Carbon balance in Amazon forests from site to region: integrating remote sensing from satellites and aircraft with ground-based tower and biometric data

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Objective: to link remote-sensing indices to flux tower and forest plot datasets to derive empirical predictions and test models of carbon dynamics at large scales. We focus on:

1. **indices of seasonal variation** in driving variables (e.g. sunlight and precipitation), and in the response of key processes (e.g. carbon fluxes and foliar activity);

2. **indices of forest structure and disturbance history** such as canopy height, canopy gap-size distribution, and stocks of coarse wood debris; and,

3. **a hypothesized relation between seasonality and structure.**

We focus on **seasonality** because ecosystem response to seasonal forcing provides a window onto mechanisms that also control long-term responses, but recent work (Saleska et al., 2003; Goulden et al., 2004) shows that such mechanisms are still not well understood. We focus on **forest structure** (a correlate of disturbance history) because recent work (Moorcroft et al., 2001; Saleska et al., 2003) shows that although carbon balance is acutely sensitive to disturbance history, the distribution of forest disturbance states across larger scales is not well known.

Methods: (A) Remote Sensing: (1) **Satellite.** We will use 5+ years of data from MODIS, focusing on the Enhanced Vegetation Index, EVI (canopy greenness) and on Land Surface Water Index, LSWI (canopy water) to reveal seasonal patterns in foliar activity. (2) **Aircraft.** We will use LIDAR data (to be acquired during the LBA-BARCA aircraft campaign in October 2005), to characterize landscape-scale forest structure in each of three regions along a precipitation transect (Manaus, Santarem, and Caxiuana). We will compare LIDAR data to recent satellite-derived indices of structure (IceSat GLAS canopy heights; IKONOS-derived crown-sizes). (B) **Integration of remote sensing with ground studies at:** (1) **eddy flux towers.** We will use eddy flux data from 12 Amazonian towers which sample primary forest, transitional forest, and converted lands to calibrate MODIS indices to predict basin-wide GPP carbon fluxes. (2) **forest plots.** We will integrate forest plot data with LIDAR-retrieved forest structure to predict landscape-scale biomass, and possibly, tree growth rates. (C) **Modeling.** We will use LIDAR data to constrain Ecosystem Demography (ED) model simulations of Amazonian carbon balance at various spatial scales and test against ground observations.

Significance: This submission proposes an innovative plan to link local to regional scale measurements in forests and converted lands to rigorously test remote-sensing based predictions of Amazonian carbon dynamics, an LBA priority topic. More generally, this work advances NASA’s national objective to **Study the Earth system from space** [by testing space-derived predictions of earth system processes] and develop new space-based and related capabilities for this purpose [by developing LIDAR-biomass metrics that could help demonstrate the potential of a future space-based LIDAR capability].
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1.1 Introduction: statement of problem and opportunity

Amazon forests play a key role in the global carbon cycle, and hence are expected to significantly influence and be influenced by future trajectories of climate, but our ability to quantify the magnitude of these influences is limited. Recent work has significantly advanced both (1) our understanding of key controlling mechanisms operating at the local plot scale, and (2) our ability to remotely sense and model a wide array of ecosystem parameters at landscape to biome-wide scale, but the satisfactory integration of these two spheres of knowledge – i.e., the rigorous testing of remote sensing based estimates at spatially-relevant distributed scales – is limited. This submission proposes an innovative interdisciplinary research plan to *synthesize and integrate LBA datasets* at local to landscape and regional-scale measurements in forests and converted lands to rigorously test remote-sensing based estimates of *Amazonian carbon dynamics*.

We focus this research plan on two facets that are both essential to understanding ecosystem carbon dynamics, and directly amenable to remote sensing technologies: (1) links between disturbance, canopy structure and forest demography; and (2) seasonality of ecosystem parameters as a window onto mechanisms controlling carbon dynamics.

Questions about disturbance and forest structure are at the center of recent debate about whether old-growth Amazon forests are net sinks for atmospheric CO\textsubscript{2} (due to either CO\textsubscript{2} enrichment, or to other causes such as increased radiation). Several eddy flux towers (Malhi et al., 1998; Andreae et al., 2002) and a network of long-term forest plots (Phillips et al., 1998; Philips et al. 2002; Baker et. al. 2004) consistently show carbon uptake. However, recent work (Saleska et al., 2003; Rice et al., 2004; Chambers et al., 2004; Rolim et al., 2005) argues that much of the apparent uptake could in fact be an artifact of recovery from anthropogenic disturbance or from recent natural disturbance events (such as ENSO), and that when averaged over appropriately large spatial and temporal scales, such uptake would disappear (Moorcroft et al., 2001). But without landscape and regional measures of the distribution and dynamics of disturbance states, this debate will be hard to resolve.

Questions about how moisture and sunlight control forest phenology and productivity are not well understood across the variable rainfall and seasonality patterns that span the Amazon basin (Sombroek 2001). Recent plot studies in these old-growth rainforests show green flushes of new leaf growth in the dry season with tree roots able to access deep soil moisture (Nepstad, et al. 1994). Flux towers show high levels of photosynthesis during the dry season (Saleska et al., 2003; Xiao et al., 2005) and remote sensing-based modeling suggests these tropical forests may be light-limited not water-limited (Nemani et al., 2003), but it has proved difficult to get process-based ecosystem models to reproduce such patterns, suggesting that important questions remain about controls on key ecosystem parameters like tree rooting profiles and hydraulic lift.

LBA datasets of remote-sensing and ground-based observations provide an opportunity to address these issues, and we propose a synthesis organized around two key questions:

| (1) What is the spatial distribution of canopy heights (i.e., disturbance states) in Amazon forests, and how does disturbance affect carbon balance across landscape and regional scales? |
| (2) What are ecosystem responses to seasonal and interannual variations at these larger scales, and what can we infer from these about the effects of variations at multi-year time scales (ENSO cycles, global climate trends) on forest carbon balance? |

To answer these questions, we propose a *synthesis and integration program*, a plan for *preparation and analysis of key datasets*, and a *leadership synthesis activity* on carbon dynamics.
1.2 Relevant past research and accomplishments

1.2.1 Forest demography and seasonality drive carbon dynamics at the plot scale

The PI (Saleska) and Brazil Collaborator Nobre are members of NASA LBA science team CD-10 (Wofsy/Kirchhoff/Camargo/Nobre), and Brazil Collaborator Rocha is a member of science team CD-04. The principal scientific results to date include two major findings: First, short-term (seasonal) variations in environmental forcing (primarily precipitation and sunlight) have radically different effects on carbon balance compared to predictions from process models (carbon uptake is highest in the dry season, models predict carbon loss, see Fig. 1A). We showed [Saleska et al., 2003; Goulden et al., 2004] that this effect reflected both higher than predicted seasonal changes in decomposition rates for the large pool of dead organic matter (soils, litter and coarse woody debris, CWD), and less than predicted variation in Gross Primary Production (which stayed high in the dry season due to absence of modeled water-limitation effects). Second, in contrast to all previously published Amazonian eddy covariance studies, the annual carbon balance was negative (carbon loss) due to recent disturbance-induced mortality event (Fig. 2), which we expect to be transient. The resultant large CWD pool proved to be critical, both as an indicator of disturbance and a source for losses of carbon (Rice et al., 2004). These results highlight the importance of local disturbance history and forest stand demography for understanding carbon balance.

1.2.2 Using MODIS data products to study vegetation dynamics and phenology

Co-investigators Huete and Brazil Collaborator Shimabukuro were PI’s for investigation LC-06/LC-19 in phase I of LBA-ECO. Principal scientific results include: use of MODIS to analyze of the seasonal dynamics and phenology of the diverse cerrado physiognomies and converted pasture areas that now make up the Cerrado Biome (Ratana et al., 2005; Ferreira and Huete, 2004), and to study basin-wide seasonal responses to precipitation (discussed further in the body of the proposal and in Huete et al., submitted).

