The Flux of Carbon from Selective Logging, Fire, and Regrowth in Amazonia

Grant # NAG5-9880

Final Report

September 1, 2001 through August 31, 2004

to

National Aeronautics and Space Administration

from

R.A. Houghton
The Woods Hole Research Center
P.O. Box 296
Woods Hole, MA 02543

The Flux of Carbon from Selective Logging, Fire, and Regrowth in Amazonia

The major goal of this work was to develop a spatial, process-based model (CARLUC) that would calculate sources and sinks of carbon from changes in land use, including logging and fire. The work also included Landsat data, together with fieldwork, to investigate fire and logging in three different forest types within Brazilian Amazonia. Results from these three activities (modeling, fieldwork, and remote sensing) are described, individually, below. The work and some of the personnel overlapped with research carried out by Dr. Daniel Nepstad's LBA team, and thus some of the findings are also reported in his summaries.

Modeling

The primary goal of this research was to develop a model that would calculate terrestrial sources and sinks of carbon from selective logging and fire, in particular, and land-use change, in general. A model used previously for estimating fluxes of carbon from land-use change was a bookkeeping model with processes implicitly, rather than explicitly, included. Furthermore, the old model had several limitations. The model developed in this work (CARLUC, for Carbon and Land-Use Change) enhances the bookkeeping model in two respects. First, it is spatially explicit, with the landscape divided into pixels of a specified size. In the Basin-wide analysis described by Hirsch et al. (2004), pixel size was 64 km^2, consistent with the resolution of the model's soil and climate inputs. We can also run the model with much higher resolution (1 hectare) for detailed small-scale studies. In contrast, the bookkeeping model was not spatial. Rather, it dealt with a few types of ecosystems within national or continental units. Second, in CARLUC, the processes of forest productivity and decomposition are driven by climate and soil characteristics. In the bookkeeping model, rates of growth and decomposition were defined outside the model and incorporated in the model structure. The incorporation of processes in CARLUC allows rates of production and decomposition to vary across both space and time, as a function of spatial and temporal variability in the driving variables.

CARLUC simulates the cycling of carbon from the atmosphere, through the ecosystem, and back to the atmosphere. The flows include both those resulting from natural ecological processes (for example, photosynthesis, tree growth, mortality, and decomposition) and those resulting from human activity (for example, burning of wood and sequestration of carbon in wood products). The model has compartments representing live tree components (stems, roots, and leaves), dead organic matter (coarse woody debris, leaf and root litter and soil humus), wood products with varying turnover times, and the CO_2 that is produced from decomposition and combustion.

In CARLUC, productivity is calculated as it is in the 3-PG (Physiological Principles for Predicting Growth) model of Landsberg and Waring (1997). Photosynthesis is driven by the amount of photosynthetically active radiation (PAR) absorbed by plants, and productivity is controlled by forest light use efficiency (LUE), which is reduced by climatic or soil conditions that are not optimal for growth.

CARLUC does not contain information about individual trees. Instead, photosynthetic production is allocated to lumped stem, leaf, and root pools, each with its own characteristic turnover time (as in CASA). Detritus enters debris and soil carbon pools, also with turnover rates. The model contains a water-balance sub-model that predicts plant available soil water, with evapotranspiration calculated using the Penman-Monteith equation.

In CARLUC, disturbance causes a redistribution of carbon from living biomass to dead biomass, CO_2, and wood products. Disturbance is represented as a transfer of a fraction of the living biomass pools to slash or product pools. We used CARLUC to calculate the net flux of carbon dioxide due to deforestation and forest re-growth (Hirsch et al., 2004) and compared the results with earlier results from the bookkeeping model (Houghton et al. 2000). Besides using the new model, the analysis also made use of more recent land-cover information derived from satellite imagery.

The fieldwork and remote sensing components of this project helped parameterize the CARLUC model for fire and logging disturbance. In addition, they were used to determine whether selective logging increases susceptibility to burning. We hypothesized that changes in forest structure as a result of disturbance lead to an increase in fuel load and a drier microclimate, both of which increase flammability. The synergistic effect between logging and accidental fire is an important dynamic to capture when simulating the impact of disturbance on forest carbon storage, because without it the effect of logging on carbon is underestimated.

