Ecosystem carbon balance in a primary tropical forest in Central Amazônia: integrating long-term eddy covariance with comprehensive ecological methods

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Project Summary: This continuation proposal primarily addresses the "carbon dynamics" theme area of LBA-ECO. We propose three components. First, at a primary forest site 67 km south of Santarem (Tapajos National Forest) in central Amazônia we propose continuing: *(1) tower-based micrometeorological* measurements of net ecosystem exchange (NEE) and concentrations of CO_2, H_2O and CO, and *(2) ground-based ecological* measurements of pool-sizes (above-ground wood, coarse woody debris, forest floor), fluxes (tree growth & mortality, fine litterfall) and isotopic composition of selected ecosystem components. Second, we propose to *fill gaps in* the experimental plan at the km 67 site with additional ecological measurements, including measurements of LAI, and mapping of tree-fall gaps over time in the eddy flux footprint. Finally, at a coastal site (Maxanguape Beach) near Natal, we will commence continuous high-accuracy measurements of marine boundary layer CO_2 and CO concentrations. The objectives of the measurements will be:

1. *Define the net source or sink of CO_2 from the undisturbed forest using complementary independent methods (eddy covariance vs. ground-based biometry);*
2. *Identify mechanisms controlling the CO_2 source/sink magnitude via independent measurements of carbon pool sizes in, fluxes to, and isotopic composition of selected ecosystem components;*
3. *Determine the variations of net exchange of CO_2 seasonally and inter-annually (including the key interannual variations brought about by ENSO drought events), and define the response of carbon sequestration in the system to climatic and other environmental variables;*
4. *Provide the experimental control at a undisturbed forest site for interpretation of the results obtained at a nearby harvested site by collaborators (Goulden & Rocha, CD-04);*
5. *Provide the flux and gradient measurements for CO_2, sensible heat, and momentum needed to define the flux of N_2O, CH_4,and biogenic from sub-canopy concentration changes or from above-canopy gradient measurements of these species;*
6. *Determine CO_2 and CO boundary layer concentrations continuously at a continental and coastal site to provide context for interpreting regional measurements from airborne platforms or orbiting sensors and to constrain models of basin-wide carbon exchange.*

The proposed work achieves objectives (1) - (3) on its own. Objectives (2) and (3) will also be enhanced via collaboration with the *Keller, Crill and de Mello, group TG-07* (ecosystem respiration). Objective (4) follows from close collaboration with *Goulden & Rocha (group CD-04)* working at a flux tower on a nearby primary forest site being commercially harvested. We will address (5) by combining our data with observations of canopy/atmosphere interchange and energy balance by *Fitzjarrald and Moraes (group CD-03)* and measurement of fluxes and concentrations of (N_2O, CH_4) by *Keller et al. (TG-07)* ^{222}Rn by *Martens and Moraes (TG-04*) and hydrocarbons (Guenther and Gatti (TG-02). Objective (6) will be met in conjunction with a separately funded LBA aircraft campaign projects (LBA CD-14, *Wofsy and Dias* LBA CD-13, *Sun and Artaxo*) scheduled for Fall 2002.

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1. Technical Plan

1.1 Introduction

Motivation for primary forest studies in FLONA Tapajós

Approximately one half of anthropogenic CO_2 emissions have remained in the atmosphere in recent decades, while oceans and the terrestrial biosphere have taken up the balance (*Dixon et al. 1994, Schimel et al. 1995, Prentice et al. 2001*). The mechanisms and location of the terrestrial "sink" for atmospheric CO_2 remain controversial. Model studies of global-scale atmospheric measurements place the terrestrial sink mostly in the northern mid-latitudes (*Tans et al. 1990, Fan et al. 1998, Gurney et al. 2002*), due to re-growth of forests on abandoned agricultural land and fire suppression *(Hurtt et al. 2002)*. However, the few site-specific measurements that have been made in tropical regions also suggest substantial carbon sinks (*Grace et al. 1995, Mahli et al. 1998, Phillips et al. 1998*) in undisturbed forests that could at least partly balance the CO_2 source attributed to tropical deforestation and logging *(e.g. Houghton 1991, Houghton et al. 2000)*. Large areas of undisturbed forest in Amazônia are typically uneven-aged with many large trees, indicating long periods of succession often assumed suitable for attaining carbon steady-state *(e.g. Anderson and Spencer 1991)*; they were until recently presumed to contribute little to changes in atmospheric CO_2. Growth enhancement by rising concentrations of atmospheric CO_2 has been advanced for a possible stimulus of CO_2 uptake by large-stature tropical forests *(Tian et al. 1998, Prentice & Lloyd 1998)*.

Keller et al. (1996) suggested several possible reasons that uptake reported at particular sites (1.1 to 5.9 tons C/ha/yr in short-term eddy flux studies by *Grace et al. 1995* and *Mahli et al. 1998*; 0.71 +/- 0.34 tons C /ha/yr in plot studies by *Phillips et al. 1998*) might not imply a regional net sink for anthropogenic CO_2, including: long-time-scale response of the forest to climatic variations, stand-level inhomogeneities such as proximity of the sensor to gaps, observational artifacts in the eddy flux method, lack of information on decomposition in plot studies, and bias in selection of ecological plots. An important observational artifact of eddy-covariance involves day/night biases that inflate estimates of carbon uptake (*Goulden et al.1996b, Lee 1998, Finnigan et al. 2002*). Eddy-covariance measurements must thus be subjected to critical scrutiny, and corroboration of carbon budgets should be undertaken by independent methods. **Accurate measurements of carbon gain and loss in a large-stature, undisturbed Amazônian forest represent a central focus of the present proposal.**

Climate variations may cause episodic bursts of anomalously high carbon loses or uptake, as indicated by correlations observed between anomalies in the global CO_2 budget and the El Nino/Southern Oscillation (ENSO) *(Marston et al. 1991, Keeling et al. 1995)*. ENSO-induced droughts correlate with increased tree mortality in the tropics *(Condit et al. 1995, Williamson et al. 2000)*. High-growth episodes would be expected subsequently in gaps left by deceased trees. Unusually strong ENSO events in the 1980s caused drastic shortfalls of precipitation in the rainforests of the Amazon Basin (*Condit et al. 1995)* and East Borneo *(Leighton and Wirawan 1986)* and recent carbon sequestration uptake could be a legacy of recent episodes of high mortality. **Direct measurement of the response of an undisturbed Amazônian forest to climatic variation represents another key focus of the present proposal.**

LBA Framework

In Phase I of LBA-ECO (1998 – 2001), we developed and deployed robust eddy flux and environmental instruments and initiated long-term ecological and biometric observations. We set out to address carbon-balance issues at one of LBA's intensive primary research sites at km 67 in the Tapajós National Forest in central Amazônia. We are measuring: **(1)** *eddy covariance* fluxes of CO_2, water vapor, heat and momentum, concentrations of CO_2, H_2O, and CO, and important environmental parameters using long-term high-resolution gas analyzers and meterological sensors, and **(2)** pool-sizes (above-ground wood, coarse woody debris, forest floor), fluxes (tree growth & mortality, fine litterfall) and isotopic composition of selected ecosystem components via ecological methods in 20-ha of long-term monitoring plots in the footprint of the eddy-covariance tower. These primary forest data are critical for addressing the central scientific question for LBA, **"How do tropical forest conversion, re-growth, and selective logging, influence carbon storage, nutrient dynamics, trace gas fluxes, and prospects for sustainable land use in Amazônia?"**

The goal of our work is to provide the fundamental basis for analysis of the LBA central question. Net releases or uptake from disturbed lands must be assessed against long-term fluxes from primary forests. Hence the sustained measurement of large-scale, net uptake or release of CO_2 from primary forests, for time scales from a season to years, and the quantitative elucidation of underlying ecological mechanisms, represent a subtext and a foundation for all of LBA-ECO.

The proposed 3 years of study will address the following three specific questions:

1. What are the magnitudes of the net ecosystem exchanges for CO_2 , H_2O, and energy at a primary forest in the Tapajós region of Amazônia?
2. How do these respond quantitativel) to environmental forcing such as seasonal or inter-annual variations of precipitation and cloudiness?
3. Which sub-components of the ecosystem are responsible for net flux response of the forest to these environmental forcings?

Our work will also provide ecosystem-level fluxes, and important data for investigating continental scale fluxes, for a variety of greenhouse gases, reactive trace gases, and aerosol-associated elements and nutrients.

The specific experimental and synthesis objectives of this study are:

1. *Define the net source or sink of CO_2 from the undisturbed forest at Tapajós km 67 using complementary independent methods (eddy covariance and ground-based biometry);*
2. *Identify mechanisms controlling the CO_2 source/sink magnitude via independent measurements of carbon pool sizes in, fluxes to, and isotopic composition of selected ecosystem components;*
3. *Determine the variations of net exchange of CO_2 seasonally and inter-annually (including the key inter-annual variations due to ENSO events), and define the response of carbon sequestration in the system to climatic and other environmental variables;*
4. *Provide the undisturbed control for interpretation of the results obtained at a nearby harvested site by collaborators (Goulden & Rocha CD-08);*
5. *Provide the fluxes and gradients for CO_2, sensible heat, and momentum needed to define fluxes of N_2O, CH_4, and biogenic hydrocarbons using concentration data for these species;*
6. *Determine CO_2 and CO boundary layer concentrations at a mid-continental site and at a coastal site to anchor regional measurements using airborne platforms and orbiting sensors, and to separate contributions of biomass burning and vegetation to regional variations of CO_2 concentrations.*

<u>Studies of the type proposed here are specifically cited (NRA-01-OES-06) as core activities of the LBA-ECO research effort:</u>

"Continuous…observations of a core set of measurements (e.g., CO_2 fluxes, trace gas fluxes, trace gas concentrations, micrometeorological conditions, radiation, aerosols, vegetation properties, and soil properties) are being made at the primary field sites over a period of 3-5 years".

1.2. Results from LBA-ECO CD-10 Phase I

1.2.1. Primary Forest Site: FLONA Tapajos, km 67

The site is in the Floresta Naçional do Tapajós (54°58′ W, 2°51′ S, Pará, Brazil), accessed at km 67 on the Santarém-Cuiabá Highway (BR-163). Temperature averages 25° C, humidity 85%, and rainfall 1920 mm/yr (*Parotta et al. 1995*). The nutrient poor clay oxisols contain little organic matter and have low cation exchange capacity (*Parotta et al. 1995*). The closed canopy, upland forest shows is characterized by large canopy emergent trees (up to 40m tall). There are no signs of recent anthropogenic disturbance other than hunting trails. The dominant emergent tree species are *Manilkara huberi*, *Hymenaea* courbari L., *Betholletia excelsa* Humb. & Bonpl., and *Tachigalia* spp.. The large logs, numerous epiphytes, and variable canopy height, qualifies this forest as primary, or "old-growth", according to the criteria given by *Clark (1996)*. We installed eddy covariance and meteorological instruments on a 60 m tower at this site, approximately 6 km W. of BR-163 and 2 km E of the scarp overlooking Rio Tapajós; permanent forest research transects were established extending 1 km in NE, E, and SE (upwind directions) from this tower.

1.2.2. Eddy Covariance Instrument and Measurements

Tower Instrumentation. During the initial funding period, we designed, built, tested, and installed a new instrument system for making eddy-covariance flux (CO_2, H_2O, heat and momentum) and concentration (CO_2, H_2O, CO) measurements, and acted as site coordinator for the primary forest tower site (km 67), contributing to design and specifications for the site infrastructure (tower, instrument sheds, and power generators).

The measurement system consists of four instrument units: two *eddy-covariance units* (at 58 m and 47 m) for measuring fluxes, a *profile unit* for measuring vertical CO_2 and H_2O concentration profiles at 8 levels, and a *ground unit* inside the hut, which includes the CO instrument. (A view of instrument placement on the tower can be found on the web at: http://www-as.harvard.edu/chemistry/brazil/tower_diagram.html). Eddy level 1 (58 m) and eddy level 2 (47 m) each have a Campbell CSAT-3 sonic anemometer mounted near a self-contained analysis unit, each with a LI 6262 CO_2/ H_2O infrared gas analyzer modified for temperature and flow stabilization and automated routine calibrations. The eddy units each draw 7 standard liters/min (slpm) of sample air from an inlet located directly behind (~10 cm) the vertical axis of the anemometer. The small separation between inlet and anemometer keeps separation errors negligibly small (1 to 2%, *Lee and Black 1994*). Analyzers are calibrated by substituting 3 standard mixtures that span the range of expected concentrations, several times daily. Calibrations are directly traceable to world absolute standards. The analyzers are zeroed by periodically replacing ambient air with dry CO_2-free air.

The profile unit (also self-contained) measures the CO_2 concentration profile by sequentially sampling from 8 vertical levels, plus a 9th event measuring simultaneously the mean concentration of CO_2 from the 8 inlets. Calibrations are done identically as for the eddy instruments. The CO concentration is determined using a modified Thermo-Environmental Inc (TEI) Model 48CTL. An air sample from 58 m is drawn at approximately 1 slpm and dried to a dewpoint of 2° C in a thermoelectrically cooled water trap. Every 15 minutes the sample is passed through a Sofnocat scrubber to catalytically remove CO and determine the instrument zero. Sample is replaced by standards at 100 and 500 ppb 4 times a day to determine the instrument response curve. Standards are humidified 2° C to minimize potential water vapor interference with this measurement. We also measure a comprehensive set of environmental and meteorological variables, including net radiation, photosynthetically active photon flux density, wind speed and direction, and precipitation. Table 1, Part A provides a complete list of the automated tower-based measurements.

The two eddy covariance units and the profile unit are tower-mounted unitary instrument packages complete with key measurement, control, and datalogging hardware. Tube lengths are kept to a minimum (~2m) between air intake and the closed-path pressure-controlled IRGA, keeping the time lag between IRGA and sonic measurements to ~1 second. This fast-response instrument maintains the advantages of closed-path designs (e.g. automated 4-point calibrations every 6 hours) while also adding some advantages (e.g. minimal travel of the air sample before measurement) attributed to open-path designs. This system is particularly suitable for very tall vegetation ecosystems where wall adsorption and signal smearing may be exacerbated by a long length of tubing between the inlet and a ground-based instrument.

