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Exploring Interactions Among the Ecological, Hydrological and Climate Systems of Amazonia (LC-04)

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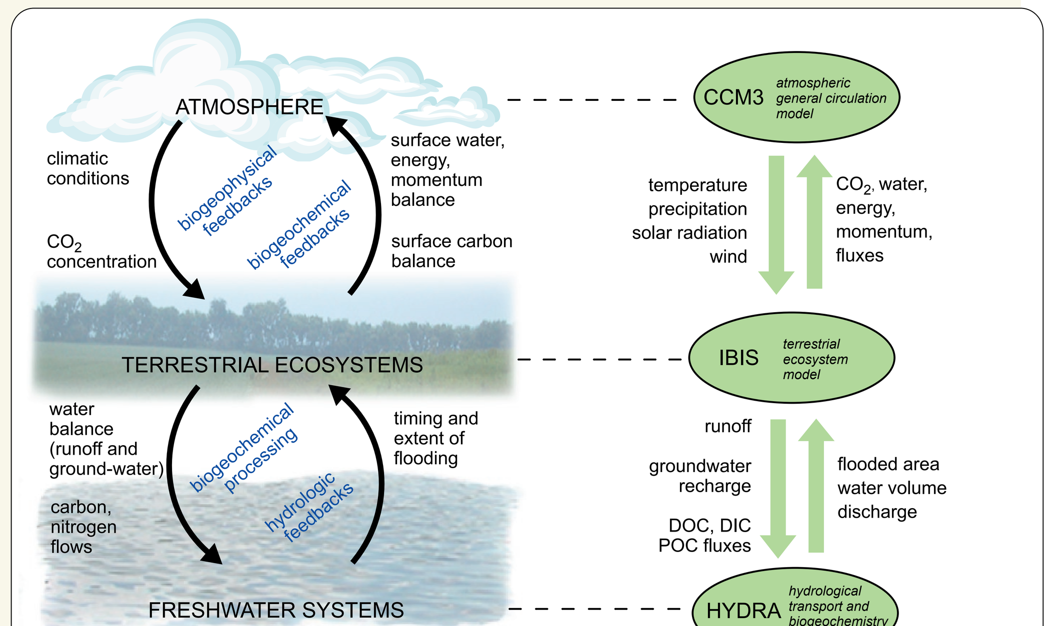
Scientific Objectives and Approaches

This proposal describes a research project that focuses on the large-scale, integrated behavior of environmental systems in the Amazon basin. We aim to address several broad research questions:

- How do the terrestrial ecosystems across the Amazon behave? How do they interact with the freshwater and climate systems of the region?
- How do the terrestrial ecosystems, freshwater systems and atmosphere of the Amazon operate as a single, integrated system?
- How does this integrated regional environmental system respond to human activity and global environmental change? How do changes in the environmental systems of the Amazon affect the rest of the Earth system?

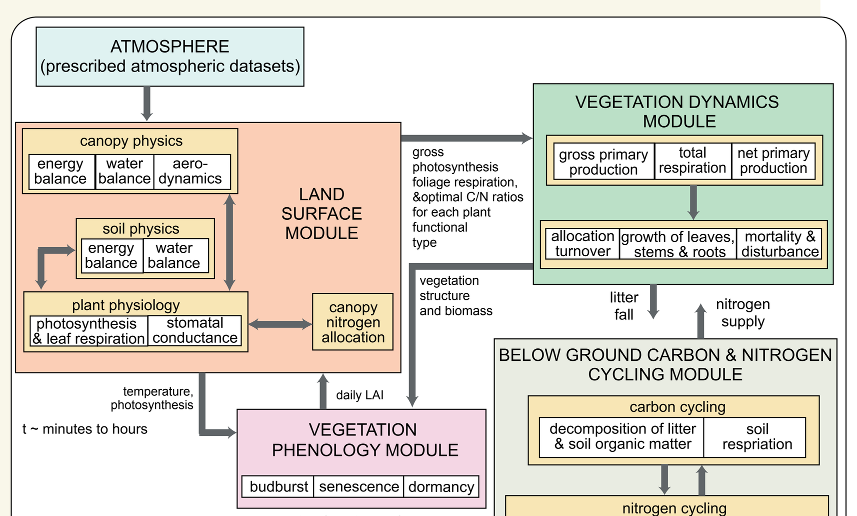
In order to address these questions, our research team is actively building state-of-the-art coupled models of terrestrial ecosystems, hydrological systems, and the atmosphere. These integrated modeling tools will be used to explore the complex behavior of regional environmental systems, and examine how they may respond to human activity and global environmental change. By considering the coupled behavior of the atmosphere, terrestrial ecosystems, and freshwater systems, we will explore the rich dynamics of this regional environmental system – including complex responses that could not be anticipated by considering each system in isolation.

