Final Report:

Investigation Group: ND-02

Grant No. NCC5-332, LBA-Eco Phase I

Biogeochemical Cycles in Degraded Lands

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Overall Project Objectives:

The objectives of this project were to define and describe the types of landscapes that fall under the broad category of "degraded lands" and to study biogeochemical cycles across this range of degradation found in secondary forests. We define degraded land as that which has lost part of its capacity of renovation of a productive ecosystem, either in the context of agroecosystems or as native communities of vegetation. This definition of degradation permits evaluation of biogeochemical constraints to future land uses.

Activities:

The following narrative description of progress follows the same outline of research tasks in the original grant proposal:

Research Task #1 -- the Tapajos National Forest and participation in the Seca-Floresta project:

To establish a baseline of biogeochemical processes in native mature forests of the region, we have measured nutrient stocks and fluxes at the "seca-floresta" study site near the kilometer 67 site at the Tapajos National Forest. Two 1-ha plots have been trenched around the perimeter to 1.5 m depth. Since early 1999, we have been measuring volumes and chemical composition of rainfall, throughfall, and soil solution, litterfall, decomposition in litterbags, net N mineralization and net nitrification, and soil emissions of NO, N_2O, CH_4, and CO_2. A rainfall exclusion treatment ("seca-floresta") was initiated in one 1-ha plot in January, 2000, while the other plot remains as a control. The objective of the rainfall exclusion (initiated as an NSF project) is to study the effects of prolonged drought on ecosystem processes, including susceptibility of these forests to fire. The trace gas measurements were supported specifically by this LBA-Ecology project and were the responsibility of our team (ND-02). During the first three years of treatment, the most pronounced effects were lower emissions of N_2O and CH_4 in the exclusion plots compared to the control plots (Fig. 1). These results demonstrate the dynamic nature and the sensitivity to changes in soil water content of soil microbial processes responsible for these greenhouse gas emissions. In addition, these measurements in the control plot provide a baseline for comparisons with other land uses. Results of all aspects of the experiment are summarized in Nepstad et al. (2002) and the latest results of trace gas measurements are described in Davidson et al. (in press); the abstract follows:

"Changes in precipitation in the Amazon Basin resulting from regional deforestation, global warming, and El Niño events may affect emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and nitric oxide (NO) from soils. Changes in soil emissions of radiatively important gases could have feedback implications for regional and global climate. Here we report results of a large-scale (1 ha) throughfall exclusion experiment conducted in a mature evergreen forest near Santarém, Brazil. The exclusion manipulation lowered annual N_2O emissions by a factor of about 2 and increased rates of consumption of atmospheric CH_4 by a factor of >3. No treatment effect has yet been detected for NO and CO_2 fluxes. The responses of these microbial processes after three rainy seasons of the exclusion treatment are characteristic of a direct effect of soil aeration on denitrification, methanogenesis, and methanotrophy. An anticipated second phase response, in which drought-induced plant mortality is followed by increased mineralization of C and N substrates from dead fine roots and by increased foraging of termites on dead coarse roots, has not yet been detected. Analyses of depth profiles of N_2O and CO_2 concentrations with a diffusivity model revealed that the top 25cm soil is the site of most of the wet season production of N_2O, whereas significant CO_2 production occurs down to 100cm in both seasons, and small production of CO_2 occurs to at least 1100cm depth. The diffusivity-based estimates of CO_2 production as a function of depth were strongly correlated with fine root biomass, indicating that trends in belowground C allocation may be inferred from monitoring and modeling profiles of H_2O and CO_2." (from Davidson et al., in press).