Results from Phase I.

Eddy flux and profile data acquisition commenced on 10 April 2001 (Day 100, Figure 1). The net ecosystem exchange (NEE) for CO_2 is the sum of eddy flux at the top of the canopy, plus the change in within-canopy storage. The initial 9 months of data cover mid-rainy season through end of the dry season and the start of the next rainy season. NEE exhibited typical daily cycles (-20 to +10 μmol m^{-2} sec^{-1}; Fig. 1). The 24-hr net carbon exchange was small, but with a marked seasonal variation (Figure 2): net loss of carbon was observed during the rainy season (January-May), switching to net uptake in the dry season (August-November). These results contrast with both the minimal seasonality and strong uptake reported for a central Amazon rainforest near Manaus (*Mahli et al. 1998, Araujo et al. 2002*), and with the nearly opposite seasonal pattern observed in a southeastern Amazon transitional tropical forest (cerradão) in Mato Grosso (*Vourlitis et al. 2001*), which gained carbon in the rainy season and became carbon-neutral in the dry season. However our tower data appear consistent with the interpretation of atmospheric data from the central Amazon region sampled during ABLE-2B (April-May 1987) which showed small net efflux of CO_2 during the wet season *(Chou et al. 2002)*.

Fluxes measured at the two eddy levels, and the instantaneous mean canopy storage measurement, have been invaluable in assuring data quality, and in diagnosing and correcting for effects of weak vertical mixing in stable conditions. On average, we found good agreement for flux data from the two levels: cumulative divergence between the levels was less than half as big as the correction applied to adjust for lost flux, see Figure 2). Most divergence between eddy levels 1 and 2 occurred during periods of marginal performance due to a degraded sonic anemometer at level 2, or to clogged inlet filters. The observed differences allow us to quantitatively assess systematic errors from these elements of marginal performance. The instantaneous column-mean measurement has reduced the scatter in storage fluxes, which must be computed by differentiating storage below the sensor level (Figure 3c); cleaner storage fluxes aid detailed analysis of the "lost flux" problem.

Weak vertical mixing (indicated by low friction velocity, u*) reduces eddy fluxes at the top of the canopy (Figure 3b). During the wet season, increased storage within the canopy during these periods did not fully compensate for lower eddy flux until u* exceeded about 0.2 m/s. NEE (the sum of the two flux components) was essentially independent of u* for values above 0.2 m/s, indicating good resolution of NEE (Figure 3a). The drop-off in NEE at low u* we take to be indicative of "lost flux" as discussed by *Goulden et al. (1996b)* and *Barford et al. (2001*). We correct for lost flux by filtering NEE data for u* < 0.2 m/s, and replacing these data with values interpolated from nearby periods of more vigorous mixing. This correction increases estimated NEE (carbon loss) by about 1 ton C/ha over the initial 9-months of measurement (Figure 2). Note that the effect of filtering at our site is substantially smaller than at most other sites in the Amazônian forest, because we have more turbulent periods than most other sites (see Fig. 12 below).

The key hypothesis that drop-off of NEE at low u* indicates "lost flux" deserves detailed scrutiny. A major focus of our analysis and collaborations during the next phase of research will therefore to subject this hypothesis, and the general question of accuracy and reliability of eddy flux measurements, to rigorous testing (Sec. "1.3.2.1. Measurements and Analysis at FLONA Tapajos").

Carbon Monoxide

CO is a tracer of local biomass burning influence, and CO is a component of the atmospheric carbon budget with both primary biogenic and combustion sources and secondary formation from oxidation of biogenic hydrocarbons. Figure 4 shows the time series of CO concentration from April 2001 until mid January 2002. Concentrations were less than 100 ppb from day 100 until 205, when rainfall stopped, showing little variability and a weak diel cycle (Figure 5). Results were similar to the data of *Kirchhoff and Marinho* (1985) outside of Manaus. After day 205, midday mean concentrations increased to ~140 ppb, with little variability. In mid August (day 230), after several dry weeks, the CO concentration became highly variable, indicating proximate emissions. Average daily concentrations during well-mixed daylight hours reached a maximum of 200-300 ppb during the active burning season in December. The marked diel cycle in CO concentration (Figure 5, lower panel) during this period was driven by high concentrations of CO that accumulated in the nocturnal inversion layer; peak concentrations exceed 2,000 ppb on several nights. CO_2 also exhibited a nocturnal maximum as respiratory emissions accumulate below the inversion layer, which makes it makes it difficult to use simple correlation to infer $CO:CO_2$ emission ratios from burning or to separate the biogenic and combustion signals in the CO_2 data. A modeling approach utilizing data on surface fluxes and vertical mixing will be carried out in Phase-II to help separate the combustion and respiration signals in the CO_2 record.

1.2.3. Ecological measurements

We initiated a comprehensive ecological/forest mensuration study in 1999, including: (1) stand dynamics, including diameter increment for trees, mortality and recruitment; (2) seasonal litterfall and forest floor litter dynamics; and (3) necromass pool sizes. The ecological studies are intended to elucidate mechanisms driving observed fluxes, help better understand the overall carbon balance, and provide the essential, independent check on carbon balances derived from eddy-covariance data. We currently have over two years of data. Note that these measurements were not part of our proposal for LBA-ECO phase I, but had to be added when this critical component of the study was identified as a gap by the Science Team. Addition of this major effort delayed our deployment of the instrumentation at the Natal site.

(a) Stand dynamics: In July 1999, we designed and implemented a survey of trees in the footprint of the eddy-covariance tower at the primary forest site (km 67). We surveyed along four 1-km long x 50 m wide transects (5 ha each, 20 ha total). Three transects radiate from the tower in the upwind direction, and one is perpendicular to the central transect (Figure 6). This design was adopted to include trees throughout the eddy flux footprint maximum, to cover as long a transect as possible, to test for directionality in spatial distributions, and to allow for efficient sampling and re-sampling. The locations, diameters at breast height (DBH), and commercial height of all trees on the transects with DBH > 35cm were recorded. Trees with buttresses were measured above the buttress, using a ladder when necessary. The denser populations of smaller trees (10 cm < DBH < 35cm) were inventoried if they fell within the 10-m wide central strip of each transect. In all, we inventoried 2600 trees with most identified to species by an expert botanist (Nelson Rosa). In

December 1999, we installed spring mounted stainless-steel dendrometer bands on a subset of 1000 of these trees to measure tree growth rates at high time resolution (monthly, see Figure 7). In 2001, the entire initial sample of 2600 trees were re-surveyed to define longer-term average biomass fluxes, and to estimate recruitment of new trees into the smallest size class (>10cm DBH) as well as mortality (Figure 8).

(b) Litterfall dynamics: In July 2000, we began to collect litter in 40 circular, mesh screen traps (0.43 m diameter, 0.15 m^2) randomly located through the 20 tree survey area, every two weeks. Litter is dried, sorted and weighed, providing litterfall fluxes (Figure 7). We also measured the dry mass of fine forest floor litter (leaves and wood <2 cm) in 25 cm x 25 cm subplots. Chemistry measurements (total C/N/P) and selective isotopic measurements (^{13}C and ^{15}N) are being conducted at USP/CENA in Piracicaba (P. Carmargo and co-workers).

(c) Necromass. In April of 2001, all standing dead stems >10 cm in DBH and taller than 1.3 m were measured in the 20ha transect plots (Table 2). In July of 2001, fallen coarse woody debris (CWD) was measured in a series of nested subplots within the 20 ha (see design in Figure 6; results in Table 2). In September of 2001, we made additional measurements of the CWD pools using the line intercept method (*Van Wagner 1968, Brown 1974*) for comparison with the plot measurements. Within error, the two methods agreed.

Results from forest ecological and mensuration studies

The stand shows high growth rates (~ 3 tons C/ha/year), but also high mortality (~ -2.5 tons C/ha/year) and recruitment rates (0.5 to 0.6 tons C/ha/year). On balance, live above-ground biomass accumulated a small but significant amount of carbon (~ 1 ton C/ha/yr) (Figure 8), but this gain may have been balanced or exceeded by net loss from coarse woody debris (Table 2), as suggested by applying literature data for tropical wood density and decomposition rates to our volume measurements. In any case, the measured volume of standing and downed CWD lies at the high end of reported literature values (Table 2), suggesting that the live and dead biomass pools in this stand are not in equilibrium. From the combination of net accumulation in live biomass and net loss from dead wood, we infer that this stand may have experienced excess mortality in emergent trees from recent ENSO events, and is therefore a weak source of CO_2 to the atmosphere, a hypothesis we will seek to test in the next phase of our work.

1.3. Proposal: LBA-ECO Phase II

An analysis of the combined eddy covariance and biometric data generates key hypotheses that highlight scientific next steps for phase II. In the following section we outline these hypotheses, and discuss the proposed work to test and refine them.

1.3.1. Hypotheses and Outline of Proposed Work

1.3.1.1. Hypotheses

1. Long-term ecosystem carbon balance

- Hypothesis: This primary forest is close to net carbon balance, possibly a modest source.
- Initial Evidence: (a) The first 9 months of eddy covariance measurements suggest that by the time the first year is complete the net efflux will probably be slightly positive (applying the correction for "lost flux" discussed above, *cf.* Figure 2, Level 1, u*-filtered). If no "lost flux" correction is applied, the carbon balance is ~0 (Figure 2, Level 1, no filter). (b) Biometry results indicate a very dynamic forest (hypothesis 3, below) but little evidence for net carbon gain.

- Next steps for phase II: **(a)** Continue flux measurements to support or falsify the carbon balance hypothesis for multiple years; **(b)** more fundamentally, conduct analysis to answer the question: are our NEE measurements showing near carbon balance typical of Amazônia or is this site different from the sites in previous eddy flux studies (*Grace et al. 1995, Mahli et al. 1998, Araujo et al. 2002*) that showed large carbon uptake? As discussed in Section 1.3 (Proposed work for LBA-ECO Phase II), this analysis can be divided into two phases: (i) attempt to reject the null hypothesis that our site is very similar to other large-stature Amazon forests that have been studied, and (ii) if this cannot be rejected, use independent data (both ours and those of collaborators) to understand the source of different interpretations of the data.

2. Short-term (seasonal) carbon dynamics

- Hypothesis: Photosynthetic uptake and ecosystem respiration are reduced during the dry season, but respiration declines more because drought most strongly inhibits microbes in the surface layers of the soil and forest floor and CWD. Tree growth is less affected by dry season drought stress because tree roots give access to persistent deep soil water.
- Initial Evidence: (a) Nighttime NEE (ecosystem respiration) is lower during the dry season than the wet season (Figure 9a); whole-system PPFD-response curves (the sum of photosynthesis and respiration effects) indicate a net shift towards more uptake during the dry season (Figure 9b), suggesting that any decrease in photosynthesis this is more than compensated by lower respiration rates. (b) Tree growth rates are generally higher during the wet season (Figure 7), but (c) *net* ecosystem carbon uptake (negative NEE) is highest during the dry season (Figure 2).
- Next steps for phase II: **(a)** Continue measurements to verify seasonal patterns and test if the same pattern is observed in response to inter-annual variation; **(b)** initiate continuous measurements of soil moisture near the surface, and combine with ongoing data for deep soil moisture by Nepstad et al.; **(c)** combine datasets with collaborators Keller and Crill (chamber based soil-respiration) to more directly test whether the whole-ecosystem respiration measured by eddy flux truly indicates the hypothesized patterns in soil respiration.

3. Vegetation dynamics:

- Hypothesis: Despite the indication of near carbon balance from eddy flux data, the vegetation is not in demographic equilibrium. This may be the legacy of high-mortality event(s) before measurements started due, for example, to the severe 1997 El Nino drought (a phenomenon directly observed elsewhere in the neotropics by *Condit et al. 1995*, and *Williamson et al. 2000*). This event could have increased CWD and litter pools, and therefore total respiration, but reduced the total C uptake of standing stems. Conversely, mortality provides growing space for increased recruitment and competitive release of surviving stems.
- Initial evidence: Carbon in live biomass is accumulating (Figure 8), but there are unusually large stocks of CWD for which carbon loss by decomposition exceed inputs from mortality (Table 2).
- Next steps for phase II: **(a)** Continue measurements in order to assemble a long-term database, obtain higher confidence for assumptions about mortality dependence on precipitation. **(b)** Expand the sample area on which large trees are measured to reduce the largest contributor to sampling uncertainty (mortality of large trees). **(c)** Initiate measurements in the biometry plots of key factors controlling old-growth vegetation dynamics and its link to carbon uptake: (i) map tree-fall gap distributions over time, and (ii) characterize leaf-area index and canopy architecture spatially and over time. **(d)** Use new isotopic techniques to recover historical tree-growth rates on selected trees, allowing: (i) examination of long-term tree-growth trends, and (ii) analysis of recent El Nino effects on historical tree-growth rates. **(e)** collaborate with Keller, Crill et al. to

combine their detailed measurements of components of the respiration budget (losses from CWD pool) with our measurements of ecosystem fluxes and mortality inputs to CWD pool.

1.3.1.2. Proposed Work

For LBA-ECO phase II, we propose three main areas of work:

(1) ***continuation*** of the current eddy covariance and associated environmental measurements at the FLONA Tapajós primary forest site, ***supplemented*** by detailed comparison of the Tapajós measurements with those at the Cuieiras Reserve near Manaus;

(2) ***continuation*** of the current ecological measurements, ***supplemented*** by expansion of those measurements to fill key gaps needed to understand how vegetation dynamics are linked to net ecosystem carbon exchange; and

(3) ***installation*** of the CO_2 and CO instruments at the coastal atmospheric monitoring station for measuring trace-gas concentrations in marine boundary layer air.

These three areas of proposed work are outlined in more detail below. The proposed measurements (continuing and new) are summarized in Table 1.

