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# "Human Impacts on Soil Carbon Dynamics of Deep-Rooted Amazonian Forests" (#NAGW-2750)

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# "Effect of Land Use Change on the Carbon Cycle in Amazon Soils" (#NAGW- )

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## Executive Summary

In this report, we describe the considerable progress we have made towards completing the carbon budgets for selected forests and pastures sites in eastern Amazonia. We have sampled three primary forest and three pasture plots at the Fazenda Vitoria, near Paragominas, a logging and ranching center in the Brazilian state of Pará. Our findings are preliminary, partly because 14C data are so far available for only one replicate of each land use, and partly because we have identified the additional measurements needed to further constrain the model used to integrate the 14C data and our other soil measurements.

One of the pastures under study was cleared in 1975; our 14C and 13C measurements show not only that it has lost much of the labile components of forest soil carbon, but also that little new carbon has been added to the SOM from pasture vegetation. By using isotopes to study rates of soil C turnover and by extending our studies of the soil down to 8 m depth, we can show that most of the turnover occurs near the surface, most of the long-term storage of C occurs below 1 m, and both surface and deep soils are losing C in the pasture. Our preliminary estimate of loss of C from the pasture soil during the last 17 years, based on a model constrained by several different field measurements, is 2.7 kg C m-2, about one-third of which was lost from soil below 1 m depth. This loss represents about 10% of the forest soil C inventory. We also estimate that the pasture soil is still losing about 0.09 kg C m-2 yr-1 in 1992.

As we scale-up from our Paragominas study site, some surprises have been encountered. Time series analyses of Landsat TM imagery reveal extensive selective logging in the study region that virtually disappears from the images within a few years of cutting. Field sampling indicates that, counter to our earlier prediction, forest rooting zones extend to at least 8 meters even on very sandy soils. Finally, our Amazon-wide GIS database demonstrates that roughly half of the Basin has a severe seasonal drought but only one half of this seasonal area reveals substantial leaf-shedding in response to drought. These data lead us to believe that the deep-rooting phenomenon is widespread in the Basin.