Overall, LC-06 results indicate the possibility of utilizing the MODIS NDVI and EVI images for operational land cover assessments in the Cerrado and Forest regions.

1.2.3 Effect of landscape Inhomogeneities on measured fluxes

Co-investigator Parker is a collaborator for investigation CD-03 ((Fitzjarrald/ Moraes) during LBA-ECO Phase II. The Parker collaboration characterized forest canopy structure in eddy flux tower footprints using ground-based portable canopy LIDAR (PCL). The focus for CD-03 was on the effects of canopy gaps and the vertical distribution of surface area on the micrometeorology in the vicinity of the two forest eddy flux towers, including the key question of the whether changes in canopy structure caused by the selective logging at km 83 could have induced changes in local micrometeorology that affected eddy-covariance derived fluxes. These surveys are also directly relevant for understanding vegetation and carbon dynamics, and it is this application which we focus on here.

1.2.4 Balanço Atmosférico Regional do Carbono na Amazônia (BARCA) flight planning

Co-investigator Artaxo is a member of the LBA BARCA science team, and is head scientist for the Bandeirante aircraft from which the LIDAR measurements proposed for analysis here will be made. All permissions (including Brazil’s publication of the BARCA portaria in December 2004) and flight preparations are on track for scheduled BARCA flights in October 2005.
1.2.5 Data submissions to LBA DIS

All significant datasets derived from previous work of the investigators has been registered and is available through LBA-DIS. These include: complete high-quality tower datasets for the two Tapajos forest towers (whose science teams included PI Saleska and collaborator Rocha), remote sensing analysis of Huete and Shimabukuro; and ground based LIDAR surveys conducted by Co-I Parker for CD-03.

1.3 Proposed Objectives

Our overall study objective is to integrate the several components of our previous work – ground-based tower and plot observations, and remote sensing-derived observations (MODIS data from satellites and LIDAR data from aircraft) – into a larger synthesis to understand the effects of (1) canopy structure and forest disturbance states, and (2) processes controlling seasonal variations across landscape and region, on overall Amazonian carbon dynamics (see Illustration below). To address this objective, we propose two main study components: a synthesis and integration component (LBA priority 1), and a data preparation and analysis component (LBA priority 2) to produce datasets required by us for component 1, and also desired by LBA researchers generally.

1.3.1 Synthesis and Integration to answer questions about “Amazonian Carbon Dynamics”

Our objectives for synthesis and integration are summarized in the Illustration below, and can be broken into six goals:

(A) Use satellite-based MODIS products (EVI, LSWI) to assess seasonality of ecosystem properties and component C fluxes (box A in the illustration at right). We will do this at regional to basin scales, and also for pixels coinciding with key study areas.

(B) Use aircraft-based LIDAR to assess forest canopy structure at landscape scales, distributed across regions (Box B in the illustration).

(C) Test a hypothesized relation between MODIS-derived seasonality and ecosystem structure. Such a relation (between boxes A and B at right) is based on the idea that sufficiently large disturbances will affect how an ecosystem responds to seasonally varying availability of moisture and sunlight.

(D) Use regionally-distributed ground observations at eddy flux towers and biomass plots (Box G in Illustration above) to calibrate empirical models relating remote sensing observations of seasonality and structure to obtain (i) basin-wide GPP carbon fluxes and (ii) landscape-scale biomass and tree growth rates. Specifically, we will compare MODIS index seasonality to seasonality of relevant fluxes (especially GPP) at eddy flux towers, producing a statistically-derived empirical prediction of GPP from MODIS EVI and LSWI, using the Vegetation Photosynthesis Model (VPM, Xiao et al, 2005 – see Box D in the Illustration). We will also
compare LIDAR derived canopy structure to biomass and growth rates in ground plots, producing statistically-derived empirical predictions of standing stocks of biomass and, potentially, tree growth rates, Box F in the Illustration.

(E) Use remote sensing data to constrain Ecosystem Demography (ED) model simulations, and use ground observations to test landscape-scale ED model predictions. The ED model explicitly represents canopy structure at the patch scale, allowing a way to use empirical measures of canopy structure or disturbance state to be related to tree demography, stand succession state, and whole ecosystem carbon balance. We will collaborate with Prof. Paul Moorcroft’s group at Harvard University to test and constrain ED model predictions, focusing on the use of LIDAR remote sensing metrics of canopy structure.

1.3.2 Preparation and Analysis of Datasets

Core science “Synthesis and integration” goals depend on the availability of multiple datasets. Although satellite-based remote sensing products are now available, LIDAR and eddy flux tower datasets will require preparation and analysis before they can be used in this or other analyses. The two objectives for this component of the proposal are:

(A) Combine data from multiple Amazonian flux towers to produce consistent cross-site datasets Extensive data on net ecosystem exchange of CO₂ and associated environmental variables is now available at local towers across the Amazon, in forest, pasture, and agricultural sites. These separate tower datasets have yet to be combined together systematically, with consistent data-cleaning, and error-checking protocols. We will integrate tower datasets, paying particular attention to the problems of correcting nighttime fluxes, resulting in a data product to facilitate robust and reliable intercomparisons among towers, and between towers and remotely sensed data products or model simulations.

(B) Process LIDAR data from BARCA and analyze relation with ground-based biometry. The separately funded BARCA campaign, scheduled to fly in October 2005, will include an airborne LIDAR (Nelson et al., 2003) for remote sensing of forest canopy structure. Flight plans include coverage of ground-based forest plots in the regions of Santarem, Manaus, and Caxiuana. We will analyze the regional aircraft-based LIDAR data and integrate with ground-based biometric data where it exists to develop algorithms for relating LIDAR data to ground metrics (biomass, canopy height, etc).

1.4 Approach and methods for Achieving objectives

1.4.1 Study Sites and Datasets

Remote sensing MODIS datasets will be integrated with data from multiple sites. Proposed sites for study (comprehensively summarized in Table 1; detail on central Amazon sites shown in Figure 3 and Figure 4) include four main kinds of data: (1) continuous data from eddy flux towers, including environmental variables and atmosphere-ecosystem exchange fluxes of heat, momentum, carbon and water; (2) survey data from ground-based biomass plots, which at intensive sites (Manaus, Santarem) includes comprehensive accounting of live trees, dead trees, dead coarse wood stocks, and lianas; derived dynamic demographic quantities include tree growth, mortality, and recruitment; (3) data on canopy structure from airborne LIDAR surveys; and (4) data on land-use history and time since conversion or disturbance (for secondary forests and pasture or agricultural lands). Data availability is summarized in Table 1. Methods for uses of these data are described in the sections below.
Table 1. Study sites and datasets proposed for testing remote-sensing based predictions of Amazonian carbon dynamics (note: regions to be surveyed by airborne LIDAR are shaded in blue, plots already surveyed by ground-based LIDAR in bold. Sites with known disturbance histories are in red)