Objective 1. Understand the Dynamics of Terrestrial Ecosystems – Variability, Disturbance, and Long-Term Change. We will use a regional-scale terrestrial ecosystem model (IBIS) to explore the behavior of terrestrial ecosystems across the Amazon basin. First, we will continue to test the components of the model against a hierarchy of measurements being made in LBA, including tower flux data, in situ biomass and canopy measurements, isotope samples, stream-flow data, and satellite measures. Next, we will examine how terrestrial ecosystems across the basin respond to climatic variability, disturbances, and land use / land cover change. In particular, we will use the IBIS modeling system to examine changes in ecosystem functioning (including terrestrial carbon cycling, water balance, nutrient cycling), as well as changes in ecosystem structure (including leaf area, biomass, and vegetation composition).



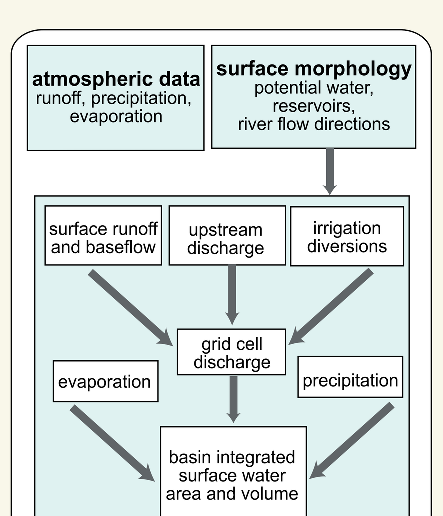
Interactions Among Ecological, Hydrological and Climate Systems of Amazonia. In our proposal, we will consider the interactions and feedbacks between the atmosphere, the terrestrial ecosystems and the freshwater systems of the Amazon basin. We will evaluate biogeochemical exchanges between these realms, as well as the biogeophysical and hydrological linkages between them. By considering the full coupling between atmosphere, ecosystems and freshwater systems, we can evaluate the complex, non-linear behavior of the full system – allowing us to consider threshold responses, or "regime shifts", in the coupled system in response to human activity and/or global environmental change.

Integrated Modeling Framework. In order to explore the interactions between the atmosphere, terrestrial ecosystems and freshwater systems of Amazonia, we will use three major modeling tools: CCM3 (an atmospheric general circulation model), IBIS (a terrestrial ecosystem model) and HYDRA (a hydrological transport and biogeochemistry model). IBIS and HYDRA were developed at the University of Wisconsin, while CCM3 was developed at the National Center for Atmospheric Research (NCAR). We have already coupled CCM3 to IBIS, and IBIS to HYDRA – allowing us to evaluate the coupled behavior of these systems.



IBIS. Schematic of the IBIS terrestrial ecosystem model. The characteristic time scales of the processes are indicated at the bottom of the figure.