## Introduction

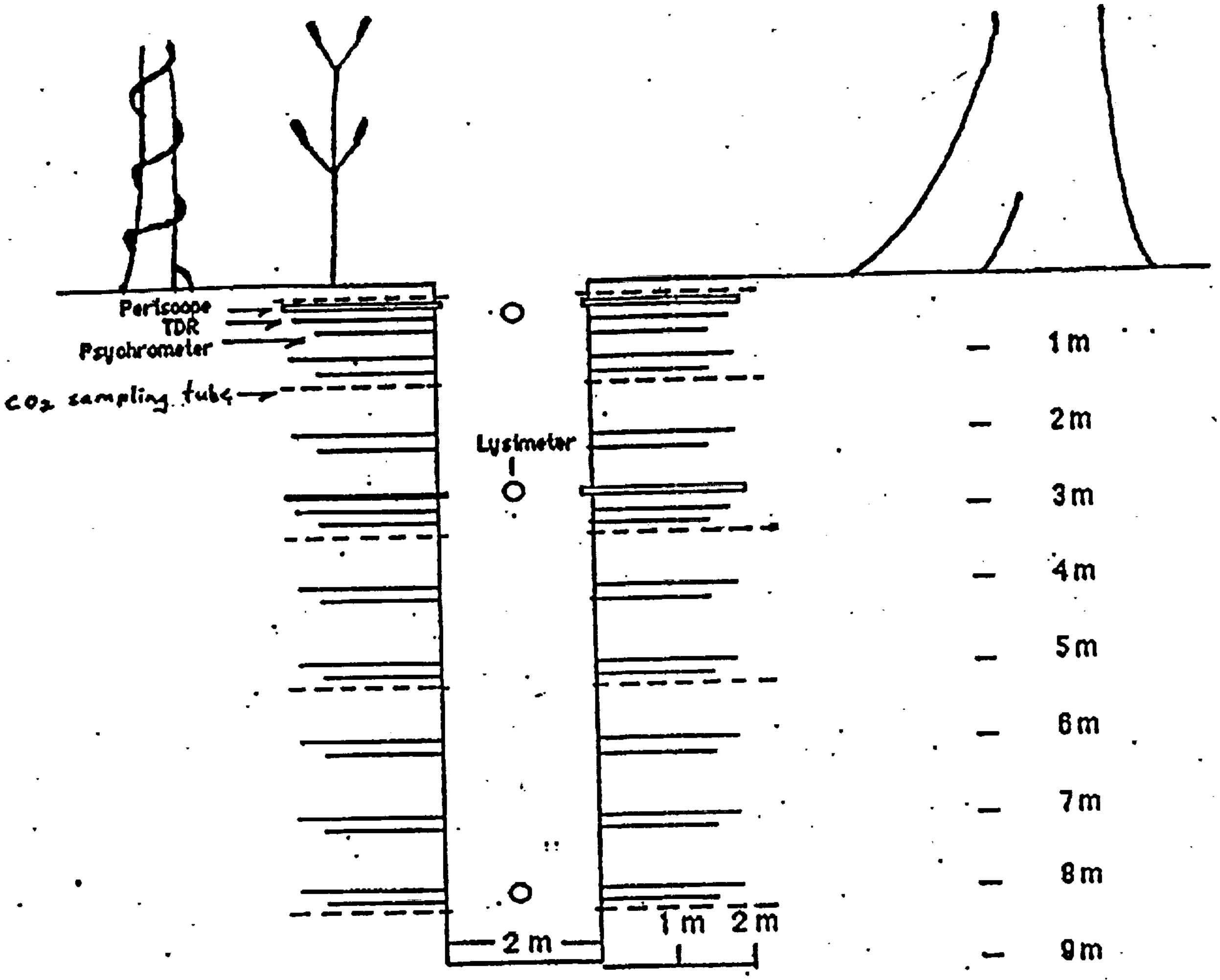
The main objective of these NASA-funded projects is to improve our understanding of land-use impacts on soil carbon dynamics in the Amazon Basin. Soil contains approximately one half of tropical forest carbon stocks, yet the fate of this carbon following forest impoverishment is poorly studied. Our mechanistic approach draws on numerous techniques for measuring soil carbon outputs, inputs, and turnover time in the soils of adjacent forest and pasture ecosystems at our research site in Paragominas, state of Pará, Brazil. We are scaling up from this site-specific work by analyzing Basin-wide patterns in rooting depth and rainfall seasonality, the two factors that we believe should explain much of the variation in tropical soil carbon dynamics.

In this report, we summarize ongoing measurements at our Paragominas study site, progress in employing new field data to understand soil C dynamics, and some surprising results from our regional, scale-up work.

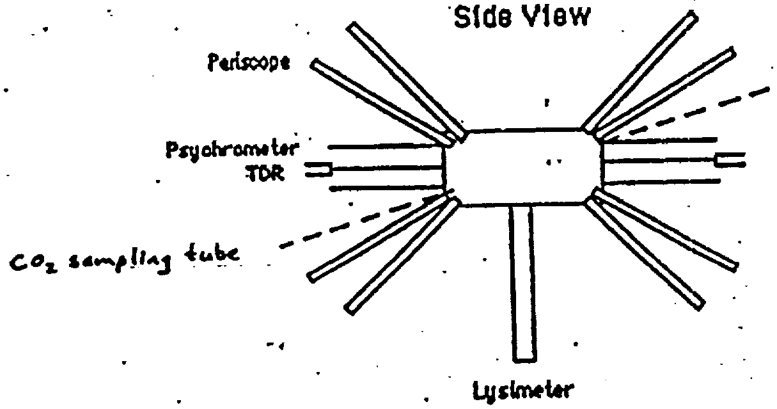
## Measurements Underway at Fazenda Vitoria, Paragominas, Brazil

Fluxes of CO2 and depth profiles of pCO2. Flux measurements are made by circulating air between a LiCor CO2 analyzer and PCV chamber consisting of a PVC ring (20 cm diameter X 10 cm height) and a vented PCV cover (10 cm height). The CO2 flux is calculated from linear regression of the accumulation of CO2 within the chamber during a 5-minute period following placement of the cover over the ring. A battery-operated pump maintains a flow of 0.7 liters/min to and from the chamber and the LiCor. Varying the flow rate from 0.4 to 1.2 liters/min had no detectable effect on measured flux rates. Eight flux measurements are taken per site and date; coefficients of variation are typically 30%.