<table>
<thead>
<tr>
<th>Study Site</th>
<th>Eddy towers</th>
<th>Biomass plots (initial census / Disturbance gradient plots)</th>
<th>Precip (mm/yr) / dry season length (mo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>São Gabriel Cachoeira, Amazonas</td>
<td>1. primary wet forest (0° 28.8’ N, 66° 30’W) started January 2005</td>
<td>BDFFP, 65 ha (early 1980s) 2</td>
<td>4000+ / 0 mo</td>
</tr>
<tr>
<td></td>
<td>2. primary rain forest, K34 (2° 36.5° S, 60° 12.5’ W) 1999-present 1</td>
<td>BIONTE. 6 ha (mid 1980’s) 3</td>
<td>2200 / 2.4 mo</td>
</tr>
<tr>
<td></td>
<td>3. primary rain forest, C14 (ZF2) (2° 35.4° S, 60° 6.9’ W) 1999-present 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* plus 1 year from Sept. 1995 - Oct 1996 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manaus, Amazonas</td>
<td>2200 / 2.4 mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. primary moist forest, km67 (2° 51’ S, 54° 58’ W) 2001-present 4</td>
<td>km67 footprint, 20 ha (1999) 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. selectively logged primary forest, Km83 (3° 3’ S, 54° 56’ W) 1999-present 5</td>
<td>km83 footprint, 18 ha (2000) 5</td>
<td></td>
</tr>
<tr>
<td>Santarém, Para:</td>
<td></td>
<td>km’s 72 and 117, 20 ha each (2001) 4</td>
<td>1920 / 4.7 mo</td>
</tr>
<tr>
<td></td>
<td>6. pasture/agriculture, km77 (3.012° S, 54.537° W) not including data gap when tower damaged by treefall</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>7. Seasonally flooded transitional forest () 2004-present 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bananal Island, Tocantins</td>
<td></td>
<td></td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>8. primary forest (1° 43.06’ S, 51° 27.60’ W) 1999-present 8</td>
<td>2 ha (mid 1990’s) 8</td>
<td></td>
</tr>
<tr>
<td>Caxiuana, Para</td>
<td></td>
<td>2500 / 2.8 mo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9. primary forest, RBJ-B (10° 4.7’ S, 61° 56.02’ W) 1999-2003 9</td>
<td>~2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10. pasture, FNS-B (10° 45.7’ S, 62° 21.5’ W) 199-2003</td>
<td></td>
<td></td>
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<tr>
<td>Jarú, Rondônia</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>11. transitional dry forest (11° 24.75’ S, 55° 19.50’ W) 1999-2002 10</td>
<td>Selective logging site (low impact and -clearcut treatments)</td>
<td>~2000 / 4 mo</td>
</tr>
<tr>
<td></td>
<td>12. pasture (9° 51.73’ S, 58° 13.81’ W)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mato Grosso Sinop Cotriguaçu</td>
<td>Fatura Farm, Tocantins</td>
<td>Transitional zone with different age classes of regrowth of both primary forest and cerrado.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Old secondary forests from 1970’s and before</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Secondary forests with varying age classes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 PI: Higuchi, INPA, Brazil. See e.g., Higuchi et al. (1997), Chambers et al. (2004).
4 PIs: Wofsy, Harvard University, USA/Camargo, CENA/USP, Brazil. See Saleska et al. (2003), Rice et al. (2004).
5 PIs: Goulden, UC Irvine, USA, Rocha, USP, Brazil. See Rocha et al. (2004), Goulden et al. (2004), Miller et al. (2004).
6 PIs: Fitzjarrald, SUNY, USA, Moraes, UFSM, Brazil. See Sakai et al. (2004).
7 PIs: Borma/Collicchio, UFT, Brazil; Rocha, USP, Brazil; Cabral, EMBRAPA, Brazil
8 PIs: Sa/Rocha (UFPA, and Museu Goeldi, Brazil. See Carswell et al. (2002). For biomass plots, S. Almeida, Museu Goeldi, Brazil.
9 PIs: Manzi (INPA), Cardoso (UFR), Brazil. See von Randow (2004); Kruijt el. at (2004).
10 PIs: Priante, UFMG, Brazil; Vourlitis, USA. See Priante et al. (2004), Vourlitis et al. (2004).
1.4.2 Synthesis and integration to address “Amazonian Carbon Dynamics”

(A) Investigate Seasonality by integrating Satellite MODIS and spatially distributed ground data

**Satellite based remote-sensing indices from MODIS:** We plan to investigate phenology and seasonal vegetation response to rainfall using 5+ years of satellite data from the recently launched Terra- Moderate Resolution Imaging Spectroradiometer (MODIS) (Justice 1998). The MODIS sensor offers new opportunities for Amazon studies with state of the art calibration, full atmosphere correction, newly developed terrestrial products, and much finer resolution (250 m) observations that facilitate cloud-filtering and noise removal. We will focus in indices which reflect (1) canopy greenness, and (2) water content.

1. **Canopy greenness via the Enhanced Vegetation Index (EVI).** Photosynthetic vegetation activity (greenness) will be determined with the MODIS “enhanced vegetation index” (EVI), from level 2G (gridded) daily reflectance at 250 m resolution, and generated as:

\[
EVI = 2.5 \times \frac{\rho_{NIR} - \rho_{red}}{1 + \rho_{NIR} + (6 \times \rho_{red} - 7.5 \times \rho_{blue})}
\]

where \(\rho_i\) are surface reflectances in near-infrared (NIR, 841-876 nm), red (620-670 nm), and blue (459-479 nm) bands; the coefficient ‘1’ is a first-order canopy background correction term; and the blue and red band coefficients, 6 and 7.5, minimize residual aerosol variations (Huete, et al. 2002). A 16-day EVI composite is generated using quality assurance (QA) metrics that remove lower quality pixels contaminated by residual clouds, shadow, and high aerosol loadings for improved spatial and temporal consistency.

The EVI focuses on spectral bands related to plant photosynthetic activity, and works by combining the chlorophyll-absorbing red spectral region with the strong leaf reflectance signal in the NIR using a semi-empirical, canopy radiative transfer equation based on Beer’s law. As such, EVI is expected to correlate with ecosystem-scale Gross Primary Production (GPP), providing a powerful tool for probing this key ecosystem flux across scales from individual sites to the globe (Nemani et al., 2003). EVI contains biological information similar to other spectral vegetation measures, e.g., the normalized difference vegetation index (NDVI), but importantly for this study, does not saturate in the high leaf area index canopies of Amazônia (LAI~ 4.5-7).

2. **Canopy water content via the Land Surface Water Index (LSWI).** Studies show that changes in leaf water content have a large effect on reflectances in portions of the NIR and shortwave-infrared (SWIR) spectral regions (Hunt and Rock 1989; Gao 1996). Studies show increases in leaf reflectance are associated with plant stress across the SWIR region (Gausman and Allen 1973; Tucker 1980), allowing inference of soil moisture status in the plant root zone.

For this proposed study, we plan to use the Land Surface Water Index, which contrasts the NIR with SWIR (~1650 nm) wavelengths,

\[
LSWI = \frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}}
\]

and is an indicator of canopy water content (Xiao 2004).

**MODIS EVI shows Amazon forests “green up” in the dry season:** The combined use of vegetation indices and water indices may yield new insights to the monitoring of soil moisture and separation of moisture signals within a canopy. To illustrate with EVI, we used five years of NASA-MODIS satellite measurements to generate a composite annual cycle of EVI in a precipitation transect spanning the eastern length of Amazon drainage (Huete et al., submitted). This analysis (Figure 5) shows basin-wide (5.8 x 10^6 km²) increases in EVI (photosynthetic
activity) in the dry season, implying that Amazon rainforests green-up and are more productive in the dry season, precisely the opposite of the pattern predicted for GPP across the same region by models (Figure 6). Significant increases in rainforest activity occurred in the dry season over eastern Amazônia (5 month dry season) with smaller increases in the western portion near Manaus (~2 month dry season). A complete reversal in phenology was observed east of Cauaxi, along the “arc of deforestation”, where extensive pastures and secondary forests remain following deforestation (Roberts 2003).