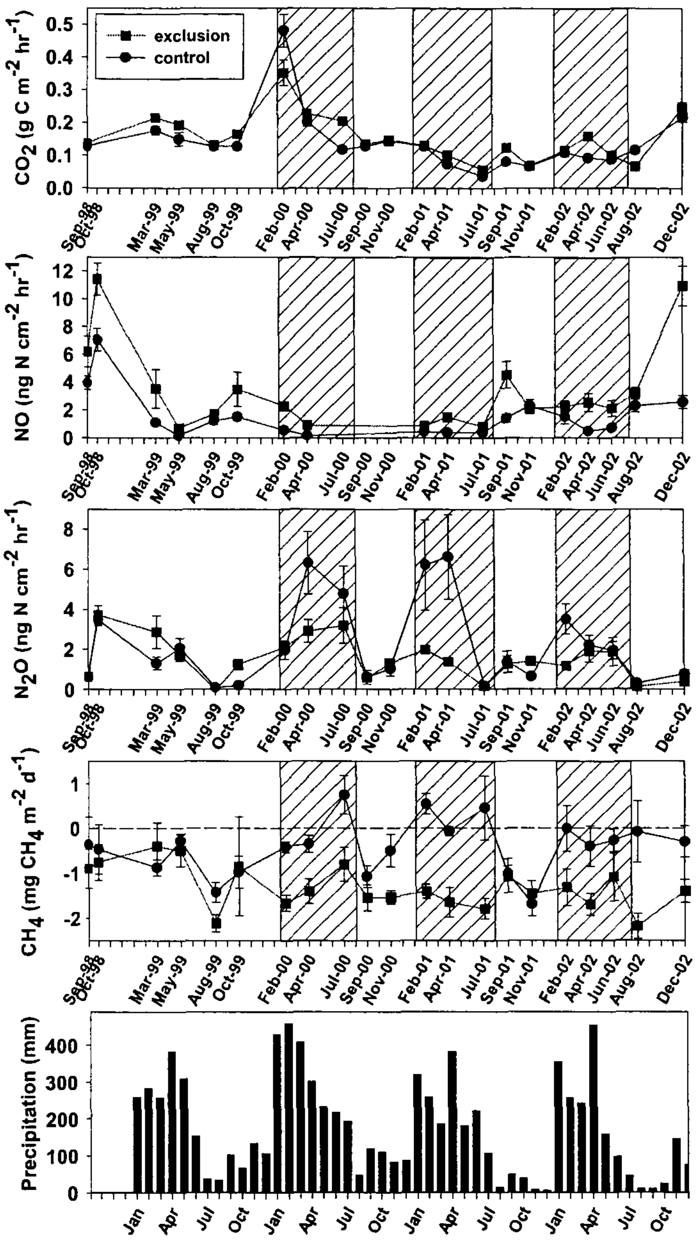

Fig. 1. Trace gas emissions at the "seca floresta" experiment at FLONA Tapajos. Shaded areas show the periods when rainfall was excluded from the treatment plot. From Davidson et al, in press.

Research Task #2 -- Chronosequences at São Francisco and studies at Igarape Acu, Paragominas, and Apeú, in eastern Pará

São Francisco do Pará: A secondary forest chronosequence was identified and characterized by co-PI Ima Vieira and her student, Arlete Almeida, near the town of São Francisco do Pará, about a one-hour drive east of Belém. This project was part of Arlete's master's thesis, and she later continued to work for the project as a CNPq-LBA-DTI bolsista. We studied the plant species composition and the rates of biomass accumulation in 12 secondary forests, with two replications of each of the following ages: 3, 6, 10, 20, 40, and 70 years. It is unusual to find capoeiras >20 years old, which made this a unique opportunity to study long-term recovery of biogeochemical cycles. We also found a remnant mature forest where we made the same measurements. The major finding of this work was that these secondary forests were classified into similar successional stages using three different methods that were entirely independent of each other -- species composition, height and diameter distributions, and supervised classification of a Landsat imagery (Fig. 2). These results summarized in a publication by Vieira et al. (2003). The abstract follows:

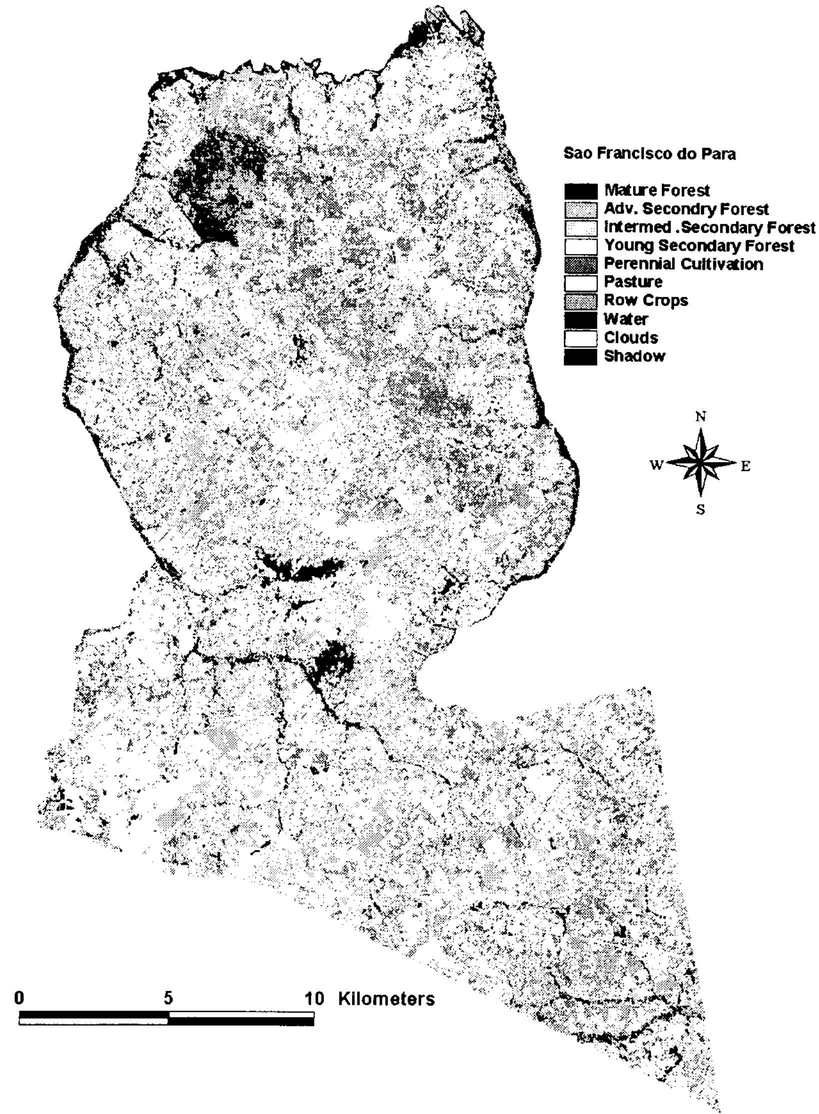

Figure 2. Supervised classification map of the municipality of São Francisco do Pará based on the 1999 Landsat 7 ETM image (Vieira et al., 2003).