1.3.2. Eddy covariance and associated environmental measurements

The proposed work provides baseline information for the primary forest , responding to the "Carbon Dynamics" theme question: "What is the (climatically driven) seasonal and inter-annual variability of the carbon dioxide flux between the atmosphere and different land cover/use types?" (NRA-01-OES-06, p 19)

1.3.2.1. Measurements and Analysis at FLONA Tapajos

Long-term Measurements

We plan to continue the time series of eddy covariance measurements to produce the long-term dataset (3-5 years) needed to answer the core questions of the LBA Carbon Dynamics theme. Our goal is to quantify responses due to successional trends or shifts in climatic forcing and infrequent events, even if these turn out to be relatively small. Hence we need to vigorously pursue detection of systematic errors. In order to detect and eliminate systematic errors or trends in measurement artifacts (see "Analysis of Eddy covariance data", below), we will commit to long-term QA/QC, cross-checking experiments, and critical, comprehensive analysis of data *(Goulden et al. 1996b)*. Long-term stability and traceability of measurements requires continual monitoring of all aspects of incoming data, maintenance of spare equipment onsite, acquisition and use of traceable long-term calibration standards for gas analyzers and meteorological sensors, and coordination among Harvard and collaborator institutions, technicians at the Santarém office, and logistics and infrastructure support at NASA-Goddard.

An early priority will be installation of instruments helpful for interpreting long-term eddy fluxes (see Table 1) consisting of:

(1) A third sonic anemometer (Gill Solent HS, acquired in phase I), which can be mounted and moved between the two levels. This is important for long-term inter-comparability (e.g., when the main sonics are replaced for repairs), and as a reference for comparisons between the two levels.

(2) Two stations of CR10x dataloggers, in the forest near the tower, to log:
  - soil temperature profiles using thermistor probes (4 depths x 4 profiles)
  - surface soil moisture using TDR probes (integrated 0.5 m depth x 8 locations)
  - ground heat-flux using heat-flux plates (8 locations).

Analysis of Eddy covariance data

The strategy has four parts, each discussed below. They are:

1. **assess reliability and accuracy of eddy covariance measurements of net carbon flux;**
2. **address science questions about forest carbon balance by analyzing appropriately aggregated eddy covariance data;**
3. **integrate eddy flux and biometry data to reveal ecological mechanisms controlling net fluxes; and,**
4. **compare results of analyses (1)-(3) with similar results from nearby selectively harvested site (together with collaborators Goulden and Rocha, CD-04) in order to address the question of how land-use change (selective harvest) affects carbon storage.**

1. **Assessing reliability and accuracy of eddy covariance measurements**. Eddy correlation measurements may have a variety of systematic biases (Goulden et al. 1996b, Lee 1998, Finnigan 1999, Sakai et al. 2001, Finnigan et al. 2002). Bias between day and night present the most significant issues: atmospheric stratification and net release of CO_2 prevail at night, while buoyancy and uptake of CO_2 dominant in the day. The fetch is longer and footprint larger at night, with higher turbulent frequencies and more significant advection due to thermal or topographic flow. Most of these effects lead to an underestimation of positive fluxes at night and thus overestimation of net carbon sequestration (Figure 3). Using detailed analysis of extensive data, and independent observations of some of the important processes in the ecosystem at night (e.g. soil respiration), we have developed and implemented effective strategies (adapted from McMillen 1988 and Baldocchi et al. 1988) to correct for effects of stratification, and for non-ideal sensor and terrain effects, and applied these successfully at other research sites, including a mid-lattitude temperate forest (Harvard Forest, see Goulden et al. 1996a), and a boreal forest (Goulden et al. 1998). A key step in correcting underestimates of flux during stratification is to determine, by detailed analysis of extensive data, when there is evidence of "lost flux" (u*<0.2 m/s at Tapajós); we estimate NEE for these periods with values interpolated from periods of more vigorous mixing (u*>0.2 m/sec). The effect of this correction at Harvard Forest was to reduce annual net uptake from 3.2 to 2.1 tonnes C/ha/yr (Goulden et al. 1996a). The corrected value was subsequently shown to be consistent with independent long-term carbon accounting of biomass stocks (Barford et al. 2001).

Determination of a convincing, error-bounded carbon balance for the Tapajós primary forest site (similar to that successfully produced for Harvard Forest and Boreas sites) is a high priority for this project. Our strategy has three components:

(a) Self-consistency checks among multiple datasets (e.g. two different levels and profile data) across different times, weather patterns, and meteorological conditions. The set of questions include: is there a consistent indication of "lost flux" due to a trend in nighttime NEE with u*? (see Figure 3) Is there a flux divergence between the two eddy levels (Figure 2), and if so, under what conditions and at what times does it occur?

As an example of this kind of analysis, we note that the general pattern indicating "lost flux" discussed in the results section above (a drop-off at low u* in top-of-canopy eddy flux that is incompletely compensated for by increased storage flux, see Figure 3) does not hold universally. Late in the dry season, we observed a period during which there was essentially no lost flux (Figure 10a), and "correcting" NEE using the u* filter had virtually no effect on accumulated carbon balance (Figure 10a, inset). This intriguing observation raises the question: is there a plausible mechanism (shifts in mesoscale circulation, nighttime boundary-layer dynamics, river breeze, or timing and magnitude of fluxes) that would explain why this period does not have the lost flux observed during other periods? Relevant data (e.g., mesoscale circulation) are being collected by collaborators Fitzjarrald and Moraes (CD-03) that will be invaluable for this analysis.

(b) Transport tracer study. Trace gas species that are essentially inert within the canopy (e.g.^{222}Rn, N_2O) but whose emissions from the soil may be measured, can be used as tracers of transport mechanisms from the forest canopy to the overlying atmosphere *(Trumbore et al. 1990, Ussler et al. 1994)*. Turbulent exchange of CO_2 should be similar to other trace gases, so comparison of radon-derived gas exchange rates with estimates for CO_2 flux by eddy correlation provide a direct test of our corrections for "lost flux." Collaborators **Martens and Moraes (TG-04)** have undertaken a tracer study using radon, and combining their data with ours will enable just such a test. Keller, Crill, and de Mello's (TG-07) measurements of N_2O and CH_4 are also suitable for this end.

Initial comparisons of our CO_2 data with ^{222}Rn from Martens & Moraes (TG-04) are extremely promising (Figure 11). The profiles of CO_2 and ^{222}Rn through the canopy exhibit a high degree of coherence and similarity (Figure 11a), including a curious peak late in the day near the ground for both species. The observed similarity gives confidence that canopy-atmosphere gradients (Figure 11b) will provide robust inter-comparison of ^{222}Rn and CO_2 fluxes. For example, the Rn-CO_2 regression of Figure 11b (inset) for a 1-week period gives a tight slope (0.00275 ±0.00005 pCi l^{-1} ppm^{-1}, R^2=0.8), providing a well-constrained, independent ratio for nighttime fluxes of CO_2 and ^{222}Rn.

(c) Independent assessment via biometry. Net CO_2 uptake or release must appear as corresponding changes in ecosystem stocks of carbon. When carbon stocks are monitored for a sufficiently long time, the data place independent constraints on the aggregated eddy flux measurements (*Barford et al. 2001*). The ecological component of this study (see section 1.3.2) will provide key data for changes in aboveground biomass and necromass for an independent biometric test of accumulated eddy covariance fluxes. Preliminary results already appear very promising.

Our Phase I data support the feasibility of aggregating eddy flux measurements to obtain defensible carbon balance at the km67 site:

(a) The pattern of nighttime NEE vs u* (Figure 3a) at km 67 allows unambiguous identification of "lost flux" for most observing intervals. This is not always possible (e.g., nighttime NEE vs u* graphs show no clear threshold at some Euroflux eddy covariance sites, see Aubinet et al, 2000). We have also found that measuring an instantaneous column-average CO_2 storage (as opposed to interpolating through time and space between different levels of the canopy profile CO_2) significantly reduces noise in the storage flux calculation (Figure 3b). This is important for generating a clear NEE vs. u* signal, and hence, for clearer identification of periods with a "lost flux" issue.

(b) The site has a high frequency of turbulent nights (relative to the adjacent km83 site, see Figure 12d; and to Manaus sites, see *Araujo et al. 2002*). This means that more "good" data (from periods of vigorous mixing) are available (40-50%, as opposed to only 10% or less for some flux sites) for filling the gaps created by filtering.

(c) The full difference between application of the u* filter versus no filter (Figure 2) is only ~1 ton C ha^{-1} yr^{-1}at this site, a noticeably smaller effect than observed at km83, Manaus (*Araujo et al. 2002*), and some other sites. This result reflects the prevalence of higher u* at km67, and possibly other factors.

2. Addressing science questions about carbon balance in primary forest. Two key questions are the focus of this component:

(a) What are the magnitudes of the net ecosystem exchanges for CO_2 , H_2O, and energy at a primary forest in the Tapajós region of Amazônia?

(b) How do these respond (quantitatively) to environmental forcing such as seasonal or inter-annual variations, dry periods, and cloudiness?

Answering these questions is a fundamental prerequisite to addressing the central scientific question for LBA: "How do tropical forest conversion, re-growth, and selective logging, influence carbon storage, nutrient dynamics, trace gas fluxes, and prospects for sustainable land use in Amazônia?" With empirically defensible aggregations of eddy flux (the output of component 1), we will be in a strong position to provide reliable flux data for one primary forest site. Our data for fluxes and for environmental driving variables (e.g. PPFD, temperature, precipitation), together with our measurements characterizing the forest (e.g. tree size-distribution, tree-fall gap distribution, canopy architecture), provide the basis to interpret the site to in the context of broader spatial scales.

Our Phase I data already begin to address ecosystem response to seasonal forcing. The 4-5 year dataset anticipated by the end of Phase II should to begin to characterize the response of whole-forest carbon balance to inter-annual variations in climatic drivers. Answering the second question relies on maintaining excellent long-term precision for measurements of both fluxes and environmental parameters.

3. Integrating eddy flux with biometry data to elucidate ecological mechanisms controlling net flux. Eddy covariance is a powerful tool for investigating patterns in whole-forest net flux at both short (day to day) and long (annual) timescales. Biometric surveys directly resolve subcomponents of the ecosystem, but only at medium to long timescales. We will combine the eddy flux data with biometry measurements to infer how subcomponents of the forest comprise the whole-ecosystem response to climatic variation on a wide range of timescales. We have already begun this kind of analysis on the initial data (see Hypothesis 3 regarding "Vegetation Dynamics", above, in section "1.3.1.1. Hypotheses"). The study of *Barford et al. (2001)* provides an example of integrating vegetation/ecological data and eddy covariance measurements to understand whole-ecosystem function in a mid-latitude forest.

4. Comparison of our primary forest with data from selectively harvested treatment site (collaborators Goulden and Rocha, CD-04) addresses the question of how a prevalent land-use change (selective harvest) affects carbon storage, i.e. Question 3b of LBA Carbon Dynamics theme, "How does selective logging change the storage and cycling of carbon in forests?". Our measurements in Phase II in the primary forest site at km 67 will serve as the control for the selectively-logged "treatment" site (km 83) of the FLONA Tapajós.

Most of the selective logging took place in August-September 2001 at km 83. Initial comparison of data from the two sites during the pre-harvest period shows excellent suitability of the treatment-control pairing of the two sites (Figure 12). Coherence between the two sites was very high for both NEE and PPFD; the light response curves were virtually identical and nighttime NEE vs. u* curves were similar, indicating similar "lost flux" corrections and overall climatic response. The close agreement between these independent systems is remarkable both ecologically and in terms of instrument calibration. There is, however, a distinct difference between the distribution of nighttime u*, with notably fewer intervals with u* > 0.2 at km 83. Application of the u* filter leaves a smaller fraction of usable data at km 83, a difference that will have to be carefully assessed. We already know that the difference between using the u* filter, or not, is significantly bigger at km 83 due to this factor. We will work closely with research group CD-04 during phase II of LBA-ECO to fully understand inter-site similarities and differences and to analyze the impact of harvest on carbon cycling.

1.3.2.2. Eddy fluxes across sites: FLONA Tapajos (Santarem) versus Reserva Cuieiras (Manaus)

It is very important to distinguish true differences in ecosystem carbon exchange from measurement artifacts caused by inter-site variations in instrumentation, local meteorology or topography. "Studies that carefully evaluate the results from eddy covariance flux towers will be essential" (NRA). We propose a vigorous study to address this need, focused on understanding the similarities and differences between eddy flux measurements at FLONA Tapajós (this proposal) and the two towers at Reserva Cuieiras (*Araujo et al. 2002*). This study will be undertaken jointly by the team at Harvard, and the team at INPA in Manaus, **CD-400 led by A. Nobre**.

The sites exhibit many contrasts: FLONA Tapajos, km 67 is extremely flat, and has virtually uniform soil type. Reserva Cuieiras has a corrugated landscape, with a mosaic of flat upland plateaus underlain by seasonally dry clay soils interspersed with valleys carved by a crosscutting drainage network of steams that consist of sandy soils that are often saturated or inundated. Though the vegetation type is fairly uniform in the plateaus, two eddy flux towers (sites C-14 and K-34) on plateaus 20 km apart exhibited significantly different patterns of NEE, which *Araujo et al. 2002* attribute in part to differences in topography between the two tower sites (K-34 has significantly more area of lowland saturated soils and inundated vegetation).

We will conduct a detailed analysis, starting with the basics of inter-comparison of instruments and data processing and covariance calculations. As part of the instrument inter-comparison, the Harvard group will assist the INPA group to design and build an automated calibration sequence to investigate the sensitivity of the gain of the fast response sensor (and hence, of eddy fluxes) to diel variations in temperature and barometric pressure. For the data inter-comparison, we will examine the derivation of aggregated data, paying special attention to how interactions between analysis methods and site-specific meteorological issues might influence the aggregated NEE.

1.3.3. Ecological measurements

Carbon dynamics theme, question 2 asks "How do biological processes such as mortality and recruitment or succession following land use change influence the net annual carbon balance for different land cover and land use types?" This part of our proposed work will provide an important foundation for answering this broader question by first posing a narrower one: how do these biological processes (mortality and recruitment) influence net carbon balance in response to climate forcing, even in the *absence* of anthropogenic land use change?

1.3.3.1. Ongoing Measurements

Table 1B summarizes the proposed Ecological measurements.