We propose to extend this initial analysis by first, repeating a similar analysis with LSWI and, second, by using deviations of EVI/LSWI indices from the composite annual cycle to investigate the effects of interannual variability.

Comparing remote sensing indices to local site data. A core objective of proposed work is to directly relate such broad scale remote-sensing observations to a distributed network of sites where local observations can be directly linked to controlling processes and mechanisms. To accomplish this, we will extract MODIS indices from 7x7 pixel arrays of 250 m resolution for each of the study sites in Table 1. To minimize the problem of residual cloud contamination and poor data quality (particularly strong in the Amazon), we will apply quality assurance (QA) information in the spatial domain to retain and average only the best quality pixels in the 16-day interval to obtain time series. In addition, we plan to also generate ‘composite year’ vegetation phenology profiles by averaging all 5+ years (2000-present) of QA-filtered, 16-day composite data (as with the basin wide data presented in Figure 5).

We illustrate the proposed objective by comparing EVI with flux tower data in the forest (km67 and km83 towers average) and pasture/agricultural (km 77 tower at site that was pasture when measurements began in 2000, and was cleared and converted to rice production in 2001) in the Tapajós region (see Figure 4A). This comparison (Figure 7) shows: (1) distinct differences in EVI seasonal profiles between forest and pasture/agricultural sites, with forest EVI following essentially the same trend (with high dry-season EVI) as the basin-wide analysis (albeit with more noise and a less discernible peak), while the pasture/farmland EVI shows a distinct drop in the dry season; and (2) rough correspondence between EVI seasonality and that of tower-derived GPP, across both sites, especially as distinct from ecosystem model simulated GPP for the forest, which by dropping in the dry season diverges strongly from both EVI and tower-derived GPP.

We note that although pasture/farmland EVI averaged over several years appears to under-predict the magnitude of the GPP drop at this site, this is likely a consequence of a discrepancy of averaging periods (the km 77 GPP is based on only the 18 months reported by Sakai et al. (2004), which spanned the dry-season conversion of this site from pasture to farmland).

This initial analysis illustrates the power of integrating remote sensing and ground data. The generality of studies conducted at a single site or a small number of sites may be questioned (as some have questioned results from the Tapajós because of concern that it is anomalous (Grace 2004)), and a surprising remote sensing-based observation (as in Figure 6) may raise concerns that it is due to an artifact (arising, e.g., from a seasonal interference pattern induced by cloud cover or aerosol), but the consistency between the independent EVI and tower-derived GPP observations in the Tapajós forest, lends confidence to both findings.

We propose to extend this initial analysis to eddy flux datasets from towers across the Amazon (see Table 1), using LSWI as well as EVI, combining them using the Vegetation Photosynthesis Model (VPM) to produce tower-calibrated predictions of GPP carbon fluxes across the Amazon basin over all years for which MODIS data are available. We have
contributed to a similar analysis for the Tapajos region alone (Xiao et al., 2005), and now propose to extend it to the Amazon basin as a whole.

(B) Investigate links between ecosystem structure and carbon balance using aircraft-based
LIDAR data and spatially distributed biomass data

Remote sensing data provide a powerful means to obtain the distribution of disturbance across the landscape: low canopy height, relative to the potential on a given soil, implies recent disturbance. Disturbance patterns and the distribution of stand ages are the key to accurately scale carbon balances measured at local points to larger regions, since the time since disturbance regulates the carbon cycle at gap scale (see “Flux v. height/age” in page 3 Illustration, box C).

Our primary task for this objective is to use aircraft LIDAR data (sample data depicted in Figure 8) on canopy structure over landscapes near the Manaus, Santarem, and Caxiuana eddy towers to: (1) sample the distribution of canopy heights (and hence, of disturbance states) across Amazonian landscapes, and thereby (2) directly estimate key components (aboveground biomass, tree growth rates) of landscape-scale carbon balance which can be compared to ground-based measurements of these components, and (3) indirectly estimate landscape-scale carbon balance by constraining demographic model simulations thereof (see Project Goal (D), below).

Ground-based Portable Canopy LIDAR surveys (which retrieve data comparable to that obtained from above, see Figure 9) show that: (1) LIDAR metrics effectively retrieve aboveground biomass of stands in different biomes around the world, and also explain biomass variation within plots in the km67 tower footprint (Figure 10), and (2) LIDAR metrics show potential for retrieving tree growth rates. There are two approaches to estimating aboveground growth: (a) conduct repeated LIDAR surveys and obtain growth from the difference between surveys, and (b) uses the texture of the outer canopy as a predictor. The surface of the outer canopy is flat and smooth in young, rapidly growing forests and becomes progressively more rugose as stands age and decline in growth rates (Parker and Russ 2004, Hiroaki et al. 2004, Nadkarni et al. 2004). The shape of the mean PAR transmittance profile mirrors this developmental pattern in structure (Parker et al. 2002, Parker et al. 2004b). Two measures of this texture, the slope of the outer canopy hypsograph and the variability of the outer canopy height, show promise as indicators of growth (Figure 11), and we will test these in Brazil.

Secondary tasks focus on comparing LIDAR data with other remote-sensing metrics obtained in the Amazon region, including: (1) canopy structure via the Geoscience Laser Altimeter System (GLAS) sensor on IceSat (http://icesat.gsfc.nasa.gov; Zwally et al., 2002), which was tasked for and has successfully acquired a number of spots in the Tapajós region (GLAS acquires a footprint ~70 m spaced 175 m along its ground track, and the return waveform has a vertical resolution of 15 cm.); (2) crown diameter retrieved from high-resolution IKONOS images using an automated crown detection algorithm (Palace and Keller, unpublished data).

(C) Test hypothesized relation between MODIS-derived seasonality and forest structure/age

High-frequency time series of remote sensing data (like that acquired by MODIS) are ideal for acquiring detailed information on seasonal patterns (e.g. Figure 5; Xiao et al., 2005). LIDAR sensors are ideal for revealing forest structure, disturbance state, and perhaps carbon balance (Hurtt et al., 2004) but, with the indefinite deferral of VCL satellite launch, do not have a long-term satellite platform for large-scale spatial coverage (the GLAS sensor is short term).

The MODIS data indicates that seasonal patterns may in fact contain information about the disturbance state of forests, perhaps because differential access to deep soil water by forests in different states (e.g. young secondary forests have less access to deep soil than old-growth forests) is revealed in seasonal patterns of EVI. For example, in the central Amazon
precipitation transect EVI showed a complete reversal in phenology east of 50 W (in the vicinity of Cauaxi), along the “arc of deforestation”, where extensive pastures and secondary forests remain following deforestation (Roberts 2003) (Figure 5). Likewise, a “seasonality index” (October EVI minus May EVI) generated for the Tapajos clearly shows that human-disturbed areas (evident from a Landsat ETM image) have reduced (or reversed) seasonality (Figure 12).

Since this kind of analysis can easily be extended to the continent (Figure 13), we will test whether even subtle variations in disturbance state (e.g. those not visible on a Landsat ETM) can be detected by careful analysis of MODIS index seasonality. We will do this in two ways: (1) direct comparison to aircraft LIDAR surveys; and (2) analysis of MODIS indices at sites of known disturbance state or stand age (see Table 1). Disturbance classes include pastures, capoeras, and secondary forest regrowth of varying but known age. Of key importance will be selecting secondary forests of common age and rainfall seasonality conditions.

(D) Integrate seasonality, structure and carbon balance data to test ED Model simulations

The distribution of canopy heights predicted by demographic models can be translated into the distribution of gap ages and thus the landscape-scale carbon flux can be assessed. Hurtt et al. (2004) showed that spatially-distributed measurements of canopy height in Costa Rica (retrieved via LVIS, an aircraft-based LIDAR) can constrain the Ecosystem Demography model (ED) to predict the actual spatial distribution of carbon fluxes across a region.