Objective 2. Investigate the Interactions between Terrestrial Ecosystems and Freshwater Systems – Hydrological and Biogeochemical Linkages. First, we will examine the hydrological connections between terrestrial ecosystems and the rivers, streams, floodplains and wetlands of the basin. We will use our terrestrial ecosystem model (IBIS) to examine how the surface water balance responds to climate variability and land use / land cover change. We will also use our large-scale hydrological transport model (HYDRA) to examine the effects of changing water balance on river discharge, as well as the extent of wetlands and flooding. Next we will consider the biogeochemical linkages between terrestrial ecosystems and the freshwater systems in Amazonia. In particular, we will consider the transport of carbon from terrestrial ecosystems into freshwater systems, and the biological processing of carbon within aquatic ecosystems. The transport of carbon from terrestrial ecosystems to the rivers and wetlands of Amazonia is particularly relevant to the goals of LBA-ECO, as it may represent a significant fraction of the basin's carbon balance.



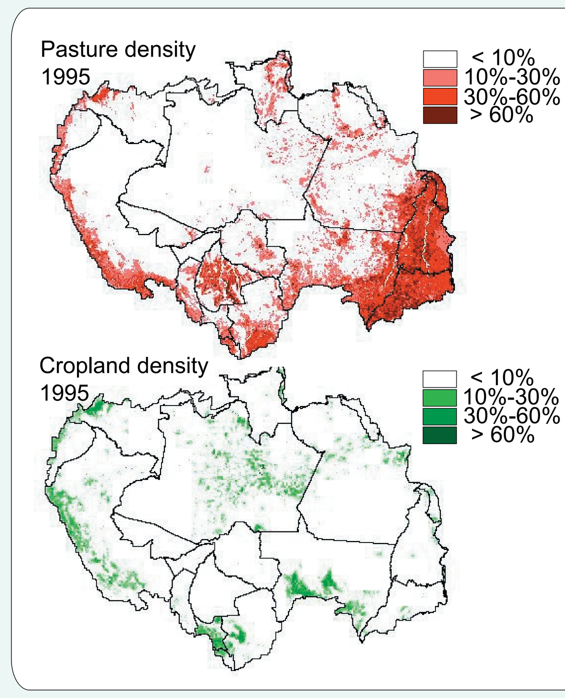
HYDRA. Schematic representation of the input and products of the HYDRA hydology transport model.

Objective 3. Explore the Interactions between Terrestrial Ecosystems and the Atmosphere – Physical and Biogeochemical Linkages. We will use a fully coupled climate – ecosystem model (CCM3-IBIS) to investigate how the climate and ecosystems of Amazonia will change in response to different scenarios of land use, rising CO_2 (considering both the ecological and climatic effects of CO_2), as well as different patterns of sea surface temperatures in the tropical Atlantic. We will use the modeling studies to evaluate the biogeophysical feedbacks of changing land cover conditions (either directly from land use practices, or indirectly through climate changes) on the regional climate, as well as the biogeochemical feedbacks of changing terrestrial carbon balance on atmospheric CO_2 concentrations and the global climate.

Key Past Results

Some key advances were made in the following areas during our LBA-ECO project, in the period 1998-2002:

1. Land Use and Land Cover Change. While changes in land cover (e.g., forest or non-forest) can be monitored from space, satellite-based data generally do not describe patterns of land use (e.g., cropping systems, pasture management, conversion among uses, and abandonment of agricultural lands). To alleviate this problem, we have used a combination of historical remote sensing products (i.e., Landsat and AVHRR data), long-term agricultural census data, and other ancillary data, to construct estimates of land use activity and land cover conversion for the Amazon basin. Unlike other land cover data products – which only show the extent of forest and non-forest systems – our data depict the patterns of land cover and land use, particularly the establishment and abandonment of croplands and pasture systems. Our initial land cover dataset for the Amazon basin, which depicts the fraction of each 5-minute (~9 km x 9 km) grid cell that was devoted to different agricultural practices during the middle 1990s, is now completed (Cardille et al., Global Biogeochemical Cycles, 2002). This snapshot can be used to describe land use practices – including cropland and pasture conversions – or to drive ecosystem models, as in our research. Recently, we also completed a long-term historical dataset of land use and land cover, showing changes in deforestation rates, creation of croplands and pastures, and the abandonment of agricultural lands between 1980 and 1995. We are now exploring the use of 250 m MODIS data for improving the satellite-basis for these land use products.



