Final Report for LBA-ECO Team CD-08 Phase I
NCC5-336
Carbon Dynamics in Vegetation and Soils

Susan Trumbore, Jeffrey Q. Chambers
Dept. of Earth System Science, University of California, Irvine, USA

Plinio Camargo, Luiz Martinelli
Lab. Ecologia Isotopica, Centro de Energia Nuclear na Agricultura (CENA), Piracicaba, Brazil

Joaquim Santos
Instituto de Pesquisa Amazonicas (INPA), Manaus, Brazil

PROJECT SUMMARY

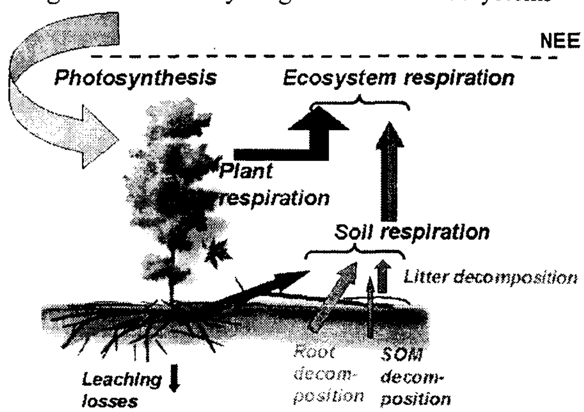
The overall goals of CD-08 team in Phase I were to quantify the contributions of different components of the carbon cycle to overall ecosystem carbon balance in Amazonian tropical forests and to undertake process studies at a number of sites along the eastern LBA transect to understand how and why these fluxes vary with site, season, and year. We divided this work into a number of specific tasks: (1) determining the average rate (and variability) of tree growth over the past 3 decades; (2) determining age demographics of tree populations, using radiocarbon to determine tree age; (3) assessing the rate of production and decomposition of dead wood debris; (4) determining turnover rates for organic matter in soils and the mean age of C respired from soil using radiocarbon measurements; and (5) comparing our results with models and constructing models to predict the potential of tropical forests to function as sources or sinks of C.

This report summarizes the considerable progress made towards our original goals, which have led to increased understanding of the potential for central Amazon forests to act as sources or sinks of carbon with altered productivity. The overall picture of tropical forest C dynamics emerging from our Phase I studies suggests that the fraction of gross primary production allocated to growth in these forests is only 25-30%, as opposed to the 50% assumed by many ecosystem models. Consequent slow tree growth rates mean greater mean tree age for a given diameter, as reflected in our measurements and models of tree age. Radiocarbon measurements in leaf and root litter suggest that carbon stays in living tree biomass for several years up to a decade before being added to soils, where decomposition is rapid. The time lags predicted from ^{14}C, when coupled with climate variation on similar time scales, can lead to significant interannual variation in net ecosystem C exchange.

B. Background and Objectives

A major goal of the LBA experiment is to determine the status of the Amazon region as a source or sink of carbon. Carbon storage capacity in Amazonian Forests, and the capacity for interannual variation in net ecosystem exchange (NEE), is determined by the amount and the residence time of C in ecosystem components. Carbon enters terrestrial ecosystems through a single process, photosynthesis, but can be returned through a variety of processes, collectively referred to as respiration (Figure 1). Net ecosystem exchange can be directly measured by eddy covariance. However, these measurements do not provide direct information about the processes contributing to the net flux, or why the site may be accumulating or losing carbon (Keller et al., 1996)