The Ecosystem Demography Model, version 2 (ED2) is an integrated biosphere model incorporating plant community dynamics, soil carbon and nitrogen biogeochemistry, and land surface biophysics (Medvigy et al. 2004). The fast-timescale (hourly to seasonal) fluxes of carbon, water, and energy are captured using the leaf photosynthesis and soil decomposition modules of ED (Moorcroft et al. 2001) coupled to a multi-layer, leaf and soil implementation of the LEAF-2 biophysical scheme (Walko et al. 2000). Long-timescale changes in the biophysical, ecological, and biogeochemical structure of the ecosystem are captured using the ED model’s system of size- and age-structured partial differential equations that explicitly track the changes in the vertical and horizontal heterogeneity of ecosystem structure that result from the ecosystem response over yearly, decadal, and century timescales.

Run in forward mode, ED generates a distribution of patch ages and associated canopy height distributions, and responds to seasonal variation in environmental drivers by generating seasonal patterns of foliar phenology and photosynthesis. But MODIS-derived EVI can also be used to prescribe the temporal pattern of leaf phenology in ED, and LIDAR-derived canopy structure data be used to constrain ED predictions of landscape-scale carbon fluxes. Other large-scale models (IBIS, TEM) that have used for the Amazon do not incorporate forest demography and cannot capture the observed carbon cycle effects of disturbance. But ED, when constrained by actual canopy heights, should be able to predict carbon balance (net loss, in sites subject to recent disturbance events, and net uptake in sites long undisturbed).

Prof. Paul Moorcroft’s group at Harvard has been funded by NSF to apply the ED model to South America, and we will collaborate with him to use our aircraft LIDAR data on the distribution of forest canopy heights to constrain ED model predictions of landscape scale carbon balance, which can then be compared to observed fluxes derived from the network of eddy flux towers and biomass plots (Table 1).

1.4.3 Preparation and analysis of datasets

The work proposed here covers two categories: (1) integration of eddy flux data from multiple towers across Amazonia, and (2) analysis of airborne LIDAR data from LBA-AIR-ECO (BARCA) and integration with ground-based biometry.
(A) Combine eddy flux data from multiple towers across Amazônia to produce reference datasets

Extensive data on net ecosystem exchange of CO2 and associated environmental variables is now available from a network of local towers distributed across the Amazon, in forest, pasture, and agricultural sites (12 towers are listed in Table 1, spanning a range of annual rainfall from 1500 to over 4000 mm). Individual tower datasets are available on LBA-DIS through the Beija-flor web search engine. However, in the experience of many potential users of this data, actually assembling and using these datasets, especially for making consistent comparisons across sites, is problematic: datasets are often at different stages of processing and levels of quality assurance, the same variables may be recorded in different units, and all datasets embody site-specific peculiarities that could potentially introduce systematic biases in intersite comparisons if they are not properly accounted for (see discussion, point 2 below, about different nighttime loss corrections at the Tapajós forest towers).

There is thus a strong need for systematic integration of tower datasets using consistent data-cleaning and error-checking protocols (see attached letters from other LBA investigators Costa, Denning, Foley, Potter, and Shuttleworth, supporting this proposed objective and the closely related synthesis leadership activity). We propose to undertake this task, with the goal of producing a user-friendly data product to facilitate robust and reliable intercomparisons among towers, between towers and remotely sensed data products or model simulations, and for constraining regional-scale atmospheric inversions (as planned for BARCA).

Key subcomponents of the proposed tower integration task are:

0. Obtaining base hourly data sets for each tower. We will consult with PI’s for each tower dataset to obtain the appropriate best quality datasets from each tower through 2005 (we note that the research team assembled for this proposal includes investigators – Saleska, Rocha, Nobre – who collectively represent one-third of the Amazon towers listed in Table 1). We do not anticipate recalculating hourly covariances for this project, but in some cases we might explore with tower research groups the value of sensitivity analyses in different methods of covariance calculations.

1. Checking for long-term drifts in sensor calibration. In long-term tower observations, small drifts in calibration or offset in sensors can become a potentially large source of systematic bias and cause interpretation errors upon comparison between towers or between different times at the same tower (e.g., drift in photosynthetically active radiation (PAR) sensors can cause an apparent difference in observed light use efficiency between towers or over time). We will check for and work to correct such issues, for example, by: (a) using tests for long-term trends at the same time of day or month of year, and (b) by cross checking between different sensors that are related to the same variable (e.g., \( T_{\text{sonic}} - T_{\text{airs}} \), the difference between sonic temperature and true air temperature, which varies with atmospheric water vapor, can provide an objective means of detecting problems in either sonic anemometers or IRGA-derived water vapor).

2. Assessing reliability and accuracy of nighttime measurements, and using multiple approaches to correct for potential underestimation of nighttime fluxes. Eddy correlation measurements are known to be subject to systematic biases (Goulden et al. 1996, Lee 1998, Sakai et al. 2001, Finnigan et al. 2002), with an underestimation of nighttime fluxes (and consequent overestimation of long term carbon sequestration) presenting the most significant issue. Currently, such problems are typically diagnosed and corrected by examining the effect of vertical mixing intensity (measured as friction velocity, or \( u^* \)) on measured nighttime NEE (expected to be independent of vertical mixing, since respiration physiology should not depend on atmospheric turbulence) (**Figure 14**).
In the Tapajos forest, an approach that relied on uncorrected NEE measurements alone would have suggested a significant difference in forest carbon exchange between the two tower sites (Figure 15), but application of a consistently applied u* correction algorithm brings the two sites into agreement in terms of carbon balance (analysis suggests that the cause of inter-site differences arises from slight differences in tower footprint topography (Figure 16)). This illustrates the importance, in a data integration plan like that proposed here, of developing methods to account and correct for intersite artifacts that could otherwise introduce bias.

However, application of u* correction methods to all towers in the Amazon may be problematic. First, the footprint topography differences between the Tapajos towers are small compared to differences between the Tapajos and other sites, and consequently u* correction may be ambiguous or insufficient to correct for larger differences. We therefore plan to apply at least three different approaches for correcting nighttime fluxes: (a) conventional u* correction, as described above; (b) taking the limit of daytime NEE as PAR approaches zero, and using this limit (derived for a subset of data several weeks long at a time) as an estimate of nighttime respiration. This approach is consistent with the u* correction in the Tapajos, and in sites with more complex topography may be more suitable since daytime eddy fluxes are often more reliable; and (c) using the strength of the nighttime temperature inversion (rather than u* alone) as a means to segregate nighttime fluxes into representative and unrepresentative modes. This follows because inversion strength is directly connected to a plausible mechanism (cold air drainage) for underestimation of CO2 efflux. Recent work at km83 (Goulden et al, submitted) shows that: (i) variations in topography (Figure 16) are correlated with nighttime temperature variations (colder in low-lying areas); (ii) nighttime underestimation of fluxes is largest when the temperature inversion is the strongest, and (iii) above-canopy temperature gradient partitions measurements into undermeasured and representative more distinctly than does u*.

3. Using consistent methods to partition NEE into component fluxes. A key goal is the partitioning of measurements of net exchange into components, GPP and $R_{tot}$. Such partitioning is particularly desired for comparisons to MODIS-derived EVI (an index of photosynthetic activity and GPP). We will partition NEE consistently from one tower site to the next, in order to avoid artifact-induced differences in site-site comparisons.