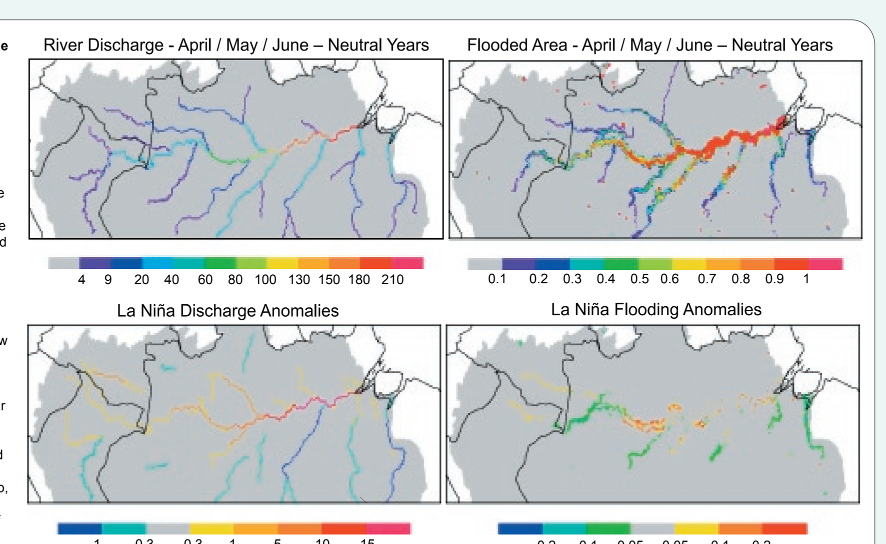
Agricultural Land Use in Amazonia – 1995. While satellite data can monitor changes in land cover (e.g., forest or non-forest), it is more difficult to describe land use practices (including crop and pasture management, shifting cultivation practices, and agricultural abandonment). We developed a technique to statistically combine satellite data (from AVHRR) with detailed agricultural census data (from county-level census records in Brazil, Peru, and Bolivia) to describe the patterns of land use across the basin (Cardille et al., in press). Here we show a snapshot of land use practices across the whole basin, depicting the area used for pastures (including both managed and natural pastures) and croplands.

2. Carbon Storage and Exchange. A comprehensive study of the terrestrial carbon balance must involve many temporal scales, ranging from hourly fluxes, seasonal and annual carbon budgets, to interdecadal changes in biomass and soil carbon pools. Initially, our work focused on carbon fluxes at the hourly and daily timescales, to help us evaluate our models against micrometeorological flux tower data (e.g., Delire & Foley, 1999; Botta, unpublished work). After these preliminary studies, we concentrated our research efforts on the study of carbon cycling on longer timescales, including the effects of disturbances and of climate variability on ecosystem dynamics and carbon exchange.

a) Disturbances, Interannual Climate Variability and Large-Scale Ecosystem Dynamics. We used the IBIS ecosystem model to examine how climate variability and disturbances in climate – such as fire, windthrow or insect herbivory – affect ecosystem functioning and vegetation composition across the basin. Botta and Foley (Global Biogeochemical Cycles, in press) compared several simulations with varying treatments of climate variability (i.e., constant climate every year, or a varying climate from year to year) and disturbance rates. Our results demonstrated that interannual climate variability and natural disturbances strongly affect vegetation structure and composition across the basin. In particular, we showed that interannual climate variability and disturbances can cause large increases in the geographic extent of savanna and grassland areas, and a significant decrease in soil and vegetation carbon content in these ecosystems. It appears that climate variability disturbances are crucial in maintaining these systems.