"Secondary forests may become increasingly important as temporary reservoirs of genetic diversity, stocks of carbon and nutrients, and moderators of hydrologic cycles in the Amazon Basin as agricultural lands are abandoned and often later cleared again for agriculture. We studied a municipality in northeastern Pará, Brazil, that has been settled for over a century and where numerous cycles of slash and burn agriculture have occurred. The forests were grouped into young (3-6yrs), intermediate (10-20 yrs), advanced (40-70 yrs), and mature successional stages using 1999 Landsat 7 ETM imagery. Supervised classification of the imagery showed that these forest classes occupied 22%, 13%, 9%, and 6% of the area, respectively. Although this area underwent widespread deforestation many decades ago, forest of some type covers about 50% of the area. Row crops, tree crops, and pastures cover 8, 20, and 22%, respectively. The best separation among land covers appeared in a plot of NDVI versus band 5 reflectance. The same groupings of successional forests were derived independently from indices of similarity among tree species composition. Measured distributions of tree height and diameter also covaried with these successional classes, with the young forests having nearly uniform distributions, whereas multiple height and diameter classes were present in the advanced successional forests. Biomass accumulated more slowly in this secondary forest chronosequence than has been reported for other areas, which explains why the 70-year-old forests here were still distinguishable from mature forests using spectral properties. Rates of forest regrowth may vary across regions due to differences in edaphic, climatic, and historical land-use factors, thus rendering most relationships among spectral properties and forest age site-specific. Successional status, as characterized by species composition, biomass, and distributions of heights and diameters, may be superior to stand age as a means of stratifying these forests for characterization of spectral properties." from Vieira et al. (2003)

This chronosequence study also included nutrient cycling measurements. We measured trace gas emissions ten times between October 2000 and June 2002. Co-PI Dr. Cláudio Reis de Carvalho is analyzing nutrient stocks in foliage and soils. Another CNPq -LBA-DTI bolsista, Karina de Fátima Rodrigues Pantoja, measured litterfall, and litter is being analyzed for nutrient concentrations. Preliminary analyses indicate that N_2O emissions are correlated with leaf litterfall-N, both increasing with forest age. These results suggest that cycling of N is gradually recovering during secondary succession. These results will allow us to estimate rates of biogeochemical cycling of C and N as secondary forests regrow in an area of historical slash-and-burn agriculture and to relate these rates of nutrient cycling to the successional stages identified by remote sensing and verified by ground-based measurements. Analysis are ongoing.

Mulching experiment at Igarape Açu: We collaborated with the SHIFT project at Igarape Açu, where an ongoing mulching experiment is testing alternatives to slash and burn farming for small land holders. We measured trace gas emissions from burned, mulched, and fallow treatments. Significant emissions of N_2O and CH_4 from mulched plots demonstrate nutrient and greenhouse gas losses that will be compared to burning emissions on a rotational basis at the end of a full crop-fallow cycle rotation. Results were presented as a poster at the Fortaleza LBA meeting; an abstract follows:

"The use of fire in traditional slash-and-burn agriculture causes loss of nutrients from agroecosystems and emissions of pollutants to the atmosphere. A mulching technology has been developed as an alternative to burning that conserves nutrients and eliminates emissions from fire. However, mulching could also affect nutrient inputs to the soil and the microclimate of the topsoil, which, in turn, could effect emissions of nitrous oxide (N_2O), nitric oxide (NO), carbon dioxide (CO_2), and methane (CH_4) from the soil. The objective of this research was to compare emissions of these greenhouse gases from the soil under conventional slash-and-burn agriculture, the alternative mulching strategy, and native secondary forest (capoeira) vegetation.

The study site is within the municipality of Igarape Açu, Pará, where small-holder agriculture is the dominant land use. A 20-year-old fallow field was prepared for planting during the dry season of 2001. One field (2 ha) was cut and burned and another field (2 ha) was chopped and mulched. Both fields were planted in maize in January 2002. The mulched plot was fertilized with 12 g/plant of 60 – 60 – 30 kg ha^{-1} NPK (urea, triple superphosphate and potassium chloride). Cassava was planted under the maize in February 2002, and the maize was harvested in May 2002. The plots were weeded, and leguminous trees *Acacia mangium*, Willd, and *Sclerolobium paniculatum*, Vogel, were planted in 2 m x 2m spacing in June 2002. The cassava was harvested in June 2003, and the site was allowed to return to fallow, enriched with the planted N-fixing trees. Eight polyvinyl chloride (PVC) rings (20cm diameter) were inserted about 2 cm into the soil in each of two plots per treatment. An additional eight rings were installed in an adjacent fallow field with 20-year-old *capoeira* vegetation. Flux measurements of CO_2, N_2O, NO, and CH_4 were repeated about every other month.

A large pulse of N_2O emissions was observed in the burned and mulched plots in January 2002. This large emission was probably due to a release of readily available N following site clearing and wet soil conditions early in the rainy season that promoted denitrification. The N_2O fluxes in the mulched plot peaked after fertilization in March 2002 and then gradually declined over the next year, but remained elevated relative to the burned field and the capoeira. The moist soil microenvironment under the mulch maintains conditions favorable for N_2O emissions from denitrification. In contrast, the N_2O emissions declined in the burned plot once the pulse of available N released during the site preparation was spent, and N_2O emissions were always low in the nutrient poor capoeira. Nitric oxide (NO) emissions were not significantly different between burned and mulched fields, but were lower in the capoeira. Apparently, the burned and mulched fields still had some residual available N to be released as NO throughout 2002 and into 2003.

Soil respiration (CO_2 flux) was elevated in the burned plots in December 2001 and January 2002, which may have been due to decomposition of dead roots. Respiration in the burned and mulched plots remained higher than the *capoeira* throughout the study, presumably because of active growth of the crop roots and gradual decomposition of the mulch. The CO_2 fluxes were not significantly higher in the mulch field compared to the burned field. The decomposition of the mulch must be slow relative to the rate of crop root respiration.

The moist, carbon-rich conditions under and in the mulch also stimulated net methane production at all dates after the mulch application. The CH_4 emissions are highly variable within the mulched field, indicating "hot spots" of anaerobic microsites that are favorable for denitrification and methanogenesis. In contrast, the burned field and the capoeira were generally net consumers of atmospheric CH_4.