Key data products from this analysis will include: High resolution hourly data for all available towers, available as compressed ascii files, a separate file for each tower. Each tower file will include a common timestamp column (universal time), local time, and use common column names across files for the same variables to facilitate inter-site comparisons; Medium resolution daily averages, including whole-day averages, daytime-only averages and nighttime-only averages; and Low resolution monthly averages for detecting broad seasonal patterns.

Features to enhance value to multiple data users. Product files will include both corrected and uncorrected fluxes, flags to indicate when data are suspect, flags to indicate filled values vs. directly measured data values, and documentation. This will allow users who desire an estimate of carbon balance over an interval to calculate totals using a statistical “best estimate” in place of missing or suspect values, and will also allow users who desire to test model simulations to focus on direct measurements, with suspect data and filled values screened.

(B) Process LIDAR data from BARCA and integrate with ground-based biometry

Background. The separately funded BARCA campaign, scheduled to fly in October 2005, will include an airborne LIDAR (the Portable Airborne Laser System, or PALS) for remote sensing of forest canopy structure deployed on a Bandierante aircraft. The BARCA-deployed PALS is similar to that described in Nelson et al. (2003), except it incorporates an
upgraded laser rangefinder (Riegl LD90-3300-VHS-FLP). The Reigl laser on the BARCA mission has a range of 400m and a sampling frequency of 2000 Hz.

The raw dataset will be acquired at nominal height 300 m and speed 100 knots, returning data with ground-spacing of ~0.026 m and spot size of ~1 m. Ranges of both first and last returns from each laser pulse are acquired and stored. Laser data is interleaved with GPS positions. Simultaneously a video camera acquires images with a common timestamp and GPS coordinates, allowing later comparison of laser data with ground images (as illustrated in Figure 8) to facilitate interpretation of anomalous data and check coordinates with known landmarks.

The BARCA budget and science priorities will allow for the acquisition of at least 20 hours of LIDAR data, and flight plans include flights over tower footprints and ground-based forest biomass plots, as well as landscape-scale surveys in the regions of tower sites near Manaus, Santarem, and Caxiuana (see Table 1 and Figure 3). We have sought and obtained initial agreement with investigators responsible for managing biomass plot studies in Manaus (Regina Luizão from INPA and BDFFP) and Caxiuana (Leonardo Sá from Museo Goeldi) to (a) facilitate accurate overflights of plots during BARCA and (b) collaborate in post-flight data comparisons (the PI for this proposal is also an investigator on many of the Santarem plots).

Proposed Data Processing. BARCA funding does not include support for post-flight data analysis, so we propose here to process BARCA-acquired regional LIDAR data, and integrate with ground-based biometric data to develop algorithms relating LIDAR to ground metrics.

The raw PALS data will be post-processed using IDL programs developed by R. Nelson to: (1) identify the ground from the trace of first-return ranges (this is achieved by connecting the intermittent ground returns with a spline), and (2) interpolate time, GPS position and ground height for every laser shot. Subsequent metrics for biomass and growth estimation will be extracted from these data as discussed in the main part of the proposal (and Parker & Russ 2004).

1.5 Relevance and Anticipated Results of proposed work

This research is relevant to the LBA research priority to achieve a better understanding and quantification of Amazonian carbon dynamics. The results will be embodied in the following deliverables:

“Dataset” deliverables:

- quality-assured multi-year MODIS data products for all Amazonian regions and study sites.
- Systematically integrated and error-checked LBA tower flux data through 2005 in a common reference dataset for comparison among sites, with models and remote sensing data, and for assimilation into the planned BARCA atmospheric inversion study of Amazon C balance.
- Landscape-scale distributions of forest canopy heights derived from airborne LIDAR over the Manaus, Santarem, and Caxiuana regions.

“Synthesis and integration” deliverables:

- Amazon basin-wide estimates of GPP carbon fluxes across multiple years, by synthesis of MODIS data with LBA flux tower data.
- Landscape-scale estimates of tree biomass, and possibly, tree growth rates in the Manaus, Santarem, and Caxiuana regions by synthesis of LIDAR data with survey plot data.
- Ecosystem Demography process model simulations of landscape-scale carbon balance as constrained by LIDAR–derived canopy height distributions.
Fig. 1: Tapajós National Forest: (A) Mean seasonal cycle of observed NEE, solid line (± SD across 2000–2003, shaded area), and simulated NEE (± SD across non–El Niño years from 1980 to 1995) for the tower region with the TEM model (dotted curve) (Tian et al., 1998) and IBIS model (dashed curve) (Botta et al., 2002). (B) Seasonal cycle (±SD, as in A) of observed Gross Primary Production, GPP (dashed curve) and total respiration, Rot (solid line). (C) cycle of observed PAR (solid curve, left axis) and monthly precipitation (solid bars, right axis, ±SD across years, from July 2000 to July 2003), together with model-input precipitation (hatched bars). Source: Saleska et al. (2003).

Fig. 2: Gross (upper panel) and net (lower panel) carbon fluxes to live trees, dead coarse woody debris (CWD), and total aboveground mass in the Tapajós (km 67) during 1999-2001, with eddy flux-derived carbon balance shown for comparison. Net aboveground losses are driven by decomposition from the large stock of CWD, inferred to be deposited by recent disturbance events.

Fig. 3. TRMM-derived annual rainfall (upper left panel), shows context for synthesis and integration along precipitation transect in the Amazon drainage (black rectangle, lower panel), in which we propose integration of MODIS indices with ground datasets (eddy flux towers, starred sites; biomass plots, red sites), and airborne LIDAR (red sites). Not shown are additional eddy flux sites further south (see Table 1 for complete list).

Fig. 4 (Above). Example of landscape-scale study (comparable study near Manaus not shown). (A) the Tapajós National Forest region: flux towers in forest (at km67, km83), and in pasture/ag (km77); LIDAR remote sensing area (green box); and large-scale biomass transects T1-T4. (B) km67 tower footprint, with 4 1-km long x 50m biomass transects (left), and coarse wood debris (CWD) subplots (expanded, right). (C) layout of sample biomass transect (10 ha each, T2 shown).
GPP for 2001-2002 (data from an identical PALS slated to survey Amazon sites in October 2005. ecosystem cover (lower panel) (Nelson et al., 2003). We propose analyzing (upper panel) along with co-registered video of corresponding heterogeneous

Fig. 8. Sample data series from Portable Airborne LIDAR System (PALS) (upper panel) along with co-registered video of corresponding heterogeneous ecosystem cover (lower panel) (Nelson et al., 2003). We propose analyzing data from an identical PALS slated to survey Amazon sites in October 2005.

Fig. 10. Cross-biome comparisons of forest biomass vs. ground LIDAR-derived local outer canopy height (LOCH). Inset: Within-site comparison for LBA km67 site biomass (2001 survey) vs. ground LIDAR LOCH (2003 survey), binned into 100m long x 10m cross-track plots.

Enhanced Vegetation Index (EVI) 

Fig. 7. Santarem region ground-test of EVI and model simulation: Upper panel: Mean cycle of observed forest GPP (± SD across years, green shaded area), 2000–2003 (Saleska et al., 2003), IBIS model-simulated GPP (brown line ± SD across neutral years in 1980-1995) for the tower region (Botta et al., 2002), and MODIS EVI (average 2000-2004). Lower panel: cycle of observed pasture/farm GPP for 2001-2002 (Sakai et al., 2004), and EVI. Note different EVI scales in forest vs. pasture/farm sites.

Fig 9. Comparability of LIDAR-derived outer canopy height from the ground surface looking upward, and from a crane, looking down-ward, in a mature mixed species deciduous stand, Leipzig, Germany.