Tree wood and litter dynamics

We will continue monthly dendrometry and mortality measurements in the sub-sample of 1000 trees, bi-weekly litterfall collections from 40 litter baskets, and biannual re-surveys of the entire 20-

ha study plot area. Continued measurements of CWD and forest floor litter over time will allow an assessment of temporal change in the above-ground necromass pool.
Dendrometry method study: We will conduct a sub-study of the grow-in effect for dendrometer measurements. A second band will be placed on a subset of trees, and the time to convergence between the new and the original band (now on the trees for >2 years) will be assessed.
Analysis: measurements regularly spaced in time (monthly for dendrometry and bi-weekly for litterfall) will allow, after several more years of measurement, development of a "canonical mean year" based on the long-term average. Each year's month-by-month deviation from the mean year can be correlated with deviations of potential driving variables (e.g. precipitation, cloudiness) from their means, giving insight into long-term mechanisms (see *Barford et al. 2001*, for an example of this kind of analysis applied to long-term eddy flux data).

1.3.3.2. New vegetation measurements

We plan to: **(a)** expand plot size for large trees to increase statistical resolution of the biomass flux measurements; **(b)** initiate two studies of stand-level ecophysiological parameters (mapping of tree-fall gaps, and characterization of canopy architecture) in the eddy flux tower footprint ; and **(c)** reconstruct long-term historical tree-growth in the Tapajós using novel isotopic methods (^{18}O in wood cellulose) that promise to give annual growth rates in trees lacking visible annual rings.

(a) Expansion of biometry plots for large trees

The 95% confidence interval on net flux to biomass is ±1 ton C ha^{-1} yr^{-1}, with the biggest contribution coming from the small sample of large-tree mortality (Figure 8) due to the episodic character of tree mortality. A single large tree can represent a substantial fraction of the mortality flux in a given year. We would like to statistically resolve smaller fluxes.

The error associated with mortality (and hence net aboveground biomass flux) can be reduced by expanding the sample size for large trees only. The cost in terms of increased effort is moderate because the density of large trees is low. Therefore, in addition to continuing the tree dynamics measurements according to the current design, we propose to expand surveyed area for very large trees (>60cm DBH) to 75 ha (see shaded region in Figure 6). This will almost quadruple the area on which these very large trees are sampled, allowing the sampling uncertainty associated with mortality to be roughly cut in half.

(b) Mapping of tree-fall gaps and characterization of canopy architecture (LAI)

Stand-level ecophysiological parameters (such as tree size-distribution, spatial and age distribution of tree-fall gaps, canopy architecture) provide links for our two main categories of measurements, environmental driving variables, and ecosystem fluxes. The NRA calls for Phase II "studies that propose to fill observational gaps at LBA flux tower sites to ensure that all needed driving and state variables and key physiological and ecological processes for models are measured." To respond to this call, we propose to add to our existing study of tree-size distribution by initiating two complementary studies suitable for our biometry plots: (i) mapping of tree-fall gaps over time, and (ii) measurements of canopy architecture over time.

(i) Mapping Tree-fall gaps. When a tree falls in a forest, it often brings down one or more nearby trees, creating an opening in the canopy and a local disturbance regime (principally, the addition of light near the ground). This initiates a small-scale successional sequence (gap-phase regeneration) that eventually leads to the replacement of the lost tree(s) by one or more new trees *(Picket and White 1985, Hubbell et al. 1999).* The spatial and age distribution of such forest gaps is a key indicator of overall "inertia" in forest structure and demography, and hence, of the timescale

and plausible range of possible longer-term changes in forest carbon dynamics *(Moorcroft et al. 2001)*. We plan biennial surveys to produce a detailed mapping of tree-fall gap sizes and locations on the biometry transects (Table 1B), as a time series.

In each survey, we will visually identify forest gaps (contiguous areas with canopy <5m in height, after *Hubbell et al. 1999*), and use a laser range-finder to measure the dimensions of each gap in the biometry plots. For some gaps, the time of gap formation will be identifiable because the tree-fall which created the gap will have been noted as part of the monthly dendrometer survey.

(ii) Canopy architecture: LAI and branch distributions. Leaf Area Index (LAI) is coupled to photosynthetic and transpiration capacity of the forest and to light penetration. Thus LAI is a key link between stand characteristics and a main component of carbon fluxes (gross ecosystem exchange); it is observable by remote sensing and has been used to scale flux data at individual locations to broader patches of forest (e.g. *Aber and Melillo et al. 1999, Schlesinger 1991*). Seasonal and inter-annual variations in LAI (due, for example, to seasonal or inter-annual variations in precipitation or soil moisture availability) may be expected to drive variations of whole-forest photosynthetic capacity, light penetration and carbon flux. LAI is thus an important variable that mechanistically links climate variations to variations in carbon exchange.

Measurement Method

Several methods have been devised to measure parameters of leaf area/unit ground area (LAI), gap fraction, light extinction and branch area and structure, both directly and indirectly (*Norman and Campbell 1989*). Optical methods such as the LAI 2000 or hemispherical photography are convenient, but cannot separate light interception of branch and bole from leaf area, and results depend on assumptions (e.g. random leaf and shoot distribution) that may be invalid (*Fassnacht et al. 1994, Gower and Norman 1991, Kucharik et al. 1997, 1998, Innes 2001*).

A new instrument, the Multi-band Vegetation Imager (MVI), has been developed that provides data on LAI and classifies separate image components as sunlit or shaded leaves, branch and bole, blue sky or cloud (*Kucharik et al. 1997, 1998, 1999*). The instrument records visible and near-infrared spectra, above or below the canopy (see *Kucharik et al. 1998*). The MVI was tested against destructive methods during the Boreal Ecosystem-Atmosphere Study (BOREAS) and found to significantly improve estimates of LAI in hardwood and conifer canopies over other optical techniques (*Kucharik et al. 1997, 1998*). The MVI's ability to distinguish canopy components and architecture should improve scaling of carbon, water and heat balances from the plot to stand level.

One problem that can affect any optical method in high-LAI forests such as the Tapajós is saturation in canopies with LAI values > 6.0 (*Kucharik 1998*). Thus, conventional optical methods may not be capable of detecting true inter-seasonal or inter-annual variations in this high LAI forest. The MVI is not restricted to below-canopy measurements, but can acquire images at any point above or within the canopy looking up or down. Therefore, if high LAI-induced saturation proves to be a problem, we can circumvent it by recording two separate views, one toward zenith and one earthward, made at mid-point in high LAI canopies (6.0 – 12.0).

Proposed Design

We will calibrate the MVI instrument against litter fall measurements of total LAI in a temperate deciduous forest (Harvard Forest, MA) where annual leaf production (and LAI) is well-characterized by end-of-season litterfall measurements. Estimates will be conducted simultaneously using a LAI 2000 instrument to obtain calibration coefficients for correction of previous LAI data.

We will perform leaf area measurements of fresh litter then dry and weigh each leaf to obtain specific leaf weight (SLW) data, allowing conversion from optically derived LAI to mass values.

Leaf area will be measured on a 100 meter transect. We will sample five 100 x 30 m image swaths of the canopy centered at random along the midpoint of the 20 x 1000 m foot print plots. Leaf area will be estimated by the methods of Kucharik et al. (1998).

(c) Reconstruction of long-term historical tree-growth via isotopes of ^{18}O in wood cellulose

Dendrochronology and dendroecology have been successfully used in temperate zones to infer historical climate, tree growth and carbon assimilation rates, and interrelations among these phenomena. These methods have not been applied in the tropics because many tropical tree species form rings intermittently or not at all. Three recent scientific and technical advances, however, open the way to tropical dendrochronology and dendroecology in trees without visible annual rings:

(i) mechanistic understanding of controls on ^{18}O composition of tree wood cellulose: In a recent set of greenhouse, field and model studies Roden and colleagues showed that the oxygen isotope composition of the α-cellulose component of wood depends primarily on the oxygen isotopic composition of source waters and evaporative enrichment at the leaf where photosynthate is produced. The Roden-Lin-Ehleringer (RLE) model (*Roden et al.*, 2000) gives a mechanistic underpinning to resolve wet-dry cycles in tropical trees lacking rings, and suggest that cellulose ^{18}O should have an annual cycle in ecosystems such as Tapajós with markedly seasonal rainfall, even when temperature is constant and tree-growth maintained through the year.

(ii) Rapid α-cellulose extraction chemistry. Standard chemical extraction techniques for cellulose have until recently involved toxic reagents, complex and extremely time-consuming (1 sample per technician day of lab work). New techniques (*Brendel et al. 2000, Evans and Schrag, 2002*) now allow extraction of 100 + samples per day using simple techniques and non-toxic reagents.

(iii) Rapid automated online measurements of ^{18}O in cellulose. Advances in continuous flow mass spectrometry make $\delta^{18}O$ measurements fast, simple and precise (0.2 to 0.3 per mil)*(Brand, 1996)*. Small sample sizes (~ 100 μg) allow sub-annual resolution even for slowly growing trees, and fast processing means that the required high volume of sample processing is feasible.

Pilot studies on tree cores from Costa Rica (Evans and Schrag, 2002) and from our primary forest site in Brazil (Figure 13) suggest that $\delta^{18}O$ in α-cellulose does in fact reveal annual oscillations. This interpretation will be confirmed by ^{14}C measurements on wood cellulose (^{14}C measurements are already being undertaken by LBA collaborators Carmago & Trumbore (CD-08)).

These new methods may enable estimation of long-term tree growth rates and carbon assimilation in the tropics. We plan a pilot study focusing on Tapajós trees. The short-term goal will be to reconstruct recent historical growth rates of selected trees and then combine the isotopic record with rainfall data in the Santarém region, to determine how climate has affected tree-growth rates. Eventually, we hope to obtain 100+ year records of tree growth that may be used to test the CO_2 enrichment hypothesis: if increased CO_2 is indeed stimulating excess carbon sequestration in undisturbed forests, we may be able to observe it in the long-term record of tree growth.

The pilot data shown in Figure 13 are from a core extracted from a live tree using an increment borer. The data are a compelling demonstration of the feasibility of the isotopic method, but issues remain due to the asymmetry of tree stems. Accurate reconstruction of tree growth rates requires that the samples be taken along a radial line. The starting point of tree growth is frequently not the geometric center of the tree, however, so we propose that future samples be taken from recently downed trees in which the true origin can be identified. An initial set of samples will be taken from the stumps of trees recently harvested at the km 83 site.

1.3.4. Coastal Site: Marine Boundary-Layer concentrations at Natal

Long-term measurements of background concentrations of CO_2 over continents, when compared with adjacent marine stations, provide valuable constraints on the magnitude of CO_2 fluxes on regional to continental scale. We plan continuous observations of CO_2 at the new coastal site at Natal, recently completed by INPE and run by Brazilian collaborator V. Kirchhoff. These observations will allow us to define the CO_2 gradient between the coast and the Tapajós region, a key parameter to place the observations of the upcoming LBA Airborne Science investigations (especially **LBA-Airborne component CD-14**) in a longer-term context. The instrumentation will be a copy of the profile system installed at the Tapajós site, sampling at one level with frequent calibration using gases traceable to world standards. This site will be the only equatorial Atlantic station in the CMDL network. Simultaneous CO data will distinguish marine vs. terrestrial air and allow removal of samples affected by local emissions.

Work on this system is 90% complete. It was delayed in Phase I by the emergence of biometric observations as a higher priority, and by the stiff logistical problems encountered in the installation of the tower instruments (e.g., one shipment took 14 weeks to get through customs, incurring $10,000 in storage fees). Shipment is expected in a few weeks.

1.4. Plan for Integrative Science

The proposed work here is a key element for a range of complementary projects. We propose an integrative science plan with two levels: (1) focused collaborations with other research groups on specific empirical and modeling questions; and (2) active participation in broad synthesis activities across LBA via workshops and meetings.

1.4.1. Focused Collaborations

The core set of measurements proposed here for the Tapajos primary forest site at km 67 (eddy flux and biometry) play a key role in a range of collaborations we are undertaking with other LBA research groups. The collaborations in which we are most active are:

- Selective Harvest Experiment (collaborate with *Goulden & Rocha*, **CD-04**). A central collaboration is to determine the effects of selective harvest on ecosystem carbon cycling. Results from the pre-harvest comparison appear very promising (see discussion of Figure 12).

- Trace-Gas (CH_4, N_2O, Rn) profiles and gradients (collaborate with *Fitzjarrald and Moraes,* **CD-03***; Keller, Crill & de Mello,* **TG-07***;* and *Martens & Moraes,* **TG-04***).* Trace gas data provide information about canopy transport rates, giving an independent evaluation of filtering and filling the eddy flux data for CO_2. Initial analyses with ^{222}Rn (Figure 11) (section 1.3.1.1. “Measurements and Analysis at FLONA Tapajos”) are very promising.

- Components of Ecosystem Respiration *(collaborate with Keller, Crill & de Mello,* **TG-07***).* Group TG-07 is making extensive chamber-based measurements of components of the ecosystem respiration budget, including respiration from soils, tree-boles, and components of CWD. We plan to collaborate by combining our net ecosystem eddy-covariance fluxes with their component fluxes, for purposes of providing a consistency check on eddy-flux and chamber-based measurements, as well as for understanding respiration dynamics.

- Integrative Modeling studies. *(collaboration with* **LC-08***, and others).* The work proposed here will generate a core dataset for use in model evaluation studies. We have already begun working with G. Hurtt and P. Moorcroft (**LC-08**) to use our data to evaluate their Ecosystem Demography (ED) model *(Hurtt et al 1998, Moorcroft et al., 2001, Hurtt et al.,* *2002)*. ED makes regional simulations, but its predictions can be evaluated at a variety of spatial and temporal scales. We envision using data to test predictions at the local scale for hourly to yearly predictions of surface-atmosphere CO_2 fluxes (net ecosystem productivity, NEP). These data will help assess model capability to capture diurnal, seasonal and inter-annual variation in CO_2 fluxes at our site. ED also predicts forest structure and demographic turnover, which can be tested using the forest inventory data of the kind that we will continue to produce as part of this work.

- Integrating NEE with isotopic data (collaboration with Ehleringer/Martinelli, **CD-02)**. Stable isotope analyses of ecosystem pools and fluxes provide important constraints for testing interpretations of whole-ecosystem flux data. We propose to work in Phase II with Ehleringer/Martinelli (CD-02) to integrate our NEE data with their isotopic data at km67. Their isotope studies will also provide key context for understanding and verifying physiological mechanisms that underlie seasonal ^{18}O variations in wood cellulose (see above, “1.3.3.2. New vegetation measurements” and Figure 13).