b) Long-Term Climatic Variations and the Carbon Cycle. Most studies of climate variability in Amazonia have concentrated on the El Niño – Southern Oscillation phenomenon. But by analyzing long-term historical climate data in the Amazon, we have found that there are several modes of climatic variability in the Amazon, including previously undocumented modes that are approximately 24-28 years in length. Using IBIS to simulate the basin-wide carbon balance over the last century, we show that these variations in climate generate strong variations in terrestrial carbon balance on short (~3-4 year, linked to ENSO), intermediate (~8-9 year), and long (~24-28 year) time scales (Botta et al., Geophysical Research Letters, 2002). Our analysis of the simulated carbon balance on interannual timescales (3-4 year) show that the response to ENSO varies regionally, which impacts interpretation of the interannual-scale CO_2 measurements at the different micro meteorological tower sites (Foley et al., Global Biogeochemical Cycles, in press). On interdecadal timescales (24-28 year), we found important variations in the carbon balance in time and space, which raises serious questions regarding the use of short-term observations and modeling exercises to study the regional carbon cycle.

Simulations of River Discharge and Flooding. Using the IBIS ecosystem model and the HYDRA river routing model, we simulate patterns of mean monthly river discharge and flooding across the Amazon and Tocantins basins at a 9 km resolution. The maps at near right show river discharge for the mean of the Neutral (neither El Niño or La Niña) April, May, June (high-flow) season (top right) and the differences of the La Niña composite from the Neutral for the high-flow season (bottom right). The figures at far right show fractional flooded area for the mean of the Neutral high-flow season (top, far right) and differences of the La Niña composite from the Neutral for the high-flow season (bottom, far right). These composites are constructed by averaging the simulated discharge and flooded fraction separately for those months that occur during El Niño, La Niña, and Neutral conditions for each of the twelve months of the year from 1950 to 1995.



3. Land Surface Hydrology. The Amazon basin includes a complex network of rivers, streams, floodplains, and wetlands. Until recently, however, most large-scale hydrology studies have concentrated only on water balance and river discharge – and did not consider floodplain and wetland dynamics. Moreover, an understanding of the dynamics of individual sub-basins within the Amazon basin has been severely limited by a lack of data. Given the importance of the freshwater systems in Amazonia, it was necessary to improve our ability to simulate the complex hydrological systems of this basin. Our research efforts in this area have included the development and testing of new algorithms that simulate large-scale hydrological processes (including discharge, wetland dynamics, and flooding), as well as the determination of large-scale geomorphic and hydrological characteristics of the Amazon basin.

b) Hydrological Processes of Rivers and Wetlands. We have developed a new regional hydrology model (HYDRA) to simulate the full range of hydrological processes occurring in the basin, including river discharge, flooding, and wetland dynamics (Coe et al., Journal of Geophysical Research, 2002). To test the algorithms of this model, we simulated the long-term (1939-1995) hydrological variability of the Amazon basin, including changes in discharge and flooding and compared them to ground and satellite based observations. This is the first attempt to simulate the long-term variability of freshwater systems in the Amazon. This initial simulation verified the ability of the model to reproduce the variability in discharge, river stage and flooded area. In the near future, we will improve the model by including better representations of the large-scale geomorphic characteristics of the river system, and the effects of land cover change on the water balance.

c) Interannual Climate Variability and River and Wetland Processes. Using diverse climate and river discharge data and our IBIS and HYDRA models, we investigated how climate variability impacts the river discharge and flooding in the Amazon basin over long and short time scales. We have found that long (24-28 year) and short (3-4 year ENSO cycle) modes of climate variability strongly influence the water cycle of the entire river basin. The 24-28 year mode of precipitation variability results in decadal scale variability in the river discharge of as much as 30% throughout the basin (Coe et al., Journal of Geophysical Research, 2002). The ENSO impact is more spatially heterogeneous, with decreased runoff, discharge and flooding, centered in the southeastern portion of the basin associated with El Niño, and increased runoff, discharge and flooding (centered in the northern portion of the basin) associated with La Niña (Foley et al., Global Biogeochemical Cycles, in press).