Figure 7. Carbon cycling in terrestrial ecosystems

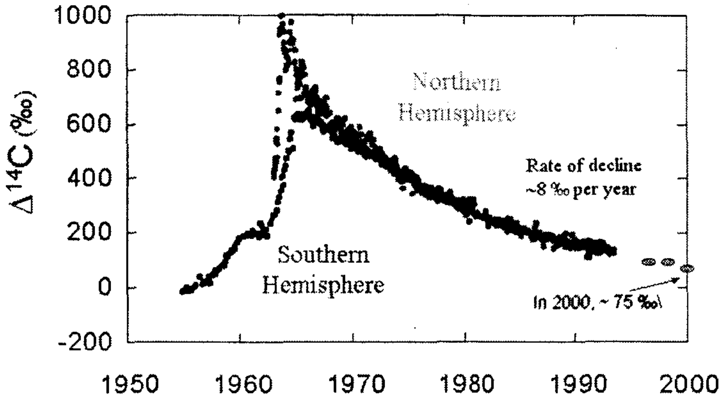


The time carbon spends in the ecosystem influences its storage capacity, since it determines how long C stocks can build up before increased decomposition and respiration offset increased productivity. The time elapsed between C uptake by photosynthesis and loss by respiration varies according to how plant C is allocated (to growth or to autotrophic respiration) and the fate of dead plant tissues during decomposition. The residence time of C in tropical forests has been a major unknown limiting our ability to predict how these forests can process and store C. Recently, innovative methods have been developed that use radiocarbon as a direct estimate of the time elapsed since C was removed from the atmosphere by photosynthesis (Trumbore, 2000; Gaudinski et al., 2000; Wang et al., 2000). Our measurements of wood dynamics in permanent plots can be used to estimate the residence time of C in the wood debris pool (Chambers et al., 2001a). The radiocarbon content of leaf and root litter, and soil organic matter may be used to determine the residence time of C in these ecosystem components (Telles, et al., in preparation; Costa et al., in preparation). Finally, the ^{14}C content in CO_2 respired from the soil surface and in incubations may be used to estimate the mean age of C respired from the ecosystem.

Summary of Radiocarbon Tracer

Radiocarbon (^{14}C) is a useful tool for studying the dynamics of C exchange between ecosystems and the atmosphere on several timescales (Trumbore, 2000 and references therein). Radiocarbon is naturally produced by the interaction of high-energy cosmic particles with the upper atmosphere. The ^{14}C formed quickly oxidizes to CO_2 and enters the earth's carbon cycle. The residence time of C in reservoirs that exchange with the atmosphere on century to millennial timescales is determined from the degree to which its ^{14}C has been decreased below atmospheric $^{14}CO_2$ values by radioactive decay (half-life = 5730 years).

Figure 8. Record of radiocarbon in the atmosphere



Radiocarbon can also be used to estimate C exchange rates on decadal timescales. Atmospheric thermonuclear weapons testing in the 1950's to 1960's roughly doubled the amount of ^{14}C in atmospheric CO_2 in the northern hemisphere prior to the implementation of the Limited Test Ban Treaty in 1963. The rate of incorporation of this 'bomb' ^{14}C provides a measure of the rate of carbon exchange between atmosphere, ocean, and terrestrial carbon reservoirs on timescales of years to centuries. Models using radiocarbon to determine the turnover time of soil organic matter fractions are summarized in Gaudinski et al (2000) and Trumbore (2000).

Summary of Phase I Activities

To date, we have focused on measurements of C stocks and fluxes at primary forest sites, with emphasis on identifying the major processes controlling C fluxes and dynamics. Measurements include:

(1) determining the stocks of C (and N) above- and below ground;
(2) age structure of forest trees and litter components (leaves, branches, roots);
(3) the influence of climate (seasonal and interannual) and topography on the growth rate of trees;
(4) the influence of soil texture on storage and dynamics of soil organic matter;
(5) quantifying fluxes and sources of soil respiration;
(6) construction of process models to extrapolate in space and time.

Summary of Important Scientific Results

The overall picture of tropical forest C dynamics emerging from our Phase I studies suggests that the fraction of gross primary production allocated to growth in these forests is only 25-30%, as opposed to the 50% assumed by many ecosystem models. Consequent slow tree growth rates mean greater mean tree age for a given diameter, as reflected in our measurements and models of tree age. Radiocarbon measurements in leaf and root litter suggest that carbon stays in living tree biomass for several years up to a decade before being added to soils, where decomposition is rapid. The time lags predicted from ^{14}C, when coupled with climate variation on similar time scales, can lead to significant interannual variation in net ecosystem C exchange.