- Regional Carbon Budgets based on Atmospheric Boundary Layer measurements. As discussed previously (section “1.3.4. Coastal Site: Marine Boundary-Layer concentrations”), the continuous high-accuracy concentration measurements made pursuant to this proposal (in both the FLONA Tapajós, and at the coastal site near Natal) will provide an essential complement to the aircraft-based concentration measurements proposed under **CD-13** and **CD-14**, and to the long-term flask sampling program proposed by Tans et al. (**TG-06**) as part of the CMDL network.

- Aerosol and trace-gas studies. CO is a tracer of biomass burning. Our measurements of CO concentration at Santarém and Natal are the basis for collaborative studies of aerosol inputs (Artaxo, **TG-02**) and of ozone (Vanni-Gatti, **TG-02**). We will also contribute to ongoing and proposed investigations of biogenic hydrocarbon emissions (Guenther et al., **TG-02**).

1.4.2. Broad Synthesis activities

We have been and will continue participation in broader synthesis activities being proposed as part of LBA, including the all-LBA science meetings, as well as more narrowly focused workshops. For example, we recently participated in the CPTEC-sponsored workshop, the first eddy-flux tower workshop, held in December 2001.

1.5. Anticipated results of the Research and Deliverables

By the close of LBA-ECO phase II, the proposed study will have delivered the following:

- four years of continuous data defining the Net Ecosystem Exchange of CO_2 for a primary forest in the FLONA Tapajós in central Amazônia;
- net fluxes of H_2O and energy for this primary forest;
- five years of ecological data, including: growth, mortality, and recruitment of trees > 10cm DBH; litterfall rates and seasonal patterns of forest floor mass; three re-surveys of coarse woody debris;
- comparison of Net Ecosystem Exchange of CO_2 for the primary forest with a harvested stand (*Goulden & Rocha*);
- measurement of seasonal, annual and inter-annual changes in NEE and quantitative determination of relationships between NEE and climatic, ecological, and other environmental parameters;

- fluxes of N_2O, CH_4, determined by *collaborators* making use of our proposed wind and flux observations as an integral part of their experiment;
- monthly mean values of the CO_2 concentration in the continental boundary layer;
- four years of continuous CO concentration at forested site and three years of CO concentration at a clean coastal station;
- education activities as given in our Education Plan;
- data products universally available as given in our Data Plan;
- analysis of CO data *with collaborators* to assess the magnitude of biomass burning influence on ozone concentrations and aerosol loading;
- analysis of CO:CO_2 relationship to segregate biogenic and combustion-derived influence on CO_2 concentrations;
- analysis and publication of the results to address scientific and societal questions.

LBA Ecology issues addressed by the work

⇒ **Theme 2 (b,c,d):** Net rates of CO_2 exchange between vegetation, soils and the atmosphere; response of these rates to selective harvest *(collaboration with Keller et al. and Goulden)* and to short-term, seasonal and interannual changes in climate and weather;

⇒ **Theme 4:** Trace gas fluxes *(collaboration with Keller et al.)*; monthly land/ocean differences between the continental boundary layer and marine values to test atmosphere-biosphere models.

The context of previous work

The proposed work will extend measurements of NEE for CO_2 in tropical forests to a new region of Amazônia, with relatively long dry season and large variance of seasonal climate. The observations will define the factors that influence net uptake at the site, especially climatic factors for this region, providing a comparison with previous work by *Fan et al (1990), Grace et al. (1995)*, *Mahli et al. (1998)* and *Araujo et al. (2002)*. The measurements should therefore help to understand if net uptake of CO_2 reported for an Amazônian forest *(Grace et al. 1995)* represents a general or regional phenomenon.

Novel aspects

The study will provide the baseline against which the effects of a selective cut on a companion site *(proposed by Goulden, Keller et al.; Fitzjarrald et all.)* will be measured. The data will be combined with observations of trace gases (N_2O, CH_4, O_3) and aerosols and with studies of the exchange fluxes between the canopy and the overlying atmosphere to define continuous net ecosystem exchange for many of the species at the heart of the LBA plan.

Filling major gaps

- The ***definition of environmental factors regulating NEE in primary tropical forest, including integration with biometric observations of component pools and fluxes***
- ***major efforts to resolve measurement issues surrounding eddy flux data using independent measurements (^{222}Rn, biometry) to test and validate C budgets from flux data***
- ***direct determination net release of CO_2 in a selective harvest*** and
- ***measurement of long-term continuous ecosystem fluxes for many other species***

will represent major advances in scientific knowledge of the current influence of tropical forests on the atmosphere, the response to environmental change, and the effects of human manipulation of land and vegetation.

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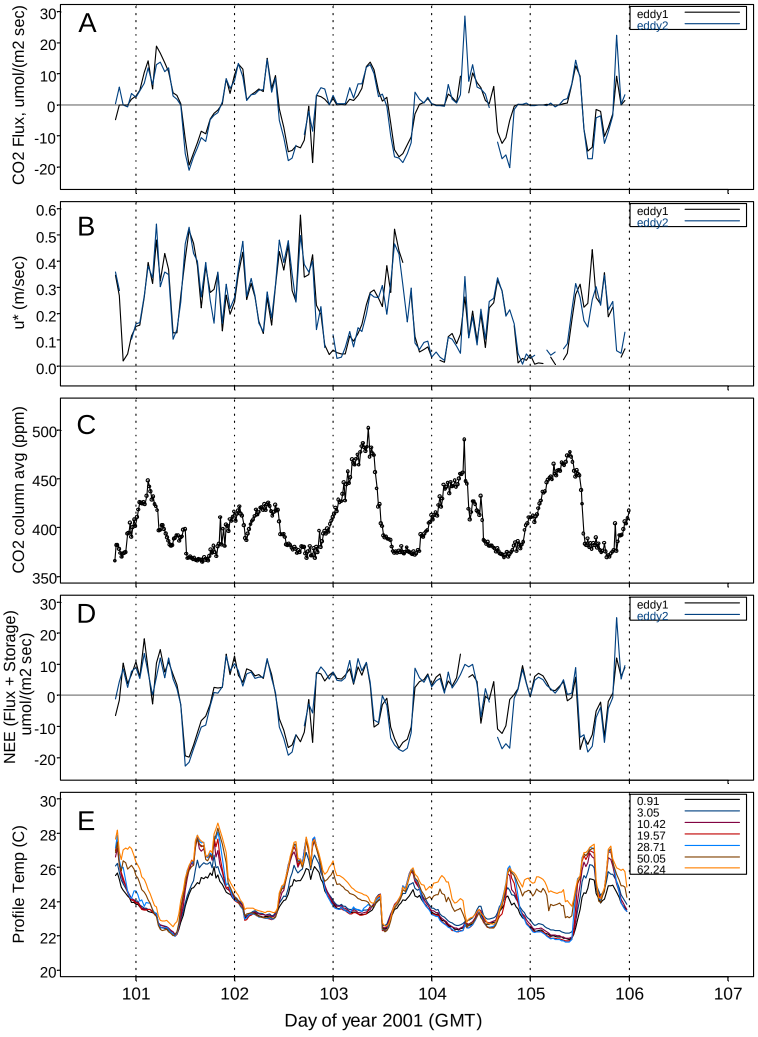


Figure 1. Hourly time series of data from the Primary Forest eddy flux tower at km 67 in Tapajós National Forest: (A) Eddy flux of CO$_2$ for eddy1 (58m) and eddy2 (47m); (B) friction velocity (u*); (C) mean CO$_2$ concentration 0-60m ("canopy storage"); (D) net ecosystem exchange (NEE = Eddy flux + d/dt<storage>); and (E) temperature profiles. On *windy nights* (days 100-102, U*>0.2 m/s (B)) CO$_2$ efflux (A) is strongly positive, temperature profiles (E) are well-mixed; CO$_2$ storage (C) is low, and NEE (D) ≈ flux (A). On *calm nights* (104-105), flux (A) and u* (B) are virtually zero, temperature profiles (E) are stratified, and CO$_2$ storage is high, causing NEE to be significantly higher than eddy flux.

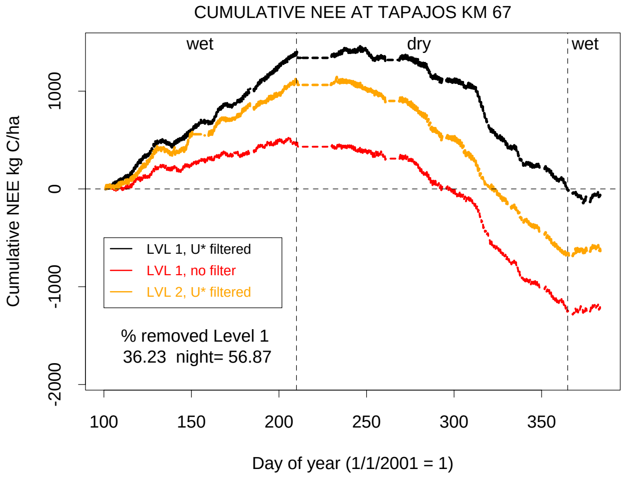


Figure 2. Cumulative net ecosystem exchange (NEE) of carbon during the first 9 months (positive values indicate fluxes to the atmosphere) at level 1 (58m, unfiltered and filtered: U*>0.2 retained, U* < 0.2 interpolated) and level 2 (47m, filtered). *Filtered level 1 values are the current "best estimate" of NEE*; 64% of hourly data are retained overall, 43% retained at night. Since carbon is emitted during the wet season, full-year carbon balance should be slightly more positive than the endpoints indicated here. Note: "zero" accumulation (---) is imposed when data were missing from any one of eddy 1, eddy 2, or canopy storage, for consistent comparison. Usually only one datum is missing, and final estimates of cumulative NEE will use these data with an interpolation and prediction method to fill the gaps).

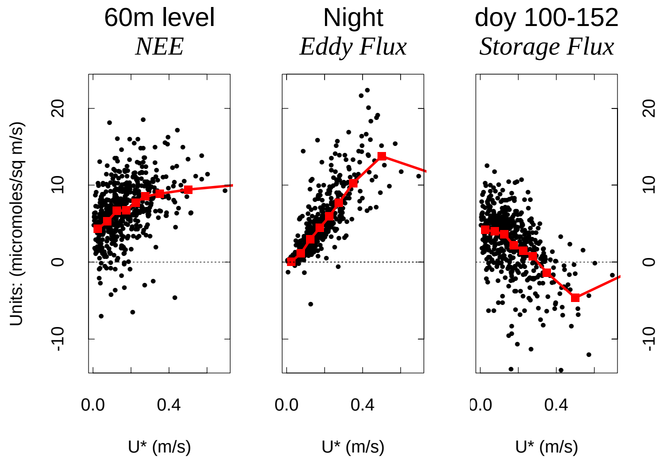
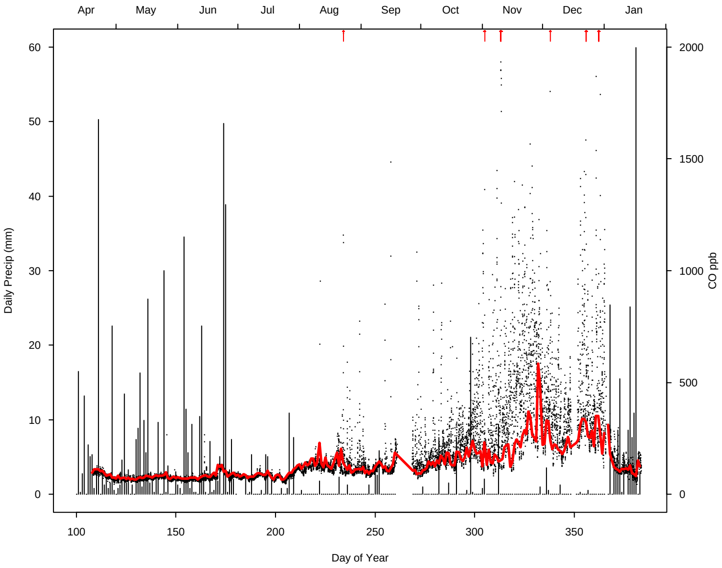


Figure 3. Relationship between friction velocity (u* = √(-1 x momentum flux) and measured values of nighttime NEE at 58 m (*left*) and its components, eddy flux (*middle*) and storage flux (*right*). As U* → 0, eddy flux decreases and storage flux increases as expected, but their sum (NEE) declines somewhat for u* < 0.2 m/sec. The associated "lost flux" is relatively small at this compared to some other LBA sites, amounting to roughly 1 ton C/ha/year between filtered and unfiltered data (see Figure 2).