Fig 11. Biomass change over two years vs. one-time LIDAR metrics: (A) maximum slope of outer canopy hypsograph (= max density of outer canopy height distribution), and (B) rugosity (SD of local outer canopy height, LOCH). Measurements from intensive plots at SERC. Points at bottom are old-growth stands; top is from a young forest.
Fig. 12. Left panel: Landsat ETM+ image of Tapajos region. Right panel: EVI seasonality (October EVI minus April EVI) extracted for box in left panel. Reds (high values) show undisturbed forest (with access to deep soil water?), while yellows (lower values) occur where disturbance is prevalent, as along the trans-amazon highway (east–west) and Santarem-Cuiaba highway (north–south) and the Santarem area in the upper left and next to the Tapajos river (blue).

Fig. 13. EVI seasonality (as in Fig 12) extended to the continental scale.

Fig. 14. Nighttime hourly NEE (mean ± S.E., by u* deciles) vs. u* (median of each decile), split into wet season (calendar days 1-199) and dry season (days 200-365) at: (A) Km 83 (July 2000 to 2001), and (B) Km 67 (July 2001 to 2002) towers in the Tapajos National Forest. Fall-off in NEE at low u* is evidence of “lost flux” during these time periods.

Fig 15. Cumulative NEE (uncorrected, and corrected by filtering values with u*<0.22 m sec⁻¹) timeseries from Km83 and Km 67 in 2001. Uncorrected cumulative NEE at Km 83 is significantly lower than at Km 67, an artifact due to more “lost flux” at Km 83. Applying the u* correction in a consistent fashion brings the cumulative NEE between the two sites into remarkably close agreement (solid lines).

Fig 16. Tapajos forest Km83 site topography as determined by the Shuttle Radar Topography Mission, with tower (black dot) and tower footprint (white lines). Elevations (dark= low; light=high) range from ~5 m asl at the Tapajos River, upper left, to ~195 m asl at plateau centers). In contrast to the drainages apparent here in the Km83 tower footprint, Km67 (not shown) has significantly less relief. Source: Goulden, Miller, Rocha (submitted to JGR).
2  Management/Data/Training and Education Plan

2.1  Management Plan

The principal investigator, S.R. Saleska, has the responsibility for oversight of all aspects of the proposed work, including data processing, scientific analysis, and preparation of papers. He has extensive related experience from phase 1 and phase 2 of LBA-ECO, when he was lead post-doctoral scientist in S. Wofsy’s group at Harvard University for managing eddy covariance measurements, and synthesizing science data from eddy flux and plot-based biometric measurements at the km 67 site in the Tapajos forest. He will supervise the post-doctoral scientist (below) for the overall project, and in particular for the “preparation and analysis of eddy flux tower” datasets component.

Co-investigator A. Huete has extensive experience in designing algorithms for retrieval and analysis of satellite-based remote sensing data, and will assist in supervising the post-doctoral scientist in the retrieval and processing of MODIS data for comparisons with the distributed network of eddy covariance data.

Co-investigator G.G. Parker (Smithsonian Environmental Research Center) is a mission scientist on the LBA-AIR-ECO/BARCA campaign, and will contribute the LIDAR instrument that will make forest structure measurements thereon. For this project, he will supervise the processing of LIDAR data collected during the BARCA campaign, and the post-processing, integration and analysis of aircraft LIDAR data together with: ground-based LIDAR measurements on select forest plots; biomass data on forest plots, and other remote-sensing derived metrics of forest canopy structure (from GLAS on IceSat, and with IKONOS high-resolution imagery). He will support and supervise a data technician in his lab for these ends, and will coordinate with the other project scientists in the comparing of LIDAR measures of canopy structure with MODIS remote sensing data, and with eddy flux tower data.

Humberto Ribeiro da Rocha (Dept. of Atmospheric Science, University of São Paulo). Dr. Rocha has extensive experience in applying eddy covariance methods to measurements of fluxes of CO2 and water vapor in Amazonian forests. He was the South American PI for the NASA investigation team CD-04 (with US PI Michael Goulden) during phases 1 and 2 of LBA-ECO (focused on eddy covariance measurements at the selectively logged forest at the km 83 site). He currently is a PI on a Brazilian-funded eddy covariance project on Bananal Island in the central-eastern Amazon, and is lead scientist for “Module 2” of the Millenium Project (proposed for funding to Brazil’s Ministry of Science and Technology) to coordinate ongoing data collection activities at a number of flux towers around Brazil. Dr. Rocha will be responsible for coordinating Brazilian scientist participation in the project to integrate eddy flux data from Amazonian flux towers into an integrated database (as lead for Millenium Module 2, he is ideally situated for this role). He will be funded by this proposal to support a data technician/programmer in his lab to contribute data products to this end, and will assist the PI in supervising the University of Arizona post-doctoral scientist on the eddy flux component of his or her work.

Antonio Donato Nobre (INPA and INPE). Dr. Nobre is trained in ecology and atmospheric science, and has extensive experience in eddy covariance methods, and in tropical forest ecological and hydrological measurements. He was responsible for the operation of the flux towers near Manaus as part of the European Union Carbonsink-LBA component, and took a leadership role in organizing the first LBA eddy flux tower workshop held during December 2001. The University of Arizona team will collaborate with Dr. Nobre and his team on the
“synthesis leadership for Amazonian carbon dynamics” component of this proposal. To this end, Dr. Nobre will be funded by this proposal to contribute to the development and organization of a follow-on workshop, “Amazonian flux towers and carbon dynamics workshop,” which will serve as a focal point for integration, analysis, and comparison of flux data from around the Amazon.

**Paulo Artaxo** (University of Sao Paulo). Dr. Artaxo is an atmospheric scientist who is a Co-Investigator in LBA-AIR-ECO (now BARCA) campaign, and is chief scientist for the Bandeirante aircraft on which the LIDAR instrument (among others) will fly in October 2005, collecting the forest structure data proposed to be analyzed here. His main post-mission role, in addition to the analysis and interpretation of data collected by his own group, is to coordinate the other mission scientists flying instruments on the Bandeirante campaign to ensure timely analysis and integration of data products; for this proposed work he will advise and consult with the U.S. investigators by telephone and at meetings on the productive integration of the LIDAR data with other datasets produced by BARCA.

**Yosio Shimabukuro** (INPE). Dr. Shimabukuro is a renowned expert on remote sensing methods and technologies and during Phase 1 of NASA LBA, was South American PI with U.S. Co-Investigator Huete on investigation LC-06 (“Validation and Evaluation of MODIS Data Products in LBA”). He will advise and assist the U.S. investigators, by telephone and at meetings, in supervising the post-doctoral scientist on the project in the remote-sensing phase of the project, in which remote sensing data will be integrated with and compared to the distributed network of eddy flux tower data.

**Post-doctoral scientist, TBD.** A post-doctoral scientist with training and expertise in the management and analysis of eddy covariance data, and possibly with expertise in remote sensing as well, will be sought for this two-year project. Year 1 will be devoted to acquisition, integration, and analysis of combined eddy covariance datasets, a process that we expect to be deeply collaborative with the broader community of researchers involved in eddy covariance measurements, both for acquisition of existing data, and for the initial intercomparison and analysis thereof, which will take place in conjunction with the proposed eddy flux tower workshop, if funded as part of the synthesis leadership component. Year 2 will be devoted to the proposed synthesis and integration activities centered on comparison and integration of eddy flux data with remote sensing data products.

### 2.2 Data Plan

All investigators have extensive experience in collecting, managing, and processing large-volume datasets, as this is inherent to eddy covariance flux measurements, processing of remote sensing, and high-frequency acquisition of laser data. In general, we will follow the pattern established during the PI’s participation in CD-10, which was based on a philosophy of aggressive compliance with LBA’s open-data policy, and included rapid registration and deposit of initial data products on LBA-DIS, establishment of automated processing protocols and algorithms for managing the data, and follow through with making more carefully checked and processed data available in a timely fashion.