4. Physical Climate System. The tropical land and atmosphere form a highly coupled system. The surface fluxes not only control the inputs of water and energy into the atmosphere, but depend themselves on the atmospheric circulation. Depending on the spatial scale, changes in land cover may strongly affect the local, regional and global atmospheric circulation (Costa, in press, Cambridge University Press). Atmospheric circulation is partly driven by the surface energy and water balance, which are linked to vegetation and soil characteristics – including canopy albedo, leaf area, vegetation height and aerodynamic roughness length, rooting depth and soil texture. During the last few years, our group has developed two fully coupled climate / ecosystem models (GENESIS-IBIS and CCM3-IBIS), to explore the two-way interactions between climate and ecosystems.

a) Relative Importance of Amazonia in Generating Its Own Climate. We have performed a comprehensive suite of simulations with the GENESIS-IBIS model to determine the relative effects of large-scale deforestation and increased CO_2 concentrations (including both physiological and radiative effects) on Amazonian climate (Costa and Foley, Journal of Climate, 2000). The results of these simulations demonstrated that the Amazonian climate may be more sensitive to local environmental changes (deforestation) than to global environmental changes ($2xCO_2$). In addition, we identified some possible non-linear interactions between deforestation and global warming on the climate of the Amazon: deforestation and greenhouse warming both act to increase the average temperature of the basin, while they have opposing effects on precipitation. These results suggest that scenarios of future climate change over the Amazon must consider the potential interactions between increasing CO_2 and rates of deforestation.

b) Trends in the Hydrological Cycle of the Amazon Basin. We examined the 20-year variability of the full hydrologic budget of the Amazon basin, using a 1976-1996 time series from the National Centers for Environmental Protection / National Center for Atmospheric Research reanalyzed meteorological data set (Costa and Foley, 1999). Within this 20-year record, there was a statistically significant decreasing trend in the atmospheric transport of water vapor both into and out of the Amazon basin. This trend is associated with a general relaxation of the southeasterly trade winds, a weakening of the east-to-west pressure gradient, and a warming of the sea surface temperatures in the equatorial South Atlantic region. While the atmospheric transport of water vapor through the Amazon basin has decreased, the internal recycling of precipitation within the basin increased and basin-wide precipitation, evapotranspiration, and runoff have remained nearly constant. Even though basin-average precipitation and runoff have remained fairly stable, other components of the Amazon basin's hydrologic cycle have been altered significantly by large-scale changes in atmospheric circulation.

c) Mechanisms of Seasonal Rainfall Changes After Large-Scale Deforestation. Berbet and Costa (submitted to Journal of Climate) investigated the argument that changes in surface albedo are the major driver of rainfall changes after deforestation, by analyzing how seasonal changes in surface albedo are related to seasonal changes in rainfall. Initially, we analyzed the observed surface albedo data of Culf et al. (1995), showing that the albedo presents a seasonal variability. We then verified that the seasonal variability in simulated albedo in the Costa & Foley (2000) experiment was similar to the field observations. Finally, we demonstrated that the seasonal changes in simulated rainfall after a full-scale deforestation is proportional to the seasonal difference in albedo.

Training and Education

Our LBA-ECO training and education plan has several major components:

1. Developing Courses in Environmental System Dynamics and Modeling

Professors Foley and Costa will work together to develop an advanced course in environmental system dynamics and modeling, with a special focus on tropical forest systems. The course will be periodically offered at institutions in Amazonia, as well as being regularly offered at the University of Wisconsin and the Federal University of Viçosa. The course will have six major components:

- System Dynamics, Mathematical Basis for Systems Theory, Practical Uses of Differential Equations
- Modeling Principles, Stocks / Flows, Control Theory, Feedbacks
- Modeling Practice – Biological Systems: Ecosystem Ecology, Community Ecology
- Modeling Practice – Biogeochemical Systems: Carbon, Nitrogen, Phosphorus, Sulfur
- Modeling Practice – Climate and Hydrology: Energy Balance and Climate, Water Balance and Hydrology
- Modeling Practice – Resource Dynamics: Freshwater, Food and Fiber

2. Building a Portable Computer Classroom: Teaching in the Amazon

Our first training and education goal focused on the development of a new course, along with the associated lecture and laboratory materials. However, in order to actually teach this course in an Amazonian setting, we also need to overcome some basic infrastructure problems. Unfortunately, we cannot always be sure that the appropriate computer systems will be available in the universities and institutes across the Amazon.

