>Fallow Veg-Ag</td>
<td>40.9</td>
<td>Trancoso 2006</td>
</tr>
<tr>
<td>Colosso</td>
<td>1.22</td>
<td>C. Amazon</td>
<td>Pasture</td>
<td>43.0</td>
<td>Trancoso 2006</td>
</tr>
<tr>
<td>Nosso Senhora</td>
<td>14.5</td>
<td>SW Amazon</td>
<td>Pasture</td>
<td>40.8</td>
<td>Biggs et al., 2006</td>
</tr>
<tr>
<td>Rancho Grande</td>
<td>0.0073</td>
<td>SW Amazon</td>
<td>Pasture</td>
<td>17.3</td>
<td>Chaves et al., 2008</td>
</tr>
<tr>
<td>Fazenda Vitoria</td>
<td>0.0033</td>
<td>E. Amazon</td>
<td>Forest</td>
<td>3.2</td>
<td>Moraes et al., 2006</td>
</tr>
<tr>
<td>Asu Mirin</td>
<td>1.26</td>
<td>C. Amazon</td>
<td>Forest</td>
<td>1.26</td>
<td>Trancoso 2006</td>
</tr>
<tr>
<td>Asu</td>
<td>6.56</td>
<td>C. Amazon</td>
<td>Forest</td>
<td>42.6</td>
<td>Hodnett et al., 2009</td>
</tr>
<tr>
<td>Rancho Grande</td>
<td>0.0137</td>
<td>SW Amazon</td>
<td>Forest</td>
<td>0.8</td>
<td>Chaves et al., 2008</td>
</tr>
</tbody>
</table>

Modified from Tomasella et al 2010
Changes in flow are associated with changes in nutrient concentration and flux.

Stream water concentration in Fazenda Nova Vida

Neill et al., 2001
Total annual DOC fluxes and net flux of carbon out of Igarapé Asu catchment in 2003

<table>
<thead>
<tr>
<th>Component</th>
<th>Carbon Flux (g m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td></td>
</tr>
<tr>
<td>DOC flux</td>
<td>2.44</td>
</tr>
<tr>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>DOC flux</td>
<td>10.83</td>
</tr>
<tr>
<td>FPOC flux</td>
<td>0.89</td>
</tr>
<tr>
<td>Net total</td>
<td>9.27</td>
</tr>
<tr>
<td>Carbon Form</td>
<td>Concentration (mg/L)</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td><strong>DOC</strong></td>
<td></td>
</tr>
<tr>
<td>Throughfall</td>
<td>14.1±4.0</td>
</tr>
<tr>
<td>Overland flow</td>
<td>10.7±1.6</td>
</tr>
<tr>
<td>Subsurface flow</td>
<td>7.5±1.1</td>
</tr>
<tr>
<td>Deep Groundwater</td>
<td>1.0±0.2</td>
</tr>
<tr>
<td>Emergent Groundwater</td>
<td>0.51</td>
</tr>
<tr>
<td><strong>CO₂-C</strong></td>
<td></td>
</tr>
<tr>
<td>Emergent Groundwater</td>
<td>20.5±1.4</td>
</tr>
</tbody>
</table>

Modified from Johnson et al., 2006
Dissolved CO$_2$ as a function of distance downstream from groundwater springs.

\[ Y = 47972(X+1)^{-0.63} \]

\[ R^2 = 0.84 \]

Johnson et al., 2009
Summary

- Greatly expanded network of investigated locations, improved appreciation for soil and landscape variance

- New insight into mechanisms of runoff generation
  - Most streamflow is baseflow, which reduces gradually with scale.
  - Most stormflow is saturation overland flow but return flow can be crucial

- Clear short term release in N but remaining question of mechanism of N removal

- Novel results regarding potential for C flux through CO₂ outgassing.
Floodplain Ecosystem Processes

- Comprised of thousands of lakes and wetlands linked to one another and to the many streams and rivers

- Modify hydrology, influence carbon and nutrient biogeochemistry, emit CO₂ and CH₄, and support highly diverse ecosystems and productive fisheries

- 1 million square kilometers
Regional extent of floodplains

Hess et al., 2003
Extension of the inundation record using records of river stage

Hamilton et al., 2004
Relation between inundation and floodplain vegetation

Martinez and Toan, 2007

Wittmann et al., 2003
## Inundation Hydrology

<table>
<thead>
<tr>
<th>Component</th>
<th>Calado (Lesack and Melack, 1993, 1995)</th>
<th>Curuai (Maurice Bourgoin et al., 2007, Bonnet et al., 2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff</td>
<td>57</td>
<td>10</td>
</tr>
<tr>
<td>River inflow</td>
<td>21</td>
<td>77</td>
</tr>
<tr>
<td>Rainfall</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Adjacent lake</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Seepage</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>CA/FA</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>
Changes in water levels (top) and floodplain topography (bottom). Arrows show changes in water levels indicating flow.
Summary

- Tremendous advances in measuring and mapping extent of inundation
- Dramatic new insight into hydrology of floodplains and mechanistic modeling of these flows
- Refined understanding of vegetation communities with flooding
- Improved forest, macrophyte, and phytoplankton production estimates.
The Regional to Basin Scale
Rede Beija Rio

- How do the inputs from small streams and in floodplains translate downstream?