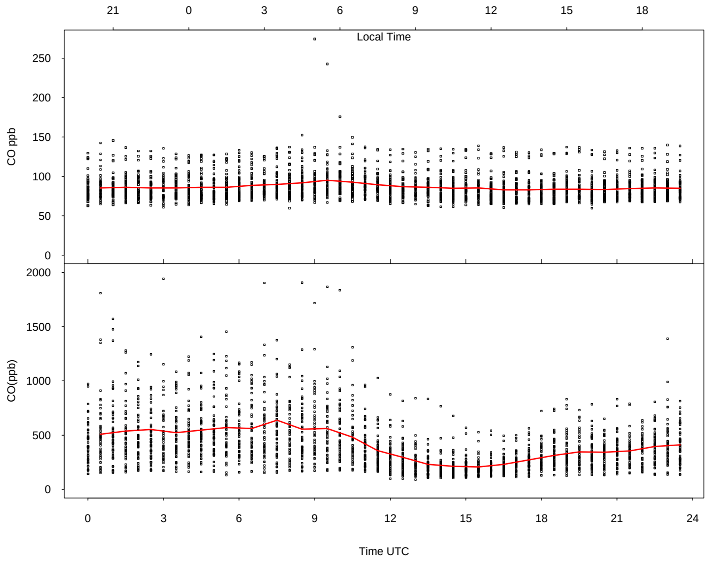
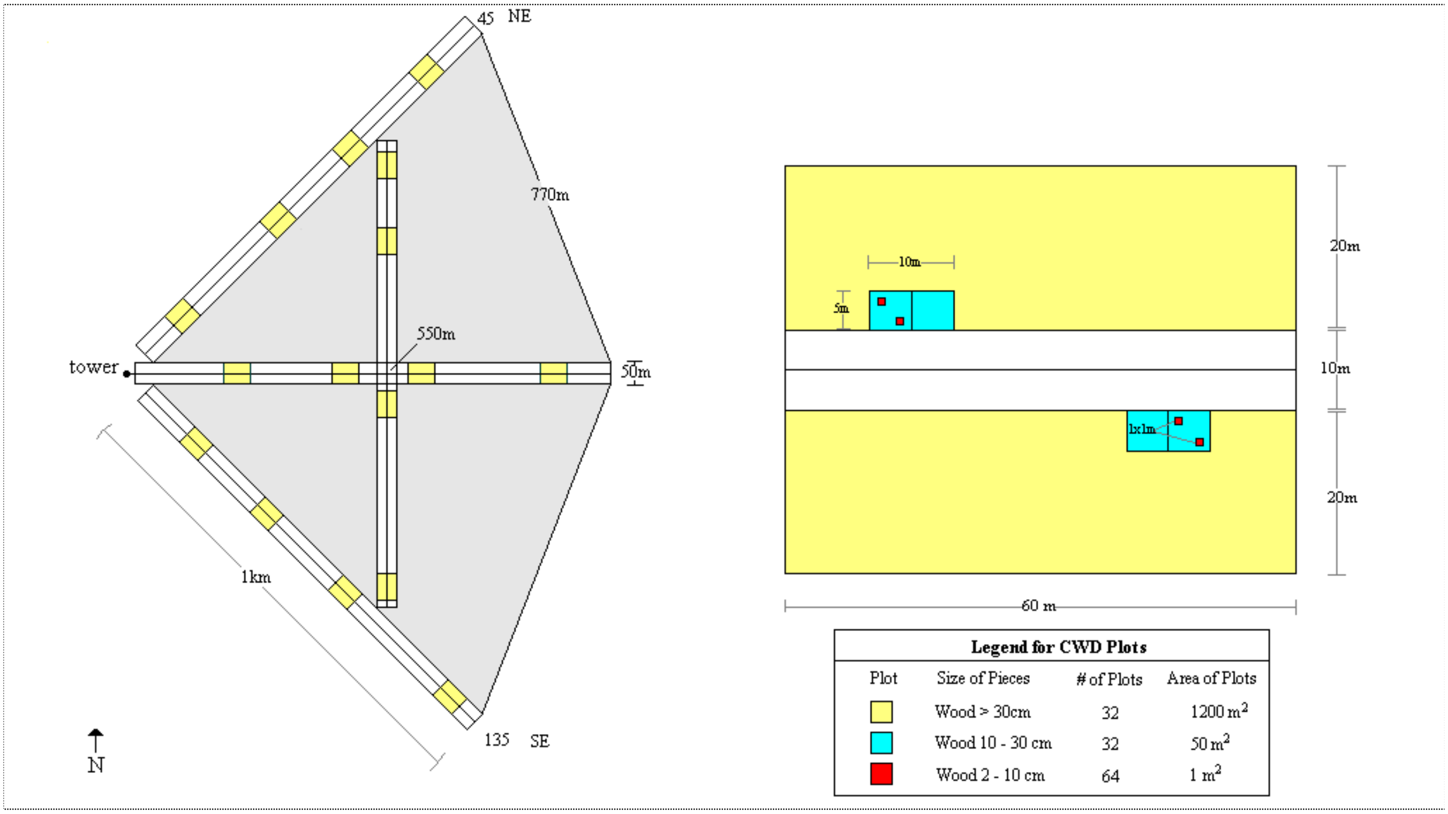


Figure 4 Time series of CO concentrations at Santarém km67 site. Individual half-hourly averaged points are shown as dots. The red line indicates average concentrations during the period 0800-1400 that are best representative of the mixed layer. Vertical bars give the daily rainfall amounts measured at km67.

Figure 5. Average diel cycles of CO concentrations during the wet season (*upper panel*) and dry season (*lower panel*) at km 67. Concentrations are much higher in the dry season, especially at night, evidencing regional fires (note the change in the ordinate scale).



Legend for CWD Plots

Plot	Size of Pieces	# of Plots	Area of Plots
🟨	Wood > 30cm	32	1200 m^2
🟦	Wood 10 - 30 cm	32	50 m^2
🟥	Wood 2 - 10 cm	64	1 m^2

Figure 6. Map of the 4 biometry transects, including Coarse Woody Debris (CWD) subplots, at primary forest site (km 67, FLONA Tapajós, Brazil). Coarse woody debris (CWD) sampling plots (expanded view, right) were assigned positions from a randomly generated X coordinate between 0 and 940 meters. In the proposed work, all large trees (>60 cm DBH) in the grey-shaded zone (~ 70 ha) will be added to our present stratified inventories and monitoring in the white zones (20 ha) and CWD plots.

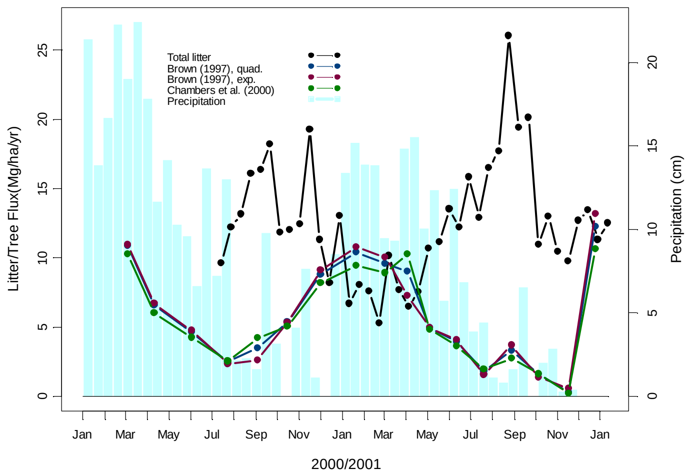


Figure 7. High-resolution tree growth rates (Mg dry matter/ha/yr, from 1000 dendrometers), litterfall (Mg dry matter/ha/yr), and precipitation, showing strong seasonality in biomass fluxes over ~2 yrs. The principal driver appears to be precipitation; note the positive correlation with tree growth and negative correlation with litterfall.

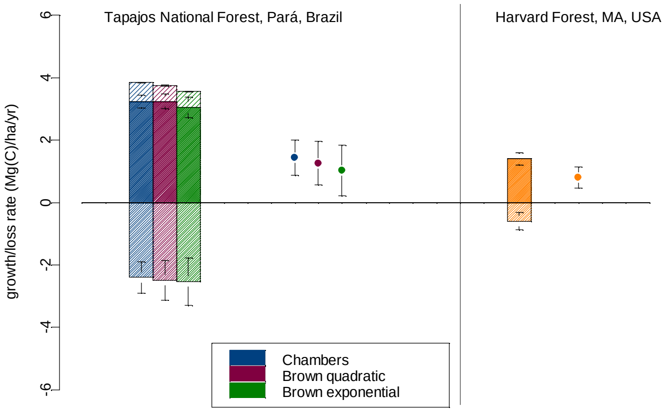


Figure 8. Gross (histograms) and net (points) carbon fluxes due to *growth*, *recruitment*, and *mortality* in the TNF (1999-2001). Data for an aggrading temperate forest (1993-2000, Barford et al., 2001) are shown for comparison. The ± 95% confidence intervals (error bars) were derived from bootstrap re-sampling. Three allometries were used for the TNF data, indicating that the magnitude of uncertainty due to allometry is smaller than the sampling uncertainty, which is in turn dominated by uncertainty of mortality flux.

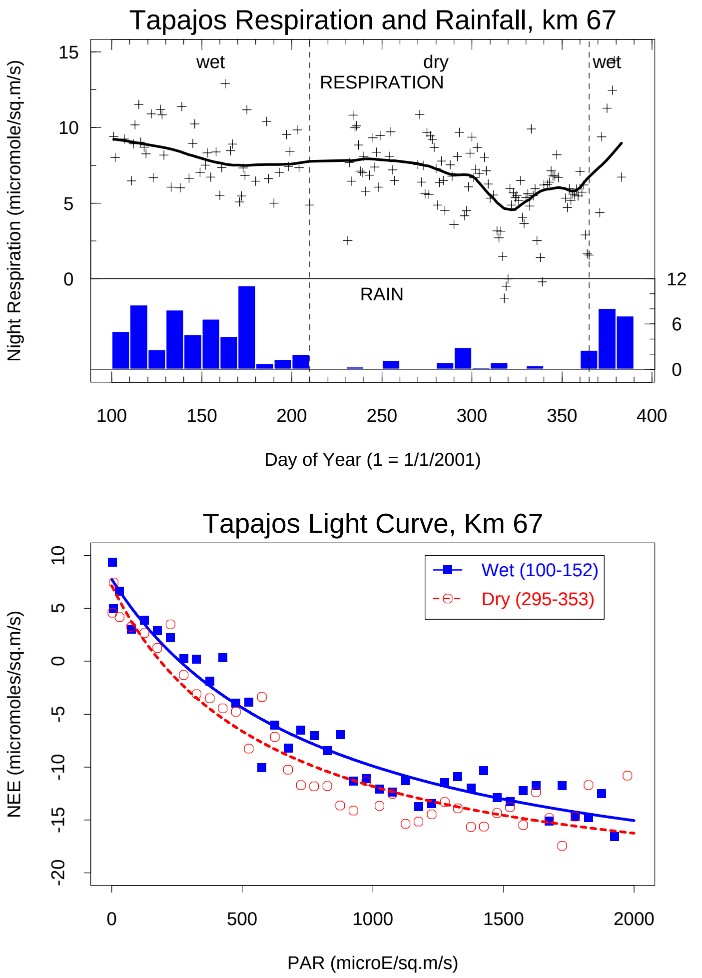


Figure 9. (*upper*) Ecosystem respiration R (night NEE, U*>0.2), shows reduced R during the dry season, abruptly increasing when rains start (histogram); (*lower*) NEE vs. PAR for dry season and wet season, showing greater net uptake in the dry season. Most of the increased uptake could be attributed to lower respiration rates..

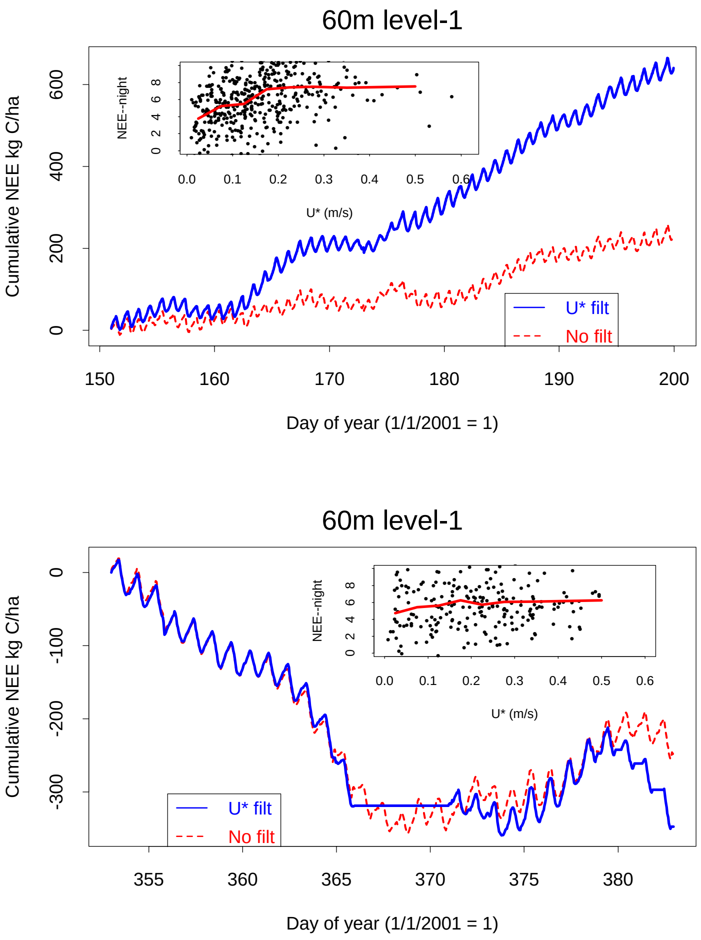


Figure 10. (*upper*) Mid wet-season (days 152-199) cumulative NEE showing net carbon loss and a significant effect of the u* filter correction. (*lower panel*) Late dry-season (days 295 – 353) cumulative level 1 NEE showing carbon uptake and little effect of u* filter. Insets show the different relationships between nighttime NEE and U*, with very little "lost flux" in the dry season.

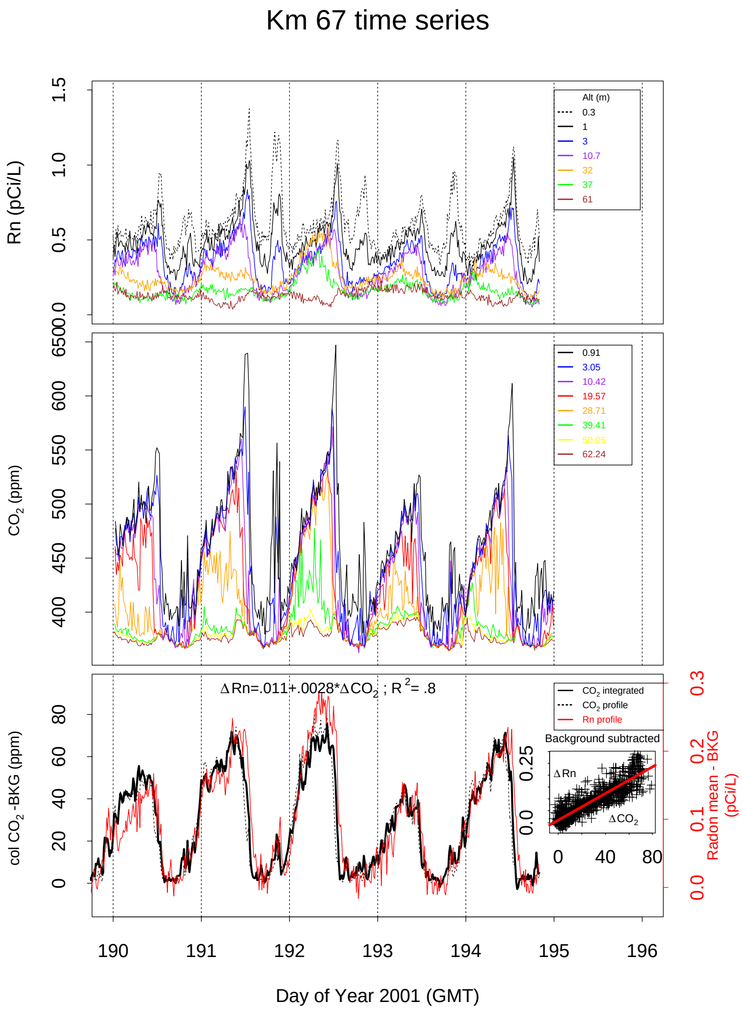


Figure 11. (a) Vertical profiles of ^{222}Rn (*upper*) and CO$_2$ (*middle*), and corresponding canopy-atmosphere gradient (*lower;* $<C>-C_t$) in July 2001 ($<C>$ is the column-average; C_t is the above-canopy value derived from U*>0.2 filter applied to data from 60m altitude). (*inset*) Scatter plot and regression line: $(<Rn> - Rn_t) = 0.011 + 0.0028\cdot(<CO_2> - CO_{2-t})$, $R^2=0.8$). Radon data from C. Martens and O. Moraes.