Significant findings:

1. An analysis of deforestation and agricultural abandonment over the Brazilian Amazon with the new model CARLUC (Hirsch et al. 20004) yielded an estimate of carbon flux that was generally similar to the estimate obtained earlier with the bookkeeping model (Houghton et al. 2001): a net release of carbon from land-use change averaging about 0.2 PgC yr^{-1} over the period 1978-1998. The new analysis gave a slightly higher net release because CARLUC simulated larger biomass values than used in the initial analysis (see abstract below).

Fieldwork

The data required by the model to calculate changes in carbon storage from disturbances include both the spatial extent and the intensity of forest disturbance (that is, forest mortality or wood volume removed). Because low intensities of disturbance may not be readily identified from space, ground-based measurements, as well as satellite data, are required to calculate a net carbon flux. Some of the fieldwork also served to evaluate the sensitivity of Landsat TM imagery for determining forest disturbance.

Fieldwork was carried out in Paragominas, Belterra, and Guarantã (northern Mato Grosso). Belterra is close to the LBA sites in Santarem. An area about 10 km x 10 km captured a portion of a 200 km^2 fire scar that burned (in 1997) and included forests with a range of logging intensities (harvests ranging from zero up to about 20 m^3/ha). We selected three levels of forest fire damage and sampled (four or five 500 x 20 m plots per forest type) biomass, LAI, and fuel loads. Undisturbed forests and forests with different levels of logging were also sampled. We acquired detailed maps (~15,000 ha of forest) in which all trees >30 cm dbh were mapped, including an indication of harvests.

Significant findings:

2. **Most logging takes place within one to three kilometers of previous logging.** Most of the logged areas in this region were located between one and five kilometers from secondary roads, and radiated out into new forests an average distance of 3 km yr^{-1}.

3. **Areas logged or burned are more likely to burn than undisturbed forests.** Based on reconstruction of a 17-year history of Paragominas through field interviews and fieldwork, most forest fires were found to occur in small forest fragments partially surrounded by cattle pasture. Forest understory fires were significantly correlated with the percentage of the forest fragment that had previously been logged or burned, demonstrating a positive relationship between logging and forest fires.

4. **Understory fires reduce forest biomass.** Fieldwork in six sites in Paragominas demonstrated that the combination of logging and understory fire reduced live aboveground biomass by more than half. The effects of understory fire on forest biomass are larger than any previously reported.

Remote Sensing

The goal of the work was to develop a rapid and reliable method for measuring areas selectively logged and burned. We evaluated the types and intensities of fire and logging that can be observed.

Significant findings:

5. **Landsat Bands 4 and 5 show the potential for monitoring the effect of fire on forest biomass.** A combination of field measurements in a large understory fire scar 100 km south of Santarém and multi-date analysis of Landsat TM and ETM images of the region revealed the potential for monitoring with bands 4 and 5 the effect of fire on forest biomass.

6. **Landsat data indicate the areas of forest burned by low to moderate intensity surface fires.** ETM+ data can be used to detect recent fire scars in the transition forest region of Mato Grosso. Preliminary results suggest that in 2001 roughly 1% of the area in two Landsat scenes burned.

Publications

Houghton, R.A., K.T. Lawrence, J.L. Hackler, and S. Brown. 2001. The spatial distribution of forest biomass in the Brazilian Amazon: A comparison of estimates. *Global Change Biology* **7**:731-746.

Abstract. The amount of carbon released to the atmosphere as a result of deforestation is determined, in part, by the amount of carbon held in the biomass of the forests converted to other uses. Uncertainty in forest biomass is responsible for much of the uncertainty in current estimates of the flux of carbon from land-use change. We compared several estimates of forest biomass for the Brazilian Amazon, based on spatial interpolations of direct measurements, relationships to climatic variables, and remote sensing data. We asked three questions. First, do the methods yield similar estimates? Second, do they yield similar spatial patterns of distribution of biomass? And, third, what factors need most attention if we are to predict more accurately the distribution of forest biomass over large areas?

The answer to the first two questions is that estimates of biomass for Brazil's Amazonian forests (including dead and belowground biomass) vary by more than a factor of two, from a low of 39 PgC to a high of 93 PgC. Furthermore, the estimates disagree as to the regions of high and low biomass. The lack of agreement among estimates confirms the need for reliable determination of aboveground biomass over large areas. Potential methods include direct measurement of biomass through forest inventories with improved allometric regression equations, dynamic modeling of forest recovery following observed stand-replacing disturbances (the approach used in this research), and estimation of aboveground biomass from airborne or satellite-based instruments sensitive to the vertical structure plant canopies.