1. Predicting the capacity of a central Amazon forest to store carbon. (Chambers et al., 1998; 2000; 2001a,b,c).

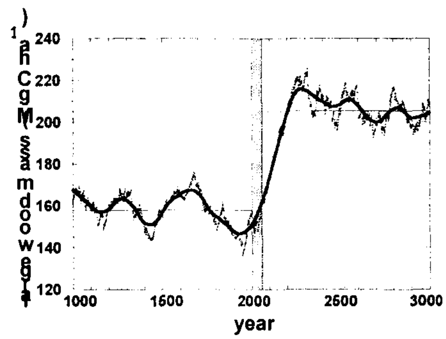


Figure 1. Carbon storage in large wood mass predicted by the stochastic-empirical model developed by Chambers et al (2001a). Changes with simulated ecosystem disturbance (variations about the mean in the first 1000 years), and response to a 25% increase in NPP (ramped up during the period shown by the gray vertical bar) are shown. Rates of C storage are of order 0.5 to 1.0 Mg C ha^{-1} yr^{-1} for disturbance.

1.a. Wood dynamics. Chambers et al (1998) constructed a stand dynamics model that integrated 25 years of information on stand dynamics (recruitment, age, and mortality) from permanent forest inventory plots, tree radiocarbon ages, and coarse litter production and decomposition (Chambers et al., 2000). The model simulates the carbon balance of large wood from the dynamics of individual trees. Chambers (2001a) used this model to explore how large wood carbon balance would respond to a 25% increase in net primary production (NPP). Because the model predicts a mean tree age at death of about 175 years, there was a lag-time of more than a century before large wood standing stock established a new dynamic equilibrium. The predicted annual sequestration rate of about 0.5 Mg C ha^{-1} yr^{-1}, however, was an order of magnitude less than indicated by a Central Amazon eddy covariance study (Malhi et al. 1998). It is notable that the mean residence time of C in a tree in Chambers' model (~80 years; a 175-year-old-tree is made up of tissues <175 years old) is substantially greater than that used in the CASA model (~40 years). This suggests that (as for soils) lack of inclusion of functional pools with different dynamics oversimplifies the C cycle in non-steady state systems.

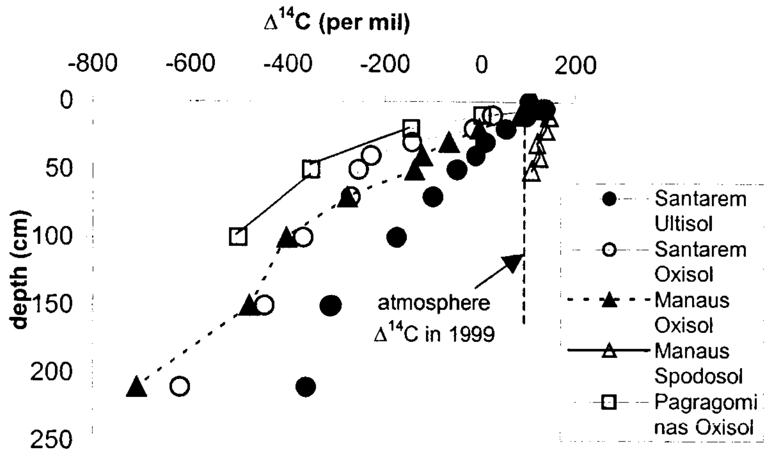


Figure 2. Radiocarbon (expressed as the deviation in per mil between the $^{14}C/^{12}C$ ratio of the sample and a standard). Positive values indicate the C was fixed from the atmosphere since atomic weapons testing in the 1960s; large negative values indicate that on average C has resided in the soil for centuries (up to –100 per mil) to thousands of years. Except for the Spodosol (an intermittently flooded, sandy, soil sampled in topographic lowland), clay rich Oxisols are contain mostly old carbon at depth.

1b. Soil C dynamics. Although soil carbon reservoirs are large in deep tropical soils, radiocarbon measurements indicate that the majority of C below ~20 cm depth is refractory (Figure 2, from Telles et al., in preparation). Simple models using radiocarbon and ^{13}C to determine the residence time of C in roots and labile and refractory soil organic C pools indicate that soil C storage rates of 0.5 to .6 Mg C ha^{-1} yr^{-1} are possible in the first years following a 25% increase in productivity. Rates of C storage decline rapidly, however, as rapidly cycling components reach steady state within about two decades (compared to a century for wood). Comparison of carbon contents of Oxisols sampled near Manaus, Brazil, over the past 20 years shows no measurable change in organic carbon stocks with time, supporting the idea that soils are not currently sequestering a large fraction of ecosystem NPP (Telles et al, in preparation).