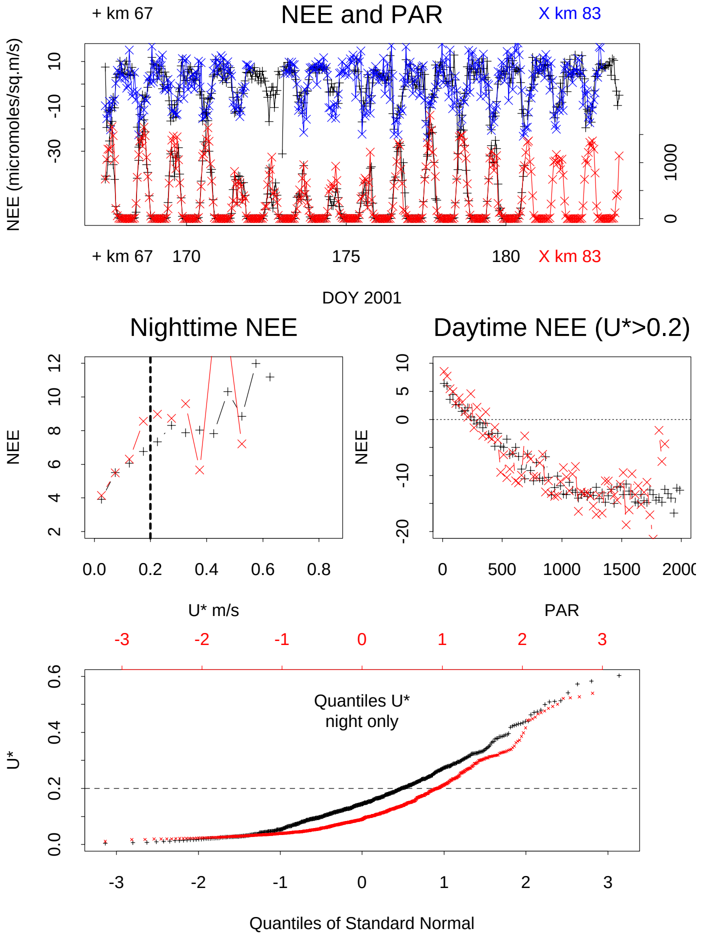


Figure 12. Km 67 vs km 83 (pre-harvest) comparison: (*upper*) time series of NEE and PAR; (*second*) nighttime NEE vs u*; (*third*) daytime NEE vs PAR; and (*lower*) distributions of nighttime u* (days 100- 190 of 2001). Note the exceptionally high coherence, and similar NEE responses between sites. Nighttime u* distributions show that nights at km83 are calmer than at km67. Km83 data from M. Goulden, H. Rocha, and S. D. Miller.

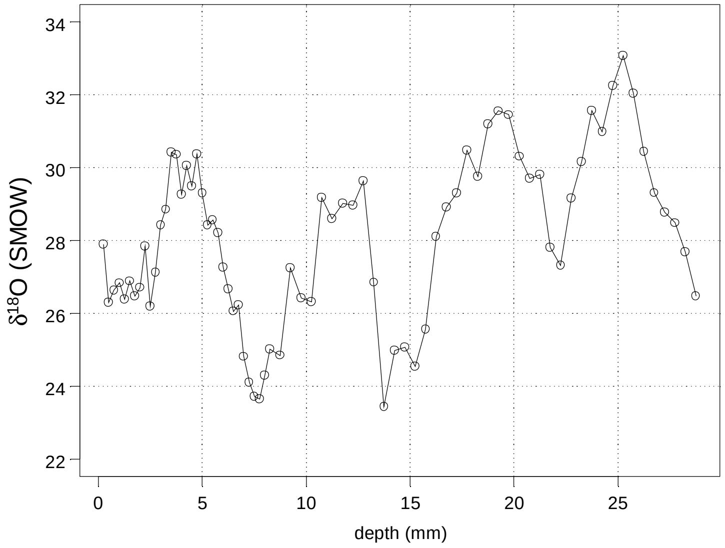


Figure 13. δ^{18}O vs depth in tree-core α-cellulose, in *Erisma uncinatum* (Quarubarana) sample without visible annual rings. This tree was observed to have high radial growth (5 mm/yr via dendrometry) prior to sample extraction (April 2001), consistent with the high apparent growth rates (5-8 mm/yr) revealed by the δ^{18}O series.

Table 1: Existing and Proposed Measurements, CD-10. (unshaded = measurements currently underway and proposed to be continued in phase II; gray shading = in progress, to be implemented by late 2002**;** blue shading = new activity proposed for phase II)

Measurement	***sensor/measurement method***	***Location/Area of measurement***	***frequency***
		<u>Tapajos National Forest, km 67</u>	
A. Eddy Covariance and associated instrumentation			
Net fluxes of CO2, H2O, momentum and heat	sonic anemometer (CSAT-3) + IRGA (LI-6262)-based instrument package	tower (2 levels: 58m, 47m)	8 Hz
CO concentration		tower, 60m	
CO2/H2O concentration (canopy storage) as: (a) profile at 8 levels (b) integrated column-average	IRGA (LI-6262)-based instrument package	tower (cycle through 8 levels: 62m down to 0.9m) tower (pull from all 8 levels simultaneously)	2-min/level every 20-min
Temperature profiles	shielded, aspirated thermistors	tower (8 levels, as above)	½ Hz
Wind-speed profiles	cup anemometers (Met One)	tower (4 levels: 64, 52,38, & 30 m)	½ Hz
Net radiation	Net radiometer (REBS Q*7.1)	tower (64 m)	½ Hz
PAR	quantum sensors (LI-190S)	tower (2 levels: 64 m up and down, + 15m up)	½ Hz
Precipitation	tipping bucket rain gauge	Tower	5-min cum
Ground surface PAR	quantum sensors (LI-190S)	forest floor: 8 sensors, distributed near tower	5-min avg
Sonic data, Intercomparison between levels	Sonic anemometer (Gill Solent HS)	Tower: alternately at level 1 (58m) and level 2 (47m)	
Soil temperature	Thermistors	forest floor: soil profiles (4 depths x 4 locations)	5-min avg
Soil moisture	TDR probes	forest floor: integrated 0.5m at 8 locations	5-min avg
Soil heat-flux	Heat-flux plates	forest floor: 8 locations near tower	5-min avg
B. Ecological Measurements			
		<u>Live Biomass</u>	
Above Ground Biomass, and long-term growth increment	Tree DBH survey	4 ha (> 10cm DBH), 20 ha (> 35cm DBH) 75 ha (> 60cm DBH)	every 2 years
High-resolution growth increment	Tree DBH via Dendrometers	Subsample (1000 stems on 4 ha & 20 ha plots)	every month
Mortality	DBH survey	4 ha (> 10cm DBH), 20 ha (> 35cm DBH) 75 ha (> 60cm DBH)	after 2 years
High-resolution mortality	survey of trees with dendrometers	Subsample (1000 stems on 4 ha & 20 ha plots)	every month
Recruitment	DBH survey	4 ha plot (grow-in to 10cm DBH size-class)	every 2 years
		<u>Necromass</u>	
Standing Coarse Woody Debris	stem survey	20 ha, all stems >10 cm DBH	every 2 years
Fallen Coarse Woody Debris	Plot survey	32 1200-m^2 plots, pieces >30 cm 32 50-m^2 plots, pieces >10 cm 64 1-m^2 plots, pieces >2 cm	every 2 years
Fallen Coarse Woody Debris	Line Intercept	40 10-m lines, pieces > 2 cm	every 2 years
Forest floor mass	Collection areas		

Litterfall	Collection Traps	40 x 0.43 m^2 area	every 2 weeks
Litter chemistry (C,N) and isotopic composition (^{13}C, ^{15}N)	Collection Traps	Subset of above	4x per year
Forest dynamics			
Leaf area index and canopy architecture	Multi-band vegetation imager	At locations of litter baskets + selected random gap and non-gap locations	6x per year
Tree-fall gap distribution	Survey	In 20-ha plots	Every 2 years
Reconstruction of long-term historical tree-growth rates	Isotopic composition (^{18}O, ^{13}C) of tree-wood cellulose	Tree cores from select trees	
Natal/Maxaranguape Coastal Site			
High-accuracy CO2/H2O concentration	IRGA-based integrated instrument	coastal observation station (10 m)	Continuous (½ Hz)
CO concentration		coastal observation station (10 m)	
High-accuracy CO$_2$ + isotopes (^{13}C, ^{18}O)*		coastal observation station (10 m)	Flask sample
O3 + other trace gases†		Coastal observation station	

[*] measurement by collaborators Tans, Bakwin et al., funded separately from this proposal

[†] measurement by collaborator Kirchhoff, funded separately from this proposal

Table 2. Standing stocks and fluxes to CWD (positive values are flow into the CWD pool). Mass estimates based on measured CWD volumes and a range of literature values for density across decay classes. Net flux range based on measured mortality inputs (scaled to mass by a range of allometries), and decomposition estimated by combining literature values for density and decomposition rates.

Stock			**Measured Volume (m^3 ha^{-1})**		**Estimated Mass (Mg C ha^{-1})**		
			fallen + standing =	total	Density 1 (a)	Density 2 (b)	Density 3 (c)
	Size class	>30cm (n=466)	97.9 + 33.9 =	131.7	22.8	29.1	30.3
		10 - 30cm (n=534)	36.8 + 2.8 =	47.6	6.6	8.3	9.1
		2 - 10cm (n=390)	19.3 + 0.0 =	19.3	3.2	4	4.4
	Total Stock		**154.0 + 36.6 =**	**190.6 (± 17.5)**	**32.6 (± 2.9)**	**41.4 (± 4.1)**	**43.8 (± 4.1)**
Flux	**Measured mortality (Mg C ha^{-1} yr^{-1})**			Decomposition rate, k	**Estimated decomposition (Mg C ha^{-1} yr^{-1})**		
	Allometry 1 (d)	Allometry 2 (e)	Allometry 3 (f)	0.15 yr^{-1} (c)	-4.9 (± 0.6)	-6.2 (± 0.7)	-6.6 (± 0.7)
	3.1 (± 0.6)	3.8 (± 1.2)	4.4 (± 1.7)	0.17 yr^{-1} (g)	-5.5 (± 0.7)	-7.0 (± 0.8)	-7.5 (± 0.8)
	Range of net flux to CWD (mortality inputs minus decomposition losses)			**-2.4 to -5.1**			

(a) Clark *et al*. (2002); (b) Delaney *et al*., (1998); (c) Summers (1998); (d) Chambers *et al*. (2000); (e) Brown (1997), equation 3.2.3; (f) Brown (1997), equation 3.2.4. (g) Chambers (2000).

2. Training and Education Plan

2.1. Summary of T&E Activities to Date

Undergraduate students

We have focused much training and education efforts current undergraduates and recent college graduates in the Santarém region. The student efforts have been concentrated on quantifying the above ground forest carbon pools and fluxes through biometric measurement at the km 67 research site.

Jorge José Pinheiro Macêdo and Ocidne Franck A. Magalhães, Santarém undergraduate students, assisted with the initial vegetation survey and layout of experimental plots in the footprint of the km 67 eddy flux tower in July 1999. These students were trained by Brazilian forester Edna Gomes Tenório Guimarães and Harvard researcher Elizabeth Hammond Pyle, who led the survey effort. Both students were trained in basic forest mensuration methods to assist with the laying out of the ecological transects and the initial measurement of the sample trees.

Kleber Portilho and Elder Campos have both been working with our group since July 2000. They were both awarded CNPQ Bolsa fellowships in January of 2000, under the sponsorship of Brazilian Co-Investigator Dr. Plinio Camargo. Both students graduated in June 2000 from the Universidade Federal do Pará in Santarém, with undergraduate degrees in biology. Their work with our group has been focused on quantifying the carbon stocks and fluxes of the above ground woody components of the forest and forest litter dynamics. Specifically, Elder has focused on understanding the annual and inter-annual cycles of forest litter production at the km 67 site. His work has centered on collecting and preparing samples for chemical analysis to include C, N and δ^{13}C. In addition, he has conducted an extensive analysis of seasonal and inter-annual litter input patterns at the site. Kleber Portilho has focused his research on tree dendrometer data examining the seasonal cycles in the above ground woody increment. Kleber has coordinated the monthly dendrometry measurements at the site. Both Elder and Kleber have been trained in forest mensuration techniques as well as data analysis and presentation methods using Excel and Powerpoint. In September 2001 Elder Campos transferred his Bolsa fellowship to work with CD-08 group to focus on soil carbon dynamics.