Hirsch, A.I., W.S. Little, R.A. Houghton, N.A. Scott, and J.D. White. 2004. The net carbon flux due to deforestation and forest re-growth in the Brazilian Amazon: Analysis using a process-based model. *Global Change Biology* **10**:908-924.

Abstract. We developed a process-based model of forest growth, carbon cycling, and land cover dynamics named CARLUC (for CARbon and Land Use Change) to estimate the size of terrestrial carbon pools in terra firme (non-flooded) forests across the Brazilian Legal Amazon and the net flux of carbon resulting from forest disturbance and forest recovery from disturbance. Our goal in building the model was to construct a relatively simple ecosystem model that would respond to soil and climatic heterogeneity that allows us to study of the impact of Amazonian deforestation, selective logging, and accidental fire on the global carbon cycle. This paper focuses on the net flux caused by deforestation and forest re-growth over the period from 1970-1998. We calculate that the net flux to the atmosphere during this period reached a maximum of ~0.35 PgC/yr (1PgC = 1×10^{15} gC) in 1990, with a cumulative release of ~7 PgC from 1970-1998. The net flux is higher than predicted by an earlier study (Houghton et al., 2000) by a total of 1 PgC over the period 1989-1998 mainly because CARLUC predicts relatively high mature forest carbon storage compared to the datasets used in the earlier study. Incorporating the

dynamics of litter and soil carbon pools into the model increases the cumulative net flux by ~1 PgC from 1970-1998, while different assumptions about land cover dynamics only caused small changes. The uncertainty of the net flux, calculated with a Monte-Carlo approach, is roughly 35% of the mean value (1 SD).

Alencar, A.A.C., L.A. Solorzano, and D.C. Nepstad. 2004. Modeling forest understory fires in an eastern Amazonian landscape. *Ecological Applications* **14**(4) Supplement: S139–S149.

Abstract. Forest understory fires are an increasingly important cause of forest impoverishment in Amazonia, but little is known of the landscape characteristics and climatic phenomena that determine their occurrence. We developed empirical functions relating the occurrence of understory fires to landscape features near Paragominas, a 35-yr-old ranching and logging center in eastern Amazonia. An historical sequence of maps of forest understory fire was created based on field interviews with local farmers and Landsat TM images. Several landscape features that might explain spatial variations in the occurrence of understory fires were also mapped and co-registered for each of the sample dates, including: forest fragment size and shape, forest impoverishment through logging and understory fires, source of ignition (settlements and charcoal pits), roads, forest edges, and others. The spatial relationship between forest understory fire and each landscape characteristic was tested by regression analyses. Fire probability models were then developed for various combinations of landscape characteristics. The analyses were conducted separately for years of the El Niño Southern Oscillation (ENSO), which are associated with severe drought in eastern Amazonia, and non-ENSO years.

Most (91%) of the forest area that burned during the 10-yr sequence caught fire during ENSO years, when severe drought may have increased both forest flammability and the escape of agricultural management fires. Forest understory fires were associated with forest edges, as reported in previous studies from Amazonia. But the strongest predictor of forest fire was the percentage of the forest fragment that had been previously logged or burned. Forest fragment size, distance to charcoal pits, distance to agricultural settlement, proximity to forest edge, and distance to roads were also correlated with forest understory fire. Logistic regression models using information on fragment degradation and distance to ignition sources accurately predicted the location of >80% of the forest fires observed during the ENSO event of 1997-1998. In this Amazon landscape, forest understory fire is a complex function of several variables that influence both the flammability and ignition exposure of the forest.

In preparation

Alencar, A., D. Nepstad, and M. Del. C. Vera-Diaz. Forest understory fire in the Brazilian Amazon in ENSO and non-ENSO Years: Area burned and committed carbon emissions.