2. ***Slow growth and great ages for some forest trees (Vieira and Camargo)***

Building on pre-LBA results by Chambers et al. (1998), we have measured radiocarbon age using both direct ^{14}C dating of tree centers and extrapolation from the last 50-years' growth rate. These results (mostly from Manaus and Acre sites) confirm that some small-diameter trees can have ages of several hundred years. Long-term permanent plot studies show some trees with no measurable increase in diameter in 20 years; the ^{14}C method may be the best way of determining growth rates in these trees.

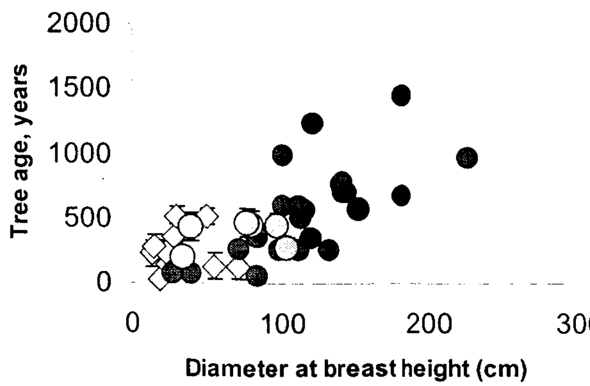


Figure 3. Summary of tree ages estimated from radiocarbon for sites near Manaus (dark circles; Chambers et al, 1998), triangles; new data based on growth rate extrapolations; and Rio Branco (light circles).

3. ***Structure and growth rate differences among three primary forests***

Biomass. We initiated permanent plot studies at the FLONA km 67 site (in collaboration with CD-10), the Reserva Duke near Manaus (with Higuchi at INPA), and the Catuaba Reserve located near Rio Branco, Acre. Stand dynamics (i.e. recruitment, mortality, damage, and growth) are being monitored annually to determine large-scale carbon balance at these sites. A subset of the trees in each stand are being monitored for monthly growth increment using dendrometer bands; a randomly selected subset of these have been sampled for radiocarbon analyses of decadal growth rates.

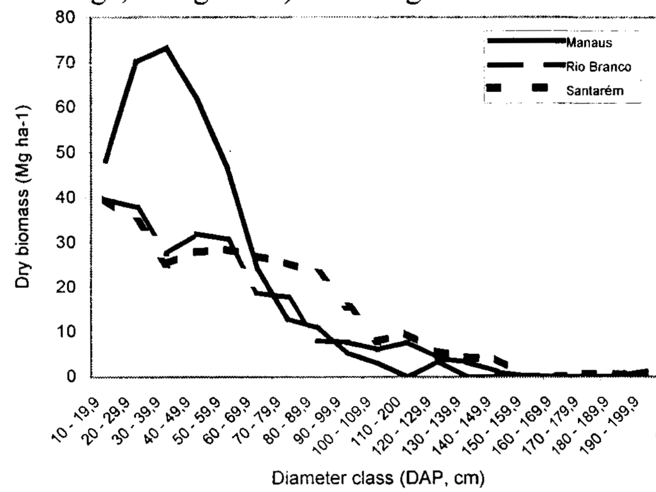
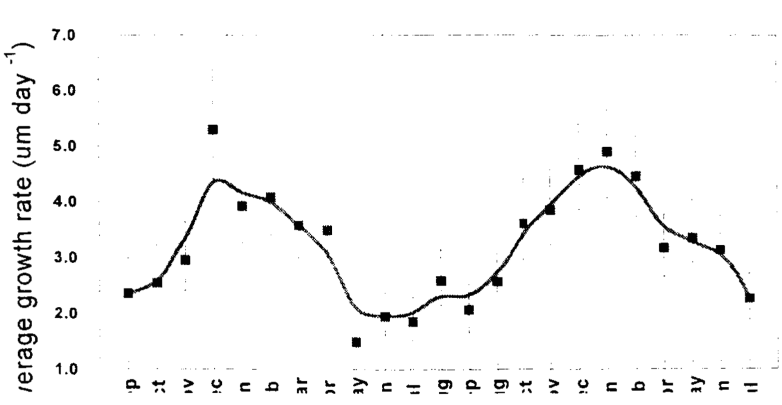


Figure 4. Differences in biomass by diameter class.