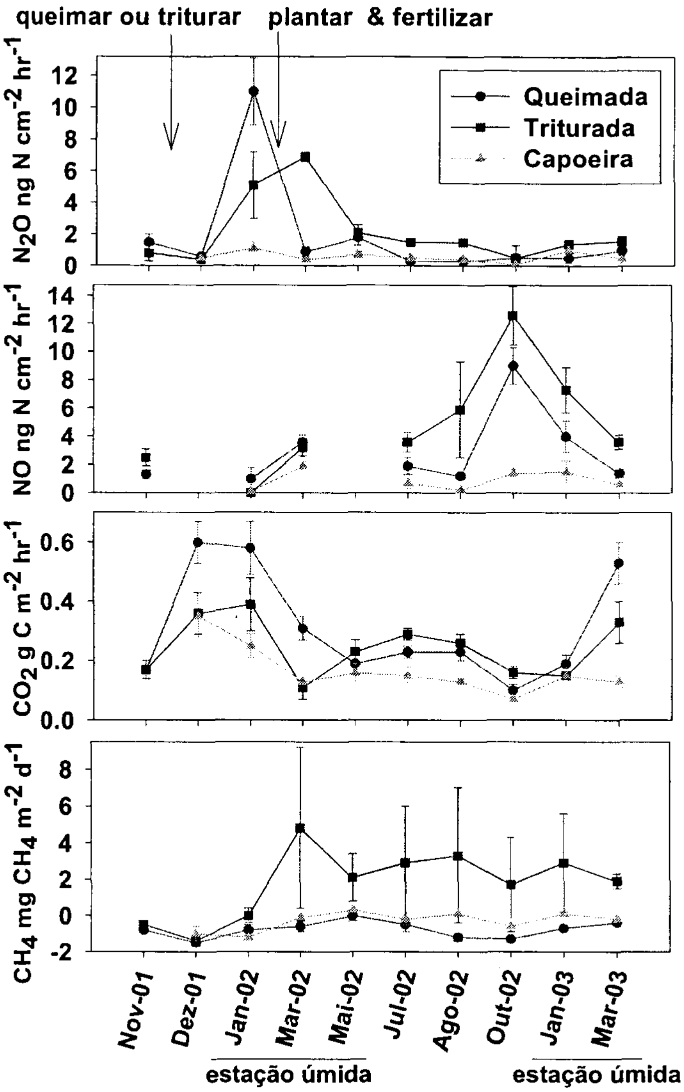

Figure 3. Trace gas emissions in mulched, burned, and native capoeira vegetation at Igarape Açu, Pará. From Davidson et al. poster presented at LBA meeting in Fortaleza

In summary, the anaerobic microsites under the mulch are promoting relatively high fluxes of N_2O and CH_4. The burning treatment and the fertilization with N in the mulched field also caused sustained elevated fluxes of NO. Although the mulching has caused increased emissions of the greenhouse gases N_2O and CH_4, the magnitude of these emissions throughout the crop cycle must be compared to the very intense emissions released during a typical site preparation fire. We are continuing to measure emissions through the fallow phase and then will compare these emissions summed over the cropping cycle to estimates of fire-induced emissions to estimate the net effect of these management practices on gaseous emissions and nutrient losses.

<u>Experimental irrigation and litterfall removal at Apeú:</u> We collaborated with Drs. Daniel Zarin, University of Florida, and Francisco Assis, FCAP, at the Apeú field site near Belém, where they are conducting an experimental manipulation of a ten-year-old capoeira. Two treatments (dry season irrigation, and litterfall removal) and a control are replicated four times, using 12 plots of 20m x 20m each. The irrigation treatment is designed to alleviate drought as one of the factors that might limit rates of regrowth of trees and activity of soil microorganisms. The litterfall removal treatment is designed to provoke a more severe nutrient

limitation. Hence, the hypotheses that rainfall and/or nutrients limit rates of regrowth of this capoeira will be tested. Our contribution was to measure the effects of these treatments on trace gas emissions from the soils. We measured trace gas emissions 20 times between August 1999 and April 2003 (Fig. 4). The results have been summarized in a manuscript by Zarin's Brazilian doctoral student Steel Vasconcelos; the abstract follows:

> "In an Amazonian regrowth forest stand, we measured the efflux of carbon dioxide (CO_2), nitric oxide (NO), nitrous oxide (N_2O), and methane (CH_4) from soil in response to increased soil moisture availability during the dry season by irrigation and decreased substrate availability by continuous removal of aboveground litter. In the absence of irrigation, soil CO_2 efflux decreased during the dry season while irrigation maintained soil CO_2 efflux levels similar to the wet season. Large variations in soil CO_2 efflux were observed in response to soil wet-up and dry-down events. Annual soil C efflux in irrigated plots was 27 and 13 % higher than control plots in 2001 and 2002, respectively. Litter removal significantly reduced soil CO_2 efflux; annual soil C efflux in 2002 was 28 % lower in litter removal plots compared to control plots. The annual soil C efflux : litterfall C ratio observed in all treatments (range from 4.0 to 5.6) was consistent with previously reported values for regrowth forests that indicate a relatively large belowground C allocation. In general, fluxes of N_2O and CH_4 were higher during the wet season and both fluxes increased during dry-season irrigation. There was no seasonal effect on NO fluxes. Litter removal had no significant impact on N oxide or CH_4 emissions. Net soil nitrification was somewhat reduced in litter removal plots. Overall, these results demonstrate significant soil moisture and substrate constraints on soil trace gas emissions, particularly for CO_2, that must be considered in models of soil trace gas emissions from tropical forests." From Vasconcelos et al. (submitted).