Abstract. "Understory fires" that burn the floor of standing forests are one of the most important types of forest impoverishment in the Amazon, especially during the severe droughts of El Niño Southern Oscillation (ENSO) episodes. However, we are aware of no estimates of the areal extent of these fires for the Brazilian Amazon and, hence, of their contribution to Amazon carbon fluxes to the atmosphere. We calculated the area of forest understory fires for the Brazilian Amazon region during an El Nino (1998) and a non El Nino (1995) year based on forest fire scars mapped with satellite images for three locations in eastern and southern Amazon, where deforestation is concentrated. The three study sites represented a gradient of both forest types and dry season severity. The burning scar maps were used to determine how the percentage of forest that burned varied with distance from agricultural clearings. These spatial functions were then applied to similar forest/climate combinations outside of the study sites to derive an initial estimate for the Brazilian Amazon. Ninety-one percent of the forest area that burned in the study sites was within the first kilometer of a clearing for the non ENSO year and within the first four kilometers for the ENSO year. The area of forest burned by understory forest fire during the severe drought (ENSO) year (3.9 millions of hectares) was 13 times greater than the area burned during the average rainfall year (0.2 million hectares), and twice the area of annual deforestation rate. Dense forest was, proportionally, the forest area most affected by understory fires during the El Nino year, while understory fires were concentrated in transitional forests during the year of average rainfall. Our estimate of aboveground tree biomass killed by fire ranged from 0.06 Pg to 0.38 Pg during the ENSO and from 0,004 Pg to 0,024 Pg during the non ENSO.

Abstracts for poster presentations:

Alencar, Ane, Daniel Nepstad, Maria Del Carmen Vera Diaz. A Extensão dos Incêndios Florestais na Amazônia Brasileira em Anos de El Niño e Não El Niño. 3rd International LBA Scientific Conference. Brasilia – Brazil, July 2004.

Hayashi, Sanae, **Ane Alencar**; Oswaldo Carvalho Jr. Análise da Intensidade da Exploração Madeireira em Áreas de Floresta Densa e de Transição na Amazônia. 3rd International LBA Scientific Conference. Brasilia – Brazil, July 2004.

Carvalho, Jr., O., **A. Alencar**, D. Nepstad, S. Hayashi. The effects of logging and understory fires on biomass in dense and transitional forests. 3rd International LBA Scientific Conference. Brazilia, Brazil, July 2004.

Alencar, Ane; Oswaldo de Carvalho Jr. Daniel Nepstad, Sanae Hayashi. The impact of understory fires in the Amazon Transitional forest. LBA-Eco Scientific Meeting, Fortaleza, CE – Brazil, November 2003.

Hayashi, Sanae, **Ane Alencar**; Oswaldo Carvalho Jr. Assessing the Utility of a Landsat ETM+ Images for Identifying Areas of Traditional Logging in West Para, Brasil. LBA-Eco Scientific Meeting, Fortaleza, CE – Brazil, November 2003.

Carvalho Jr., O, **Ane Alencar**, Daniel Nepstad, Sanae Hayashi. Forest degradation by logging and fire in eastern Amazonia: a Biomass perspective. LBA-Eco Scientific Meeting, Fortaleza, CE – Brazil, November 2003

Alencar, A., O. Carvalho Jr, D. Nepstad, **R. Houghton**, S. Hayashi. *Mapeamento de Florestas Degradadas por Fogo no Oeste Paraense.* XI Simposio Brasileiro de Sensoriamento Remoto. LBA Fire Workshop. Belo Horizonte, MG – Brazil, April 2003.

Hayashi, S. N.; **A. Alencar**. *Métodos comparativos para a detecção de extração seletiva de madeira no oeste paraense utilizando modelo linear de mistura espectral de pixel.* XI Simposio Brasileiro de Sensoriamento Remoto. Belo Horizonte, MG – Brazil, April 2003.

Alencar, A., Nepstad, D., Solorzano, L., Hayashi, S. *Forest Disturbance by Logging and Fire in Eastern Amazonia.* 2nd International LBA Scientific Conference. Manaus, AM – Brazil, July 2002.

Hyashi, S; **Alencar, A**; Nepstad, D. *Spatial Pattern of Selective Logging, in an ageing Amazon frontier: the case of eastern Pará.* 2nd International LBA Scientific Conference. Manaus, AM – Brazil, July 2002.

Alencar, A., D. C. Nepstad, S. Hayashi. *Spatial and Temporal Distribution of Selective Logging in Eastern Amazon Using Visual Interpretation Analysis of Satellite Images.* Working Forest in the Tropics Conference. Gainesville, Fevereiro 2002.

Alencar A., L. A. Solórzano. *Predicting Spatial Patterns of Forest Fires in an Old Logging Frontier of Eastern Amazonia Using Empirically Derived Functions.* First International LBA Scientific Conference. Belém, PA – Brazil, June 2000.

Abstracts to Oral presentations.

Alencar, A; Carvalho Jr., O.; Nepstad, D. **Houghton, R.**; Hayashi, S. *Mapping Biomass Loss from Forest Fires in a Dense Forest of Western Pará.* 2nd International LBA Scientific Conference. Manaus, AM – Brazil, July 2002.