Estimates of biomass derived using a single allometry equation (Chambers et al., 2000) for the three different sites show dramatic differences between the Central Amazon forest in Manaus, and those in Acrė and in the FLONA (Figure 4). Although total biomass is similar, more of the biomass is in large trees (>60 cm diameter) in the FLONA and Rio Branco sites, while the Manaus site has a greater proportion of its biomass in smaller-diameter (20 cm – 50 cm DBH) trees.

Growth Rates. Preliminary results comparing one year of growth from dendrometer bands in Santarem, Manaus, and Acre permanent plots show much slower growth in trees in Acre. Growth rates do not appear to vary systematically with tree diameter, except for trees <50 cm. We are still analyzing data from Santarem and Acre for seasonal trends.

Our longest-running dendrometer project (Manaus, ZF2), using approximately 300 trees randomly selected from three size classes equally distributed among plateau, slope, and valley forest, was developed as an INPA Forest Science Masters degree project by R. da Silva with Higuchi as advisor and Chambers as co-advisor. Initial results demonstrated significant seasonal variability in diameter increment (Fig. 5), but no variation with topography (Silva et al. in press). Although there is an obvious relation with season, the relationships between growth rate and



precipitation variables are complex.

Figure 5. Average monthly growth rate and 95% CIs for ~300 trees from DS2. Growth rates increased during the dry to wet season transition months (Sep-Dec), declined throughout the wet season (Jan-May) and were low during the dry season (Jun-August).

4. ***A respiration budget for primary tropical forest (Chambers et al., submitted)***

Chambers et al (submitted) extrapolated measurements of soil, leaf, tree bole, and dead tree bole (Chambers et al., 2000;2001a) respiration to estimate the total ecosystem respiration for the ZF2 forest. Soil respiration varied with season and topographic position, with lowest rates in lowland, intermittently inundated soils (*baixios*). Variance in bole respiration was best explained by tree basal diameter and growth rate (from dendrometer measurements). Chambers et al. estimated from their budget that approximately 72% of gross primary production is autotrophically respired. Comparision of "bottom-up" estimates of ecosystem respiration with the tower-based eddy covariance fluxes at night show agreement only on windy nights. While uncertainties in extrapolating leaf-and bole-respiration fluxes to the canopy are large, the study by Chambers et al., (submitted) suggests that respiration and growth largely balance photosynthesis in this central Amazon forest.

5. ***There is a significant lag time of several years between photosynthesis and heterotrophic respiration, with much of the lag taking place in living plant tissues (Costa et al., in preparation.)***

The radiocarbon signature of fresh photosynthetic products should equal that of atmospheric CO_2. The ^{14}C content of atmospheric CO_2 is declining at a rate of 4 to 8 per mil per year, just greater than our measurement accuracy (see section B.1, below). CO_2 measured in soil respiration and evolved during incubation of soils has $\Delta^{14}C$ values that are 10 to 30 per mil higher than the current years' atmospheric CO_2 (Figure 6), indication that the carbon being respired is on average 2- 4 years old. Radicoarbon measurements of CO_2 being respired from soil show large spatial variability, which we hypothesize is linked to leaf litter moisture.