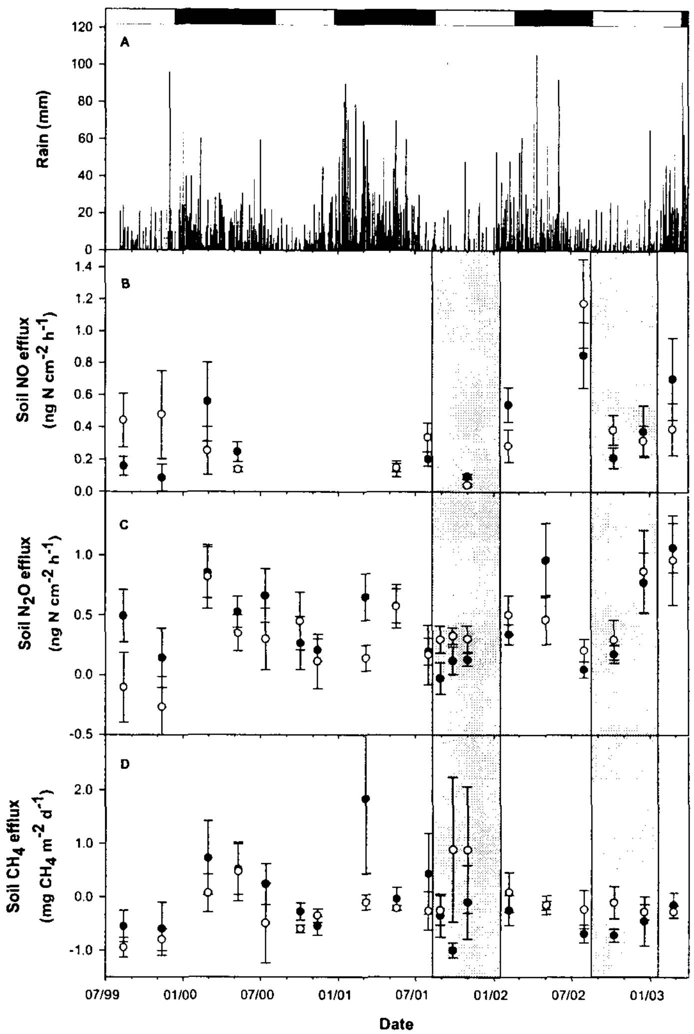

Figure 4. Trace gas emissions from the irrigation experiment at Apeu, Pará. Shaded areas indicate periods of dry season irrigation. From Vasconcelos et al.. submitted.

Research Task #3 -- Nutrient manipulation experiment:

While Apeú study provides an experimental manipulation intended to provoke severe nutrient stress, another research approach is to enhance nutrient availability during secondary succession with fertilizer amendments. A low statured, highly degraded capoeira at Fazenda Vitoria, near the town of Paragominas, was selected for this study. Twelve 20m x 20m plots were established, with three replications of each of four treatments: fertilization with 100 kg N ha^{-1}, 50 kg P ha^{-1}, N+P, and control. Fertilizer was applied at the beginning of the rainy season (January) in both 2000 and 2001. This experiment allows us to test the hypotheses that nutrient availability limits forest regrowth, biomass accumulation, and recuperation of biogeochemical cycles. Co-PI, Dra. Ima Vieira, of the Museu Goeldi, conducted surveys of species diversity and biomass on these plots in November 1999, June 2000, June 2001, and June 2002. Biomass, soil and plant nutrient concentrations, litter decomposition, and leaf area index were measured during and at the end of each rainy season (June). Trace gas emissions were measured immediately before and after fertilizer application and twice more in each season, but were consistently low.

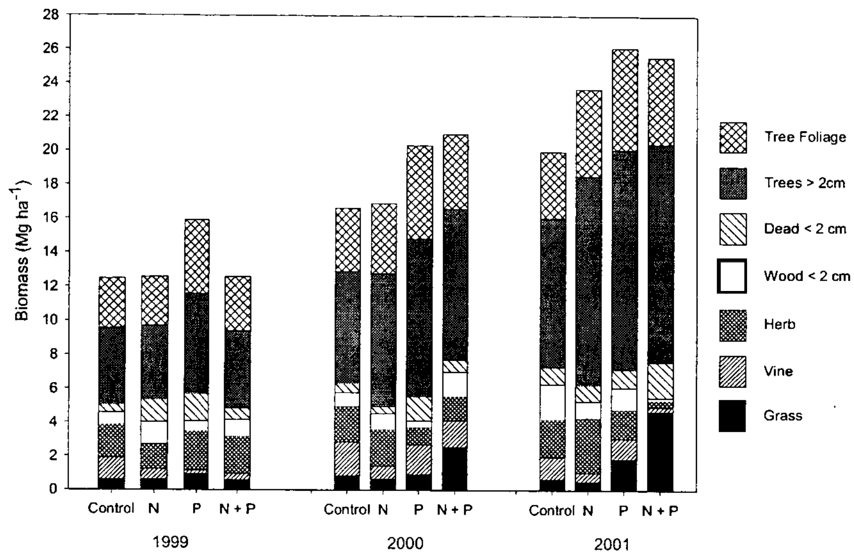

Figure 5. Responses of plant growth to fertilizer amendments at Paragominas, Pará, applied in early 2000 and 2001. From Davidson et al., in press.