As part of our LBA-ECO training and education work, we plan to build a portable computer classroom, consisting of 12 laptop PC computers, wireless ethernet cards (for laptops), wireless ethernet hubs, operating software, Stella software, other programs and customized carrying cases.

If you work in an Amazonian institution, and would like to host such course there, please contact Marcos H. Costa (mhcosta@ufv.br).

3. Training Graduate Students and Postdoctoral Scientists

In addition to our active efforts to enhance training in environmental system dynamics and modeling, we will also be training graduate students at our two universities. We plan to hire four graduate students to work in this project. Applications for graduate school positions at the University of Wisconsin are open until January 15 2003 (contact jfoley@wisc.edu). Applications for graduate school positions at UFV are open until May 15 2003 (contact mhcosta@ufv.br)

4. Public Outreach and Education

In addition to our formal education and training activities described above, our team will also actively engage in public outreach and educational activities. Below we describe our current plans:

- Write Popular Science Articles.
- Give Public Lectures.
- Build an Electronic Atlas of Amazonia.

Synthesis and Integration

In the second phase of LBA-ECO it is extremely important to achieve a high degree of synthesis and integration among the investigating teams. Our modeling and data synthesis efforts are particularly well suited to achieving this integration, and afford us numerous opportunities for collaboration. Below we describe five efforts that will aid in the integration and synthesis of LBA-ECO scientific objectives. In addition to the efforts listed below, we are would like to collaborate with as many groups as possible. If you feel that there are potential for collaboration between your investigation and ours, do not hesitate to talk to us.

1. Developing Models of the Amazon Basin: Integrating Ecology, Hydrology and Climatology

Our team is actively building models of terrestrial ecosystems, freshwater systems, and climate that are appropriate for large-scale synthesis studies of the Amazon basin. These models are publicly available (through our web site, or by request), and can be adapted to other LBA-ECO studies with ease. We will be actively working with several groups to integrate these models into their research strategy (see examples below). In addition, we will invite all LBA investigators to use our modeling tools – and we will be happy to work with any team that needs our technical help. The modeling tools we provide to the LBA community include:

- IBIS – An Integrative Terrestrial Ecosystem Model of the Amazon Basin.
- HYDRA – A Large-Scale Hydrological Model of Rivers, Wetlands, and Floodplains.
- CCM3/IBIS – A Fully Coupled Climate / Ecosystem Model.

2. Developing Large-Scale Datasets: Characterizing Ecosystems, Land Use, and Freshwater Systems

In addition to providing flexible models of the ecological, freshwater and climatic systems of the basin, we are also working to develop regional-scale datasets of environmental conditions across Amazonia. These datasets are being made available to the LBA community through Beija-flor, and other web-based distribution mechanisms. As we continue to develop and make available regional datasets for the Amazon, we will make them available to other teams. Our current available holdings include basin-wide data on:

- patterns of land use (including agricultural activity in croplands and pastures)
- patterns of vegetation and land cover
- basic geographical data (elevation, river paths, state / county boundaries, basin boundaries)
- basic hydrological data (discharge, floodplain area, river height / wetland area, channel characteristics, routing directions)
- compilations of climate data (from other sources)
- compilations of ecosystem data (from other sources)