Decomposition in tropical forests occurs rapidly, with leaves decomposing in <1 year and 50% of fine roots in ~1.5 years. The radiocarbon content of root (see below) and leaf litter suggests that the C resides in the living plant tissues for several years (up to decades) before it becomes available for microbial decay (Costa et al., in preparation). Hence a substantial time lag between C uptake by the forest through photosynthesis

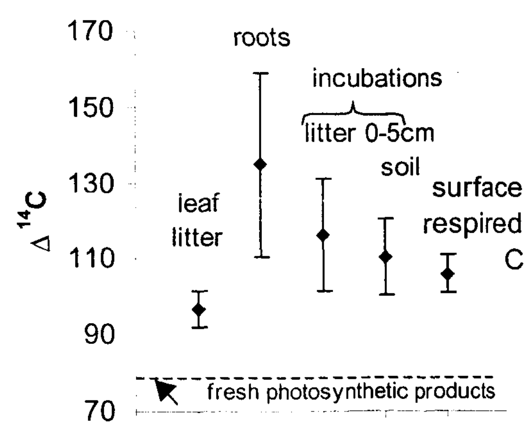


Figure 6. $\Delta^{14}C$ of carbon in fine (<1mm) roots picked from soils in FLONA sites. Although there is large heterogeneity, both live and dead roots have ^{14}C values consistent with C fixed from the

and release by decomposition exists in tropical forests that may influence predictions of C storage and release in response to regional variations in climate.

Reasons for the high ^{14}C values of leaves and roots (i.e. true longevity of these components versus the use of reallocated C to produce them) make up part of the PhD thesis of Enir Salazar da Costa and will be emphasized in Phase II measurements.

6. ***Soil texture plays a major role Carbon cycling in wetter soils differs significantly from upland soils***

Clay soils store more carbon than sandy soils along topographic gradients in Santarem and Manaus site (Telles et al., in preparation). However, the extra carbon stored in clay soils is very low in ^{14}C (negative $\Delta^{14}C$ values; see Figure 2). Highest $\Delta^{14}C$ values (positive values in Figure 2, meaning the majority of the C was fixed from the atmosphere in the past 50 years) are within 20 cm of the surface in these soils. While ^{14}C values decline rapidly with depth (with greatest decrease in soils with the most clay), the soil with high sand and very low clay content (Manaus Spodosol) maintains high ^{14}C values (the profile stops at the water table), indicating storage of young carbon in this intermittently inundated soil. We intend to increase observations of dissolved organic carbon origins and investigate C cycling in these riparian soils more intensively in Phase II.

Publications during Phase I

Chambers, J.Q., N. Higuchi, J.P. Schimel, L.V. Ferreira, J. Melack. 2000. Decomposition and carbon cycling of dead trees in tropical evergreen forests of the Central Amazon. *Oecologia* 12:380-388.

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Data Sets Available. Data collected by CD-08 are archived in Brazil and available through the Beija-Flor search engine.

Table 4. Summary of data sets available from CD-08. The final column contains data we need that are being collected by other LBA teams.

MEASUREMENT	LOCATIONS	DATA COLLECTED/PRODUCED	DATA/EQUIPMENT NEEDS
I. Biomass Dynamics			
Permanent plot information	Cautaba Reserve* FLONA* Manaus*	Maps showing locations of plots and individuals; DBH measurements and identification of individuals	
Monthly tree growth rates/wood production	Cautaba Reserve* FLONA* Manaus-Jacaranda*	Monthly diameter increments for trees*, base diameter*, species	precipitation (Higuchi), Monthly PAR (Higuchi), wood density
Annual tree recruitment, growth and mortality; forest structure	Cautaba Reserve* FLONA* Manaus-Ducke	Inventory of base diameters and species*, re-inventory in 2003 and 2006, biomass distribution in base diameter classes, stem density	Botanical Ids (Hopkins at Manaus-Ducke)
Coarse surface litter decomposition*	BDFFP and BIONTE control plots, Manaus	Annual mass loss rate, wood density, tree base diameter, time decomposing	
Large-scale tree mortality/gap formation rates	Manaus-Ducke/EEST	monthly rates from extensive trail network at Ducke, annual rates from remote sensing, minimum size quantifiable from remote sensing and ground truthing	IKONOS and Quickbird (Nelson)
Radiocarbon in cellulose from trees (data product: extrapolated ages)	Catuaba Reserve Manaus* Santarem	Radiocarbon data from cores taken from randomly collected trees in permanent plot sites	Historical climate data for permanent plot sites
II. Heterotrophic Respiration			
Fine surface litter respiration	Jacaranda	Respiratory flux, moisture content, topography, daily changes in moisture (TDR)	Continuous moisture and temperature data in soils
Coarse surface litter respiration	BDFFP and BIONTE control plots*, Jacaranda	Respiratory flux*, moisture content*, wood density*, topography, daily changes in moisture (TDR), TDR/gravimetric calibration	
Bole respiration	Jacaranda plots	Respiratory flux	