The first two year's results from this experiment showed an increase in growth of remnant grasses and trees in the N+P treatment, indicating a co-limitation of these two nutrients (Figure 5). Responses of foliar concentrations of N and P were species specific. Most of the applied P was found in the soil. Results are summarized in a manuscript (Davidson et al., in press); the abstract follows:

> "Understanding secondary successional processes in Amazonian terrestrial ecosystems is becoming increasingly important as continued deforestation expands the area that has become secondary forest, or at least has been through a recent phase of secondary forest growth. Most Amazonian soils are highly weathered and relatively nutrient poor, but the role of nutrients as a factor determining successional processes is unclear. Soils testing and chronosequence studies have yielded equivocal results regarding the possible role of nutrient limitation. The objective of this paper is to report the first two years' results of a nitrogen (N) and phosphorus (P) fertilization experiment in a six-year-old secondary forest growing on an abandoned cattle pasture on a clayey Oxisol. Growth of remnant grasses responded significantly to the N+P treatment, whereas tree biomass increased significantly following N-only and N+P treatments. The plants took up about 10% of the 50 kg P ha^{-1} the first year's application, and recovery in soil fractions could account for the rest. The trees took up about 20% of the 100 kg N ha^{-1} of the first year's application. No changes in soil inorganic-N, soil microbial biomass-N, or litter decomposition rates have been observed so far, but soil faunal abundances increased in fertilized plots relative to the control in the second year of the study. A pulse of nitric oxide and nitrous oxide emissions was measured in the N-treated plots only shortly after the second year's application. Net N mineralization and net nitrification assays demonstrated strong immobilization potential, indicating that much of the N was probably retained in the large soil organic-N pool. Although P availability is low in these soils and may partially limit biomass growth, the most striking result of this study so far is the significant response of tree growth to N fertilization. Repeated fire and other losses of N from degraded pastures may render tree growth N-limited in some young Amazonian forests. Changes in species composition and monitoring of long-term effects on biomass accumulation will be addressed as this experiment is continued." From Davidson et al., in press.

Research Task #4 -- Natural soil fertility:

This study was conducted in the state of Acre, near the city of Rio Branco. The soils of this region include both eutrophic and dystrophic soil types, so that the importance of natural soil fertility on rates of secondary forest regrowth can be addressed. Cleber Salimon, who recently defended his doctoral dissertation at CENA under the direction of Dr. Reynaldo Victoria, coordinated the project. A second student, Antonio Willian de Mello, who is currently working on a masters degree at ESALQ / USP under the direction of Plinio de Camargo, did much of the routine field work for this project. Chronosequences of secondary forests were established on both eutrophic and dystrophic soils, which were characterized chemically and isotopically at CENA. Monthly measurements of soil respiration were initiated at these sites in July 1999. No consistent differences in soil respiration were observed between eutrophic and dystrophic soils. Respiration from pasture soils was as high or higher than forest soils, indicating that pastures in this region are highly productive (Fig. 6). The results are summarized Salimon et al., in press; the abstract follows:

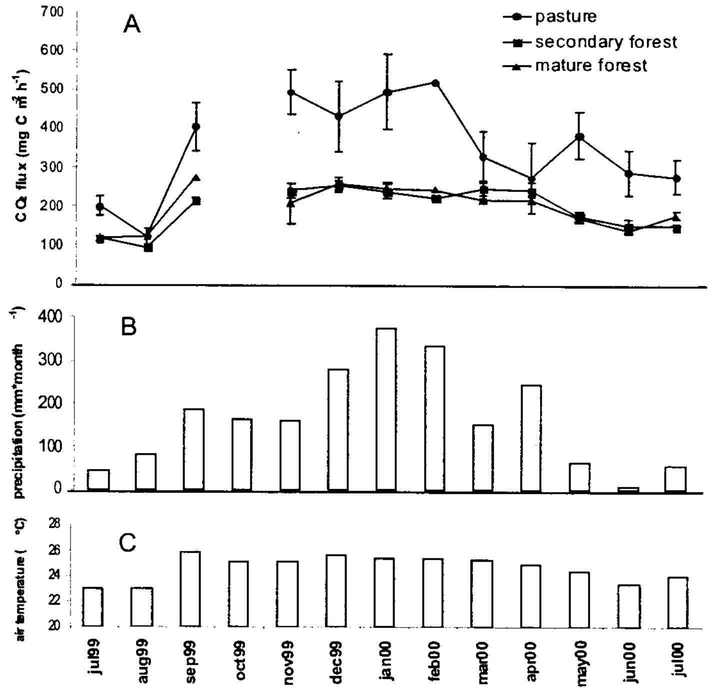

Figure 6. Soil respiration in pasture and forest study sites near Rio Branco, Acre. From Salimon et al., in press.

"Stocks of carbon in Amazonian forest biomass and soils have received considerable research attention because of their potential as sources and sinks of atmospheric CO_2. Fluxes of CO_2 from soil to the atmosphere, on the other hand, have not been addressed comprehensively in regard to temporal and spatial variation and to land cover change, and have been measured directly only in a few locations in Amazonia. Considerable variation exists across the Amazon Basin in soil properties, climate, and management practices in forests and cattle pastures that might affect soil CO_2 fluxes. Here we report soil CO_2 fluxes from an area of rapid deforestation in the southwestern Amazonian state of Acre. Specifically we addressed (1) the seasonal variation of soil CO_2 fluxes, soil moisture, and soil temperature; (2) the effects of land cover (pastures, mature and secondary forests) on these fluxes; (3) annual estimates of soil respiration; and (4) the relative contributions of grass-derived and forest-derived C as indicated by $\delta^{13}CO_2$. Fluxes were greatest during the wet season and declined during the dry season in all land covers. Soil respiration was significantly correlated with soil water-filled pore space but not correlated with temperature. Annual fluxes were higher in pastures compared to mature and secondary forests, and some of the pastures also had higher soil C stocks. The $\delta^{13}C$ of CO_2 respired in pasture soils showed that high respiration rates in pastures were derived almost entirely from grass root respiration and decomposition of grass residues. These results indicate that the pastures are very productive and that the larger flux of C cycling through pasture soils compared to forest soils is probably due to greater allocation of C belowground. Secondary forests had soil respiration rates similar to mature forests, and there was no correlation between soil respiration and either forest age or forest biomass. Hence, belowground allocation of C does not appear to be directly related to the stature of vegetation in this region. Variation in seasonal and annual rates of soil respiration of these forests and pastures is more indicative of flux of C through the soil rather than major net changes in ecosystem C stocks." From Salimon et al., in press.