The principal time sensitive data product for this proposal is the integrated tower flux dataset, which we anticipate will be in high demand. Because of this, we will establish a comprehensive plan for acquiring and turning this data around in a rapid fashion.

This plan includes initial meetings or teleconferencing with tower investigators in the U.S., Brazil, and Europe immediately on project commencement to rapidly assemble datasets and understand nuances of data treatment and processing of each tower dataset. We plan to make
data available in two stages: at an initial stage, before the proposed flux tower workshop in late Spring 2006, in which the data is made available as soon as it is assembled with minimal scrutiny, and at a second stage after applying standard approaches to data-checking and nighttime corrections, by the end of the first year of the project. To address the anticipated situation in which new versions of data are provided by tower investigators after partially completing a quality control analysis on an older set, we anticipate automating quality control analyses as much as possible so that new datasets can be “dropped in” to the front end of the control and brought up to speed. To avoid the never ending task of processing ongoing data, we propose to try to include all data generated through 2005, but to not include data after this time in the product proposed here.

2.3 Training and Education Plan

Past T&E Activities

Training and education has been an integral part of LBA research by all parties.

During LBA phase 1 and phase 2, PI Saleska’s research was conducted through CD-10, in which much of the field data collection, sample analysis and site operation were managed by Brazilian students and technicians. Initial vegetation surveys were conducted with participation of Santarem undergraduates Jorge José Pinheiro Macêdo and Ocidne Franck A. Magalhães, Dulcyana Ferreira, Kleber Portilho and Elder Campos, all students at universities in Santarém, were trained in forest ecology and held bolsas under the supervision of CD-10 Brazil collaborator Plinio Camargo. All worked several years and presented posters and talks at LBA meetings. Dulcyana and Kleber were co-authors on a major paper of the project (Rice et al., 2004), and with project related work, Dulcyana completed her undergraduate thesis and graduated with a degree in biology from FIT. Plinio Camargo’s graduate student (now post-doc) Simone Vieira, collaborated with CD-10 members on research.

PI Saleska gave several seminars for students in Brazil, including two in Santarem, and one at CENA/USP in Piracicaba at the invitation of collaborator Plinio Camargo.

T&E highlights of investigation LC-06 (investigators Huete and Shimabukuro) included:

- **Internal LC-06 group workshop at University of Brasilia** (July 4-5, 2002), in which all students involved in the project participated.
- **NASA/MODIS Vegetation Variables Community Outreach Workshop** (Missoula, Montana, July 15-19, 2002), in which Brazilian student team member Humberto Barbosa participated.
- **Short course on MODIS** offered for Brazilian students prior to XI Brazilian Remote Sensing Symposium (SBSR) at Belo Horizonte, April 5-10, 2003.
- At the invitation of the Brazil Space Agency, INPE, team members presented a short course for ~25 students on MODIS products in Goiania, Goias, Brazil on April 16-17, 2005.
- training during fieldwork campaigns at both the Brasilia National Park, Araguaia National Park, and Tapajos National Forest on field measurements (e.g. fAPAR, LAI, %Cover, radiometry) for Ph.D. students (Ana Paula Ferreira, Humberto Alves Barbosa, Fernando Del Bon Espirito-Santo).
Planned T&E Activities for LBA Phase III, Synthesis and Integration

Proposed work would provide several key training and education opportunities. During the BARCA campaign, only Brazilian citizens will fly on the plane, so a Brazilian technician or student from Paulo Artaxo’s group will be trained in LIDAR operation.

We will seek to bring a Brazilian post-doc or graduate student to the University of Arizona to work on integration of LBA tower datasets and on synthesizing tower data with remote sensing data. One candidate for this is Rafael Tannus, a student of collaborator Humberto da Rocha at University of Sao Paulo.

If funded, the add-on for leadership synthesis activities will also provide extensive opportunities for participation and education of Brazilian students particularly during the eddy flux tower and modeling workshop, just as with the previous workshop. Student involvement is expected to range from simple attendance of workshop meetings, to significant participation in planning and pre- and post-workshop data integration.
3 "Synthesis Leadership" for Amazonian carbon dynamics

We propose to lead a community effort to synthesize and integrate results from Amazonian measurement and modeling efforts in carbon dynamics, focused on eddy flux tower site measurements and model simulations. The organizing focus of this synthesis would be a workshop on “Integrating eddy flux tower sites and models to understand Amazonian carbon dynamics”, to be held in Brazil in late Spring 2006.

Motivation: Tower and biomass datasets provide powerful tools for testing models of basin-scale carbon dynamics, and initial comparisons of basin-wide models with eddy flux (e.g. Saleska et al., 2003) and remote sensing data (Xiao et al., 2005) suggest (but at one site only) that the dynamics of wet-dry season differences in carbon and water exchange have not been well captured by several prominent ecosystem models. More robust testing and comprehensive understanding requires comparisons at multiple sites spanning gradients in precipitation and dry-season length, over multiple years, but such comparisons have not yet been done. By the time of the proposed workshop there will be at least 12 eddy flux towers that have produced continuous measurements for 1 or more years (see Table 1 in the main proposal), but this distributed network of data has not yet been integrated into a common reference dataset.

Objective: to integrate multi-site eddy flux measurements (and supporting forest biometric measurements) together and to produce consistent datasets, and to use these datasets to test different model representations of key mechanisms and processes, including those which control seasonal patterns as well as long-term ecosystem response to climate changes (e.g. soil hydrology, root profiles, hydraulic lift). The scope is narrowly focused on these two objectives (production of eddy flux datasets, and comparison to models) to make this a “working” workshop conducive to making community progress towards generation of desired products.

Timing and relation to LBA-Air-ECO: The timing (in early 2006, near the front end of the main two year project period) is designed to facilitate the early production of required integrated datasets so that they will be available for use in the second year for further synthesis activities, including the remote sensing comparisons proposed in the main part of this proposal, and the LBA-Air-ECO BARCA “science/synthesis workshop”, separately proposed to this NRA for 2007 by Wofsy et al., to synthesize aircraft data and modeling to achieve top-down measurement of basin-wide carbon balance.

Organization, Funding, and Follow-up: INPA, as host Brazilian agency for LBA, is committed to taking a leadership role in organizing this workshop (see attached letter from INPA Director Gomes), and anticipates funding the travel of key Brazilian participants and students to this workshop. Non-Brazilian scientists would be expected to obtain travel support from their home institutions or sponsors. Funding proposed here (see budget justification) would support Brazilian Collaborator A. Nobre (to lead the development of this workshop in Brazil, and to supervise relevant data synthesis), and on supporting a research staff person at UofA to assist investigators in data analysis, organizing, and, most crucially, post-workshop follow-up with participants, a key to overall workshop success. Follow-up tasks include taking responsibility for putting together combined datasets, and initial drafting of at least one community paper.

Distinction of “Synthesis leadership” component from base proposal: the scope of synthesis leadership is different from base proposal, and includes synthesis of measurements with multiple modeling approaches not included there. Regarding production of integrated eddy flux data (a “Synthesis leadership” goal in common with base proposal): the synthesis leadership component will bring significant added value, including the workshop, direct involvement by the eddy flux community, a community paper, and, consequently, a higher quality end product.
4 References

Note: Names of authors who are investigators on this proposal are highlighted in bold.

1 supported, at least in part, through LBA investigation CD-04 or CD-10 (not including publications from these groups that did not have substantial participation by Saleska as senior personnel or Rocha as collaborator)

2 supported, at least in part, through LBA investigation LC-06 (Huete or Shimabukuro)


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