Isotopes in soil respired carbon	Paragominas* Santarem* Manaus* Brasilia	Carbon-13 and carbon-14 content of carbon dioxide from purified from soil respiration and soil CO2.	Soil respiration and soil CO_2 concentration data for these sites (Aduan, Davidson)
III. Soil carbon inventory and isotopes			
Carbon and Nitrogen inventory	Paragominas* Santarem Manaus	Bulk density, carbon, nitrogen content, fine roots picked from soil, soil desription, other soil physical properties	
Isotopes in soil organic matter	Paragominas* Santarem Manaus	Carbon (^{13}C and ^{14}C) and nitrogen (^{15}N) isotopes in bulk organic matter	
Isotopes in root tissues	Paragomians* Santarem*	Carbon (^{13}C and ^{14}C) in live and dead root tissue; root screens to measure isotopes in freshly grown roots	Root inventory (Silver, Nepstad)
Isotopes in leaf and litter tissues	Manaus Santarem Acre	Carbon (^{13}C and ^{14}C) compare to leaf specific area and leaf N content	Help with litterfall collection

Notes: * Data already available on LBA-DIS; (name) indicates agreed collaboration for data and or analysis, (name) indicates potential collaboration.

Training and Education. This project has been directly involved in training of 1 US post-doctoral researcher, 3 Brazilian Ph.D. students, 5 MS Brazilian students, 3 undergraduates and one technician.

III. TRAINING AND EDUCATION

People directly involved in research associated with this project are listed in the Table below, with a brief description of their activity. We have had considerable leverage of funds from CNPq and FAPESP – often the role of the NASA funds has been to pay a student until they receive a fellowship.

Name	Level	Funding Source	Description of activity/progress to date
Jeffrey Q. Chambers (USA)	Postdoctoral researcher (UCI/ INPA)	NASA	Co-investigator (promoted to Researcher as of 2/2002) Manaus/INPA measurements, training of students at Manaus
Enir Salazar da Costa (Brazil)	Ph.D student, UC Irvine	NASA	Enir's thesis work includes the C dynamics of leaves and roots in primary tropical forest and the role of these as sources of soil respiration; in addition she is working explore how land management changes cycling of C and N near Santarem
Everaldo de Carvalho Conceição Telles (Brazil)	PhD student, CENA	FAPESP	Finishing PhD in April 2002. Carbon and nitrogen stocks and isotopic signature in soils from Santarem and Manaus with a focus on spatial variability, topography, and C dynamics in soils of different texture.

Simone Aparecida Vieira (Brazil)	PhD student, CENA	FAPESP	Comparison of tree growth rates and forest age structure in Acre, Manaus, and Santarem using permanent plot, dendrometer, and radiocarbon analyses (thesis research in progress)
Roseana Pereira da Silva	MS degree, INPA, 2001 (Chambers, co-advisor)	CNPq	Thesis title: Padrões de crescimento de árvores que ocorrem em diferentes toposseqüências na região de Manaus. Thesis project: Roseana studied monthly changes in tree growth rates using dendrometer bands for trees in three size classes equally distributed among plateau, slope, and valley forests.
Rosana de Miranda Rocha	MS degree INPA, 2001 (Chambers, co-advisor)	CNPq	Thesis title: Taxas de recrutamento e mortalidade da floresta de terra-firme da bacia do Rio Cuieiras na região de Manaus. Rosana calculated recruitment, growth and mortality rates for two 20 x 2,500 m permanent inventory plots (5 ha each) from 1996 to 2000. She found that the trees were a net carbon sink of about 0.34 Mg C ha^{-1} yr^{-1} over the four year period
Bianca Felix	Technician, Manaus	CNPq LBA Bolsa	Chemical analyses of soil and vegetation samples at INPA
Patrícia da Silva Gomes	Undergraduate degree, 2001, INPA (PIBIC)		Densidade de madeira e taxas de crescimento nas parcelas permanentes da reserva florestal ZF-2. Patrícia studied the relationship between wood density and tree growth rates for 60 species on permanent inventory plots at the Biological Dynamics of Forests Fragments Project of the Smithsonian Institution. She found a negative relationship between average wood density and growth rates for these species.
Elder Campos	Undergraduate, Santarem	CNPq LBA Bolsa	Growth band measurements, links to seasonal climate
Kleber Portilho	Undergraduate, Santarem (Chambers, advisor)	CNPq LBA Bolsa	Litter composition and C/N content at km69
Erika Viera de Miranda	MSc student (in progress), INPA (Chambers, co-advisor)	NASA + CNPq	Erika is studying daily changes in stem diameter using high precision linear gauge sensors. She is relating these changes to daily variability in photosynthetically active radiation, volumetric stem water content, and leaf water potential.