Research Task #5 – High resolution imagery:

Two activities were completed under this research task. First, co-PI Tom Stone and doctoral student Cleber Salimon studied land use change detected in Landsat images of the Acre study area (the same area as the natural fertility studies described above). Their results show that deforestation in the area of Rio Branco, Acre, involves a net loss of both mature and secondary forests (Fig. 7). An abstract of a draft Salimon et al. abstract follows:

> "We studied landcover change and its temporal trends (from 1988 to 1997) in Western Amazonia, Acre, Brazil using Landsat TM imagery and remote-sensing techniques, such as normalized difference vegetation index, supervised and unsupervised classifications. Our results showed that during the period studied, mature and secondary forests declined in area by 16 and 5% respectively, during this 9-year period, while pasture increased by 18%. We also found that the amount of secondary forests in any year was smaller than values reported by other authors, presumably because deforestation in Acre has occurred more recently than in other parts of the Amazon Basin. Because of this decline in forest cover, even with secondary forests absorbing CO_2 from the atmosphere, the net effect of land use change has been as a source of carbon to the atmosphere and not as a sink." From Salimon, Stone, and Brown, manuscript in preparation.

The results of Salimon et al. in Acre are consistent with with the results of other remote sensing study in the eastern Amazon region of São Francisco do Pará by co-PI Ima Vieira, her student, Arlete Almeida, and co-PI Tom Stone, where conversion of secondary forest to pastures and row crops is also causing a net loss of terrestrial C storage. As already noted above, Vieira et al. (2003) used supervised classification of Landsat 7 ETM imagergy to group secondary forests into young (3-6yrs), intermediate (10-20 yrs), advanced (40-70 yrs), and mature successional stages. The best separation among land covers appeared in a plot of NDVI versus band 5 reflectance. Biomass accumulated more slowly in this secondary forest chronosequence than has been reported for other areas, which explains why the 70-year-old forests here were still distinguishable from mature forests using spectral properties. Because rates of forest regrowth vary across regions due to differences in edaphic, climatic, and historical land-use factors, spectral properties of secondary forests may be related to successional status, as characterized by species composition, biomass, and distributions of heights and diameters, rather than related to stand age *per se* (Vieira et al., 2003).

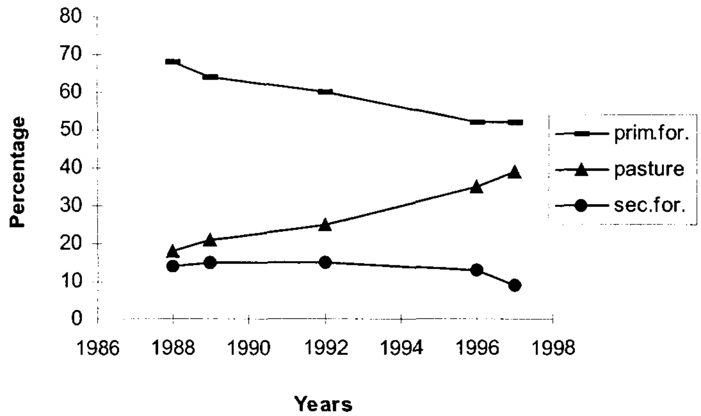

Figure 7. Percentage of each land cover type for the Catuaba Test Area, Rio Branco, Acre, determined from Landsat TM images.

Training and Education Activities

Six LBA bolsistas participated in this project:

Luciana Pimentel da Silva
Role: Bolsista ITI - CNPq /
University/Organization: IPAM

Michele Maria Corrêa
Role: Bolsista DTI - CNPq
University/Organization: EMBRAPA/CPATU

Arlete Silva de Almeida
Role: Bolsista DTI - CNPq
University/Organization: Museu Paraense Emilio Goeldi

Wanderley Rocha da Silva
Role: Bolsista ITI - CNPq /
University/Organization: IPAM

Karina de Fátima Rodrigues Pantoja
Role: Bolsista DTI - CNPq /
University/Organization: Museu Paraense Emilio Goeldi

Renata Tuma Sabá
Role: Bolsista DTI - CNPq /
University/Organization: IPAM

Two research technicians gained experience in this project and then found related graduate school programs:

Françoise Yoko Ishida
Role: Research Assistant
University/Organization: IPAM - Instituto de Pesquisa Ambiental da Amazonia
Current (2003) graduate school affiliation: CENA doctoral student

A. Willian Flores de Melo
Role: Research Assistant
University/Organization: BIOMA, Rio Branco, Acre
Current (2003) graduate school affiliation: ESALQ /USP, masters degree student

Three graduate degrees earned with support from this project :

Cleber Ibraim Salimon
University/Organization: CENA
Nationality: Brazil
Degree: Ph.D., May, 2003
Thesis Title: Respiracão do solo sob florestas e pastagens na Amazônia Sul-Ecodental, Acre.