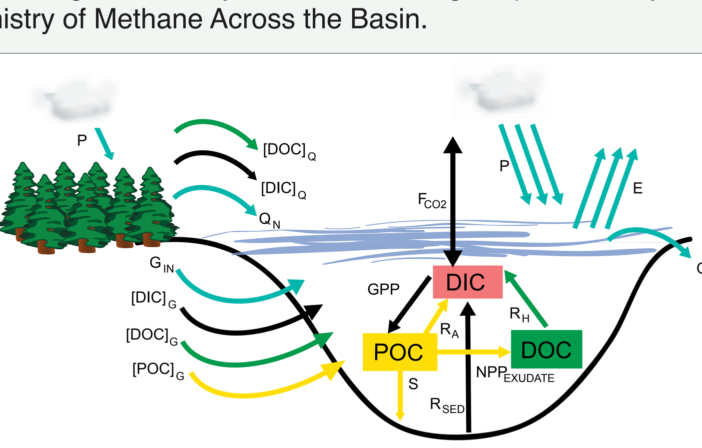
3. Wisconsin – UCSB – NASA-Ames Integrated Activity

- LBA Group TG-05 (Potter/Carvalho)
- LBA Group LC-07 (Melack/Novo)

Our first collaborative project will link LBA teams based at the University of Wisconsin (Jon Foley), the University of California – Santa Barbara (John Melack), and the NASA-Ames Research Center (Chris Potter). In this three way LBA-ECO collaboration, we will be focusing on the biogeochemistry and hydrology of wetlands and floodplains across the basin. Wisconsin will be providing hydrological modeling expertise to the group, Santa Barbara will contribute remote sensing datasets and techniques, and NASA-Ames will contribute to the development of models of methane and other trace gas fluxes. We have identified three primary tasks:

- Testing Large-Scale Hydrological Models of Rivers and Wetlands.
- Modeling the Transport and Biogeochemistry of Carbon Through Aquatic Ecosystems.
- Modeling the Biogeochemistry of Methane Across the Basin.

Framework for River Carbon Biogeochemistry Model. Here we show a framework for modeling the transfer of carbon between terrestrial and aquatic ecosystems (adapted from Bade et al., in prep). This model describes several forms of carbon, including DOC (dissolved organic carbon), DIC (dissolved inorganic carbon), and POC (particulate organic carbon). These carbon forms are transferred from terrestrial ecosystems through surface runoff and groundwater drainage (following leaching algorithms of Neff and Asner, 2000). Later, the carbon is processed within aquatic ecosystems; in this framework biological carbon fixation (GPP), respiration (R_A, R_H, R_{SED}) and outgassing (F_{CO2}) are explicitly accounted for.



4. Interactions with BIGFOOT II Activity

- LBA Group CD-15 – Cohen/M. H. Costa

The BIGFOOT II investigation will attempt to compare MODIS products – including estimates of land cover, leaf area index (LAI), fraction of the absorbed photosynthetically active radiation (f_{APAR}), and gross and net primary production (GPP, NPP) – with in-situ measurements and results of IBIS simulations. The field experiment will be conducted in an area of 5 x 5 km around the LBA primary forest site at Santarém. At the site, values of land cover, f_{APAR}, LAI and NPP will be determined using in-situ measurements. Using the meteorological data plus the land cover and LAI data collected at the site, GPP and NPP will be modeled using two different models, Biome-BGC and IBIS. The simulated NPP will be compared to local measurements of NPP, the simulated fluxes of CO_2 and H_2O will be directly compared to the measurements made by the eddy correlation system at the tower, and the simulated GPP will be compared to GPP calculations based on the CO_2 fluxes measured at the tower. We believe that the integration between our project and BIGFOOT-II will make IBIS a more robust model, significantly reducing the uncertainties related to the modeling activity.

5. Integrated activity – Calibration of IBIS against tower data at multiple towers

- LBA Group CD-04 – Goulden/Rocha
- LBA Group CD-200 – Grace/J. M. Costa
- LBA Group CD-203 – Kruijt/A. Nobre
- LBA Group CD-207 – Kruijt/Manzi

We will conduct a calibration of IBIS against micrometeorological data collected at multiple towers (Santarém, Caxiuanã, Manaus, Rondônia). Our goals are to evaluate how the land surface parameterization affect the fluxes of energy, water and carbon in different sites, and to estimate what errors are expected if a single set of parameters is used in all sites.