Ligia Cristina Toledo	MSc student (in progress), INPA (Chambers, advisor)	NASA + CNPq	Ligia is studying how respiration from coarse and fine litter responds to seasonal changes in precipitation. Her project includes quantifying daily changes in litter moisture content
Liliane Martins Teixiera	MSc student (in progress), INPA (Chambers, advisor)	NASA + CNPq	Liliane is studying how woody tissue respiration has responded to varying logging intensity at the biomass and nutrient experiment (BIONTE) permanent plots. She will also be quantifying how carbon balance differs for low, medium, and high intensity logging treatments.

Other Training and Education activities include participation in short courses (Chambers helped teach the LBA Field course in Manaus, and teaches at INPA; Trumbore and Camargo held a 2-day short course in Isotopes in Ecology course in at the Univ. Federal do Acre, Rio Branco; Trumbore and Pérez taught a similar course at IVIC, Caracas, Venezuela), seminars (by Trumbore at UFAC, Rio Branco; UnB, Brasilia, IVIC (Venezuela); Camargo at INPA , Manaus, UFAC, Rio Branco; UFPa; Santarem) Telles (INPA, Manaus and UFPa, Santarem) and Vieira (UFAc, Rio Branco, INPA, Manaus). Chambers, Telles and Vieira presented posters at the IGBP meeting in Amsterdam in 2001.

Research Significance

This research specifically addresses LBA science questions CD–Q1 (causes on interannual variation in C storage), CD–Q2 (mortality and recruitment, succession), and CD-Q3a (changes in C cycling in pasture/cropland). The information we gathered on processes and timescales of C exchange and storage in Amazon ecosystems is essential for interpreting eddy covariance data, and for extrapolating information from the stand level across broader regions.

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LUIZ ANTONIO MARTINELLI
Birth: 01/23/1959
Associate Professor – University of São Paulo
CENA-USP
Av.Centenário 303,
13416-000, Piracicaba, SP
Brazil
Tel. 55-19-3429.4674
Fax. 55-19-3434-9210
e.mail: zebu@cena.usp.br

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CURRICULUM VITAE

PLÍNIO BARBOSA DE CAMARGO
Brazilian
18 de julho de 1960
Adrress: Av. Centenário 303,
13416-000, Piracicaba, SP, Brazil
fone: 55 19 34294788
fax 55 19 34294610
email pcamargo@cena.usp.br

1. Education

Escola Superior de Agricultura "Luiz de Queiroz" - ESALQ/USP-Piracicaba, SP 1981 – 1984, Agonomyst

Centro de Energia Nuclear na Agricultura – CENA/ESALQ/USP-Piracicaba, SP 1985 – 1990, Master, Dissertation: Nitrogen dynamics of the fertilizers uréia (^{15}N) and aquamônia (^{15}N) in the soils with sugar cane.

Centro de Energia Nuclear na Agricultura – CENA/USP-Piracicaba, SP
1992 – 1997, Doctor, Thesis: Soil carbon organic matter dynamics in the soils of Amazonia because land use change.

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Dr. Plínio Barbosa de Camargo
Piracicaba, March 03, 2002