Richey et al., 2010
CO$_2$ evasion estimated at 1.14 x $10^{12}$ g-C yr$^{-1}$
What is the source of carbon driving this CO$_2$ efflux?

- Where does the carbon come from that ultimately is evaded?

- Problem: respiration rates are sufficiently large to recycle all carbon in a parcel of water but yet concentrations do not change downstream?
- In other words, water column respiration exceeds planktonic photosynthesis; hence DO is undersaturated and CO$_2$ supersaturated
Insitu processing

Mayorga et al., 2005
## Gas Exchange

<table>
<thead>
<tr>
<th>Location</th>
<th>Stage</th>
<th>Source</th>
<th>$\delta^{13}C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rio Negro/</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaded streams</td>
<td></td>
<td>C3 plants</td>
<td>-28.3 to -30.1</td>
</tr>
<tr>
<td>Shallow Purus Tributaries</td>
<td></td>
<td>Algae/C3 plants</td>
<td>-33.2 to -31.2</td>
</tr>
<tr>
<td>Solimoes</td>
<td>Falling water</td>
<td>Algae/C3 plants</td>
<td>-32.6</td>
</tr>
<tr>
<td>Early rising water</td>
<td>C4 macrophytes/</td>
<td>C3 plants</td>
<td>-22.9</td>
</tr>
</tbody>
</table>

Ellis el al. submitted
<table>
<thead>
<tr>
<th>Aquatic Vegetation</th>
<th>Areal NPP (Mg C/km²/a)</th>
<th>High-Water Area (km²)</th>
<th>Total NPP (Tg C/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooded forest</td>
<td>1150</td>
<td>160,000</td>
<td>184</td>
</tr>
<tr>
<td>Macrophytes</td>
<td>2500</td>
<td>40,000</td>
<td>100</td>
</tr>
<tr>
<td>Phytoplankton</td>
<td>200</td>
<td>20,000</td>
<td>4</td>
</tr>
<tr>
<td>Periphyton (forest)</td>
<td>100</td>
<td>160,000</td>
<td>8</td>
</tr>
<tr>
<td>Periphyton (macrophytes)</td>
<td>111</td>
<td>40,000</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>298</strong></td>
</tr>
</tbody>
</table>

Melack et al., 2010
Regionalization of Carbon Biogeochemistry

Engle et al., 2008
- NPP 300 Tg C/a
  - 62% Flooded Forest
  - 34% aquatic macrophytes
  - 4% periphyton and phytoplankton

- Enough to account for CO$_2$ efflux
  - 10% export of organic carbon
  - 2.5% export as CH$_4$
  - Remainder ≈ degassing of 210±60 Tg C/a
Basin Scale Surface Water Regimes

- Rainfall records to 1940, flow to 1903

Schogart and Junk, 2007
Episodic events

Aalto et al., 2003
Summary

- The role of large rivers in the carbon economy of the Amazon seem unequivocal.

- A similarity in discharge-concentration relationships is striking and suggests a potential constancy in process.

- But Inputs and water column processing indicate changing sources of carbon in space and time.

- Short and long-term modes of variability are evident in historic flow, although flows appear to be changing.
Did LBA meet its scientific goals?

- What are the changes in the pathways, fluxes and processing of organic matter and nutrients through river corridors?

- How can these changes be described as a function of original landscape characteristics and imposed land use?

- How much change is required to create a signal larger than natural variability at various scales, and how far downstream will disturbance signals persist?
Did LBA meet its scientific goals?

- Great strides have been made in understanding pathways and flows of carbon and nutrients through river corridors.

- Greatly improved appreciation of landscape variance and thus quantitative modeling of changing processes relative to land use.

- How much change is required remains unresolved.
  - Some evidence of changing flows
  - But downstream signature still seems like forest.
Future needs

- Small Watershed
  - The influence of the degree of fragmentation on meteorological (evaporation) and hydrological (surface runoff) processes
  - The influence of flow paths on nitrogen and nutrient exports
  - Improved upland DOC, DIC, and POC inputs

- Floodplains
  - Improved topography and bathymetry
  - Precisely leveled gauges in floodplains
  - Measurements of water velocities in floodplain channels
  - Improved LISFLOOD model

- Basin Scale Rivers
  - Close carbon budget
  - Improve models and new methodologies for upscaling local to macroscale