Valdirene Oliveira
University/Organization: University of Goettingen
Nationality: Brazil
Degree: M.S., 2001
Thesis Title: Emissões de gases - traço em capoeira enriquecida no nordeste do Pará – Brasil

Elizabeth Leslie Belk
University/Organization: University of Georgia
Nationality: USA
Degree: M.S., 2003
Thesis Title: Modeling the effects of partial throughfall exclusion on the distribution of soil water in a Brazilian Oxisol under tropical moist forest.

Graduate student exams and thesis defense: The PI, Eric Davidson, served on the graduate committees ("banca") of three students at the Universidade de Brasília and has participated in the following:

1. Ph.D. qualifying exam: Alexandre de Siqueira Pinto, October 31, 2000.
2. Ph.D. qualifying exam: Roberto Engel Aduan, November 1, 2000.
3. Ph.D. dissertation defense: Júlio Carlos Franca Resende, August 24, 2001.
4. Ph.D. dissertation defense: Alexandre de Siqueira Pinto, 2002.

Publications

Six original research papers:

Davidson, E.A., C.J.R. de Carvalho, I.C.G. Vieira, R.O. Figueiredo, P. Moutinho, F.Y. Ishida, M.T.P. dos Santos, J.B. Guerrero, K. Kalif, and R.T. Sabá. Nutrient limitation of biomass growth in a tropical secondary forest: early results of a nitrogen and phosphorus amendment experiment. Ecological Applications, in press.

Davidson, E.A., F.Y. Ishida, D.C. Nepstad. Effects of an experimental drought on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest. Global Change Biology, in press.

Markewitz, D. E.A. Davidson, P. Moutinho, and D.C. Nepstad. Nutrient loss and redistribution after forest clearing on a highly weathered soil in Amazonia. Ecological Applications, in press.

Nepstad D C, Moutinho P, Dias-Filho M B, Davidson E A, Cardinot G, Markewitz D, Figueiredo R, Vianna N, Chambers J, Ray D, Guerreiros J B, Lefebvre P, Sternberg L, Moreira M, Barros L, Ishida F Y, Tohlver I, Belk E, Kalif K and Schwalbe K. 2002. The effects of partial throughall exclusion on canopy processes, aboveground production, and biogeochemistry of an Amazon forest. J. Geophys. Res. 107, D20, 8085, doi:10.1029/2001JD000360.

Salimon, C.I., E.A. Davidson, R.L. Victoria, and A.W.F. Melo. CO_2 flux from soil in pastures and forests in southwestern Amazonia. Global Change Biology, in press.

Vieira, I.C.G., Almeida, A.S. de, Davidson, E.A., Stone, T.A., Carvalho, C.J.R. de, Guerrero, J.B. 2003. Classifying successional forests using Landsat spectral properties and ecological characteristics in eastern Amazonia. Remote Sensing of the Environment 87:470-481.

Two synthesis papers:

Davidson, E.A., Bustamante, M.M.C, Pinto, A.de S. 2001. Emissions of nitrous oxide and nitric oxide from soils of native and exotic ecosystems of the Amazon and Cerrado regions of Brazil. *In* Optimizing nitrogen management in food and energy production and environmental protection: Proceedings of the 2nd International Nitrogen Conference on Science and Policy, In: Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection (eds Galloway J, Cowling E, Erisman J, Wisniewski, J, Jordan C), pp. 312-319. A.A. Balkema Publishers, Lisse.

Davidson, E.A., C. Neill, A.V. Krusche, D. Markewitz, R. de O. Figueiredo, and M.V.R. Ballester. Loss of nutrients from terrestrial ecosystems to streams and the atmosphere following land use change in Amazonia. Chapman conference proceedings, 2003, submitted.

Summary

A nutrient manipulation experiment and a chronosequence study demonstrated that rates of regrowth in secondary forests of eastern Pará can be limited by nutrients. Nutrient loss, largely through fire, is part of the process of "degradation." Reaccumulation of nutrients is part of the process of recuperation. Our studies in Acre demonstrated that cattle pastures can be highly productive, as indicated by high rates of C cycling through pasture soils. Although there were no detectable differences in measured C cycling rates among soils of varying fertility within the Acre study, we speculate that the generally higher soil fertility in this region and the more recent history of land use change explains that apparent lack of severe degradation of these altered ecosystems compared to our studies in Pará.

Nutrient availability in pastures, secondary forests, and mature forests affects rates of trace gas emissions from soils. Hence, pasture degradation leads to lower rates of emissions, which gradually recover as stocks of plant-available nutrients re-accumulate during secondary forest succession. The water manipulation experiments at Santarém and Apeú demonstrate the importance of soil water content and seasonality of precipitation on these trace gas emissions in both mature and secondary forests.

Our remote sensing studies demonstrated that classes of secondary forests could be separated by their spectral properties. Because rates of regrowth vary depending on soil fertility and previous land use history, these successional groupings do not necessarily correspond with specific forest age classes, but rather indicate early, intermediate, and advanced successional stages. In our study in eastern Pará, where rates or regrowth were slow due to sandy soils and intensive land use histories, 40-70 years were required to reach advanced successional stages, and these were still spectrally distinguishable from mature forest.

Six LBA bolsistas participated in this project, supervised by the ND-02 team of coPIs. Two of the research technicians hired by this project were matched with graduate programs in fields closely related to this research. They are now working on graduate degrees in Brazilian universities. Two Brazilian and one American student completed graduate degrees programs (one Ph.D. and two masters degrees) while working on this research project. The PI served on three Ph.D. graduate exam committees in Brazil. Six original research papers and two synthesis papers have been published or are in press at this time. Additional manuscripts are still being prepared.