Dulcyana Ferreira joined our group in July of 2001. She is currently a second year undergraduate student at the Faculdades Integradas do Tapajós in Santarém, Para majoring in biology. Dulcyana is planning on working with our group on her undergraduate thesis. In addition to Dulcyana's undergraduate curriculum, she has also been taking supplemental English courses to allow her access to a wider body of scientific literature and ease her communications with American scientists. Dulcyana's research efforts have been focused on determining the forest litter turnover dynamics. She has taken a major role in the sampling, processing and analysis of the forest floor samples to calculate leaf litter turnover rates for the km 67 primary forest site.

Graduate students:

Simone Aparecida Vieira is a doctoral student at Universidade de Sao Paulo, CENA working with Brazilian Co-Investigator Dr. Plinio Camargo. Her research is focused on examining the long-term tree growth patterns at several different sites within the Amazon basin using carbon dating techniques. At the km 67 site she will attempt to correlate the long-term tree growth rates using ^{14}C and ^{13}C measurements with short-term tree growth rate measurements based on dendrometer bands.

Other training and education participants

Fernando Alves Leão was hired by the LBA office in Santarém to work primarily on data transfer and tower maintenance activities with our team at the km67 tower and with the CD-04 (Goulden and Rocha) team at the km83 tower. Our group provided much of his training, in technical aspects of both biometry and tower-based micrometeorological measurements from November 1999 through July 2001. As a result, Fernando became a highly competent and valued contributor to our research efforts, and was able to perform extensive troubleshooting and maintenance of the tower equipment. During the course of his tenure, Fernando was also trained in the Splus computer programming language for data analysis. On the strength of Fernando's performance in Santarém, Principle Investigator Dr. Steven Wofsy was able to write a strong letters in support of Fernando's applications for advanced education in Europe.

Daniel Ferreira Amaral moved from Belém to Santarém to take over from Fernando, and has been working as a technician assisting our team with the data downloading, data process and equipment maintenance of the km 67 tower. Daniel is also working with our engineers to learn more about the flux system components and its integrated operation, and is both performing well and learning extensively.

2.2. Proposed T&E Activities for Phase II

During phase II, we propose to continue a similar level of involvement with current or recently graduated undergraduate students and technicians and to expand our education and training activities by close collaboration with Antonio Nobre and his group at INPA.

In Santarém, we plan to further our work with Dulcyana Ferreira through advising on her thesis research. In the course of training and thesis preparation, we are planning to have her visit Harvard for a 6-8 week period during the summer of 2003. This visit to Harvard will allow her to work more closely with Harvard graduate students and researchers and expose her to new analytical techniques. During her time at Harvard, we also expect to have her visit some New England forests to increase her exposure to different forested ecosystems. We expect Dulcyana's thesis to be completed by June 2004.

The proposed collaborative study between the Harvard (S. Wofsy et al.) and INPA (A. Nobre et al.) groups focus on in-depth analysis and comparisons of flux measurements in Reserva Cuieiras (Manaus) and FLONA Tapajós (Santarém). We plan to provide an additional opportunity for advanced student training, and expect that some of the students from INPA will be residents of the Amazon region. The proposed budget for this collaborative project includes funding to bring students from INPA in Manaus to Harvard for intensive training and working meetings focused on understanding and analyzing eddy covariance data, and using these two sites as a case study. We envision that students from INPA will be long-term visitors as suitable for their needs and interests, participating in all aspects of our research group activities.

3. Data Plan

This project will generate three distinct data streams: a high-volume continuous stream of digital data from the flux tower, a continuous, low-volume digital data stream from the concentration measurement site at Natal, and an intermittent stream of analog data from ecological measurements and sample analyses. Each type presents issues that must be addressed to achieve the goal of making a reliable, quality checked data set available through the LBA-DIS in a timely manner.

The tower data set has the advantage of being recorded electronically in a compact form, but its large volume requires a comprehensive plan for routine data processing, data management, and continuous quality control. Our protocol for LBA flux-tower data (see Figure 1) follows those we have developed for long-term continuous measurements at Harvard Forest and the BOREAS NOBS site. The Plan includes the follow steps:

(1) Automated processing scripts and routines are run at the Santarém office to generate initial results and quality control parameters in useable text and graphical formats;
(2) Rapid transmission of the initial results is made via email to our laboratory for examination and quick identification of problems so they can be repaired quickly, minimizing lost data;
(3) Multiple copies are saved of an easily retrievable archive that contains all raw data, the initial results, and processing software needed to access the raw data, and these are transmitted via CD to CPTEC and Harvard University;
(4) Final data products are generated efficiently and rapidly with consistent quality control criteria.

The large volume (approximately 55 Mbyte per day) of raw data is distilled immediately to a small file containing essential results in a useable format including ASCII files and graphical images. This file is small enough to be sent as an email attachment without excessively taxing the network bandwidth available at the project office. Within hours of collection, data are available to Harvard researchers and Brazilian collaborators for examination and initial checks to identify potential problems. The full set of raw data, initial results, and processing codes are archived to compact discs, to become the primary data record. The original data set remains at the Project Office in Santarém, a copy goes to the LBA project office at CPTEC, and another copy is sent to Harvard where we begin the next level of data checking.

When the raw data are received and fully processed, the results are merged to longer time intervals, sensor recalibrations are applied, and the data are critically examined to identify and remove periods with sensor errors, local contamination, or other specific problems. Within a month of receiving raw-data archive disks at Harvard, the preliminary data sets become available on our local server (ftp.as.harvard.edu/pub/tapajos) that is harvested by the Beija-flor search engine. Data sets from other investigators working at the km 67 site should be acquired at this point for synthesis activities (section 1.4) and for intercomparisons to assess data quality. The final data set, which will be generated in annual increments, includes the merged data and derived data products with estimates of confidence intervals. The final data products will also be maintained on our local web server and delivered to the LBA final data archives.

The data from Natal will be treated similarly. On-site data processing will be used to generate initial results that are copied to our collaborators at INPE before data copies are sent to Harvard for further processing. Data and results will be archived to compact discs and in the interim, before sufficient data are accumulated to fill a disc, the data will be stored on computer disks that are protected by routine file backups. Preliminary data files will be posted monthly and final data sets generated annually.

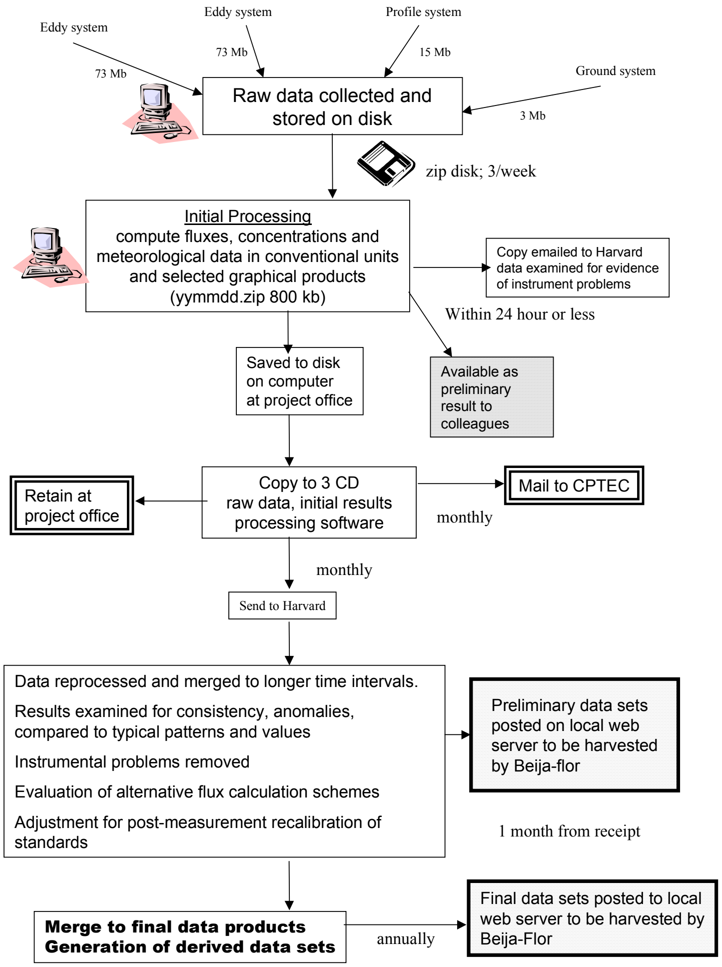


Figure 1 Flow diagram identifying the management of tower data. File sizes are based on data collected over a three day interval. Double boxes identify primary data that are left in Brazil. Shaded boxes indicate data available through Beija-flor.

Ecological field observations are initially generated as analog data (e.g. litter mass, stem diameters, gap position) and recorded manually on data sheets, which has proven to be the most reliable data recording method in the field. The data sheets are transcribed and entered into spreadsheet files that are transmitted to CENA in Piracacaiba and to Harvard. The original data sheets are photocopied to generate redundant backups and to distribute hard copies to CENA and Harvard. When received, new data are checked for measurement or transcription errors and merged with the cumulative records. The raw measurements are further processed to generate user-friendly format. Our goal will be to make preliminary versions of the results available on our local ftp server within a month of receiving all the associated raw data. Final, checked results will be made available annually.

Samples generated from the litter collections are shipped to CENA for chemical and isotopic analysis. Copies of analytical results are sent to Harvard to be merged with other data sets posted on the ftp server. Preliminary data will be made available within a month of collection/analysis. Final data are to be posted within a year. Meta-data files to define the collection protocols, computational algorithms, and any allometries being used will be included with the field data sets.

Data being collected as part of LBA-ECO phase I have already been made available, demonstrating our commitment to meet and exceed the LBA-DIS requirements. As of March 2002, the initial data sets of fluxes, CO$_2$ concentrations, and micrometeorological parameters up to December 2001 have been posted. The next level of data product requires extra time for data checking, as needed to identify site-specific quality issues during the first year of measurement and to develop the quality assurance criteria that will be routinely applied. As we gain experience with this site, we anticipate that the time required to process a data set will be shortened. Because the quality assurance issues are less complex the complete set of final CO concentrations at the km 67 site for 2001 has already been made available up to the current date. Litter collection data, tree diameters, and coarse woody debris data obtained during Phase I are also currently posted.

4. Management Plan

4.1. Oversight and personnel

The principal investigator, **S. C. Wofsy,** has the responsibility for oversight of all aspects of the proposed work: site operation and data collection, data processing, scientific analysis, and preparation of papers. He has extensive previous experience in similar projects, including two missions to Amazônia with chamber and eddy-correlation flux measurements. The co-investigators have broad experience and expertise to apply to the work. Two senior members of the team will exercise supervisory responsibility under overall direction of the PI, in addition to their roles in executing the proposed work

4.2. U. S. Investigators

S. R. Saleska is a post-doctoral research associate with training in ecology and physics. Dr. Saleska will take the lead role in managing the data processing and data quality checking and overall scientific interpretation of the results. Dr. Saleska will contribute to data synthesis activities and interactions with other investigators to address ecological questions.

J. W. Munger is a Senior Research Fellow with a background in atmospheric sciences and ecology. Dr. Munger will be responsible for CO measurements and take a major role in managing the concentration measurements at Natal. Dr. Munger will interact with other investigators making trace-gas and aerosol measurements in the Santarem area and contribute to synthesis activities intended to develop regional budgets for these species.

Additional post-doctoral and research staff personnel in Dr. Wofsy's lab will take particular responsibility for day-to-day operation of selected components of this project.

B. C. Daube is the engineer who was responsible for the design and construction of instruments deployed at Santarém and to be installed at Natal. He will continue work with this project to assist with equipment maintenance and troubleshooting.

E. Hammond Pyle is a research assistant with training in tropical botany and ecology. She has responsible for design and implementation of tree survey, and continues to assist in processing and analysis of the biometry data.

L. Hutyra is a research assistant with training in forestry. She has been responsible for establishing and implementing the ecological measurement protocols.

D. M. Bryant is a post-doctoral research associate with training in ecology.
During phase II, Dr. Bryant and Ms. Hutyra will share responsibility for coordination of the ecological measurements and checking the data. Both will contribute to acquiring and interpreting the biometric measurements and synthesis activities to develop carbon budgets for the km 67 site.

4.3. Brazilian Collaborators

Volker Kirchhoff, INPE. Dr. Kirchhoff is an atmospheric scientist who has maintained a trace-gas observation site near Natal for many years and has investigated tropical CO concentrations dating back to measurements he made during the Amazon Boundary Layer Experiment in 1987. He will be responsible for operating the measurement site at Natal. Site technicians under his supervision will perform routine service on the CO_2 and CO instruments and send collected data to INPE and Harvard. The Harvard team is providing assistance to Dr. Kirchhoff on operating precise, accurate trace-gas analytical instruments. Dr. Kirchoff will collaborate on interpretation of CO_2 and CO data at both the Natal and Santarém sites and contribute to understanding the larger-scale budgets for these gases.

Antonio Nobre, INPA. Dr. Nobre is trained in ecology and atmospheric science. He is responsible for the operation a flux tower near Manaus as part of the European Union Carbonsink-LBA component. The Harvard team will collaborate with Dr. Nobre and his team at INPA on intensive analysis and comparison of flux data from Manaus and Tapajós/km 67. These sites have different topographical and meteorological characteristics as well as different measurement instrumentation and data protocols. We seek to understand how each of these factors contributes to the inter-site differences. The Harvard-INPA collaboration is a follow-on to the first LBA eddy flux tower workshop held during December 2001. As part of this collaboration, the Harvard team will assist Dr. Nobre's group with designing and building a calibration system to upgrade the flux measurements at the Manaus tower.

Plinio B. de Camargo, CENA-USP. Dr. Camargo is an isotope geochemist who will be responsible for measurements of carbon and oxygen isotopes and chemical analyses of litter samples. He will be using the CO_2 and H_2O flux data to test hypotheses that seasonal and annual variations in ^{13}C and ^{18}O in vegetation record changes in carbon dynamics and ecosystem stress. Further, he will use ^{13}C and ^{14}C measurements in samples from trees equipped with dendrometers to compare long- and short-term tree growth patterns. Dr. Carmargo will oversee elemental and isotopic analysis of organic matter samples at CENA-USP's Laboratório de Ecologia Isotópica. This facility has advanced element analysis and mass spectrometry instrumentation (Finnigan IRMSs), technical capacity, and sample-processing capability.