Syringe samples (3 cc) are drawn from stainless steel tubes (2 m X 1/8 inch OD) inserted into the soil pit walls (Fig. 1). Samples of 1 cc are injected into a stream of zero air passing through the LiCor. The zero air is produced by filtering air drawn from the pump



Side View



Top View

Fig. 1 Design of deep soil shafts at the Fazenda Vitoria used for sampling $\Delta^{14}CO_2$ (dashed lines), coarse root biomass, root respiration, macropore water flow (lysimeters), seasonal root dynamics (periscopes), soil water content (Time Domain Reflectometry), and soil water potential (psychrometer). A wooden scaffolding (not shown) and portable work platforms provide access to any depth. Access to the shaft is from one side only. Rain and animals are kept out of the shafts with suspended plastic rooves and nylon lids (not shown).

through a soda lime scrubber. As the pulse of syringe air containing CO2 in the soil atmosphere passes through the LiCor, a peak is recorded with a datalogger. Injections of 0.5 to 3.0 cc of a standard (2.5% CO2 in air) are similarly injected to produce a calibration curve.

Isotopic Analyses of Soils and CO2. Soil samples have been obtained from three pits in pastures, three in primary forests, and three in secondary forests for 14C analysis at Lawrence Livermore National Laboratory. Soil samples are first fractionated by density and then by acid and base treatments (Trumbore et al., 1991). Stainless steel bottles holding about 0.5 L air were filled with air samples removed from the stainless steel tubes in the walls of three pits in pastures and three in primary forests. These samples are also being analyzed for 14CO2.

Coarse root biomass Root biomass in each ecosystem is measured to a depth of 8 m through excavation of 2 x 1 m shafts. All of the coarse roots (>2 mm diameter) encountered in these shafts are sorted into size class, cleaned, dried and weighed. Estimates are complete for mature forest (n=6), degraded pasture (n=4), and secondary forest (n=4).

Fine root biomass and production. Fine root production, the largest input of C to the soil, is also one of the most difficult ecosystem parameters to measure (Nadelhoffer & Raich 1992). In Amazônia, it has been measured only in the mature forests of San Carlos, Venezuela, using a maximum sampling depth of 50 cm (Vitousek and Sanford 1986, Jordan and Escalante 1980, Cuevas and Medina 1988). In Paragominas, we are measuring fine root production to 6 m depth in mature forest and degraded pasture using a combination of root phenological observations from root periscopes(Richards 1984) and sequential coring. The periscope data tell us when live fine root biomass reaches maximum and minimum levels each year, at the end of the wet and dry seasons, respectively We use these times to sample the vertical profile of live and dead fine root biomass with 36 auger borings per ecosystem. Fine root production from one sampling period to the next is calculated for each sampling depth as the sum of significant changes in live and dead root mass plus the change associated with decomposition. We arrive at the latter term by measuring the rate of fine root decomposition in buried nylon screen bags and multiplying this rate by the average dead root biomass for the two sampling periods. In sum, fine root production (frp) over a time interval (t) is a function of changes in live fine root biomass (lfrb), dead fine root biomass (dfrb) and decomposition (d):

$$frp_t = \Delta lfrb + \Delta dfrb + ((dfrb_0 + dfrb_t)/2)*d.$$

Fine root washing, sorting and weighing is extremely time-consuming and has become the rate-limiting step in our production estimates. Approximately two person-years are required to process the samples from a single sampling period, and we have not yet completed the first sampling (conducted in December, 1991) or the second sampling (conducted in July, 1992). Our production estimate during the grant period will be based on the completed analyses of these two sampling dates plus samples to be taken in December, 1992.

In a pilot study of fine root decomposition, we have found that dead fine roots placed in fine-mesh nylon bags persist for several months in the soil. Less than 10% of biomass was lost from samples left in the soil for three months. We are now installing the full decomposition study and will have one of the first estimates of fine root decomposition from the Amazon, and the only estimate below 50 cm depth.

Above-ground litter production. Above-ground litter production in each ecosystem is measured with thirty randomly-placed, 0.25-m2, elevated screen traps that are emptied at 2-week intervals. In the pasture, where litter traps are unfeasible because of dense vegetation, 0.5-m2 plots are established from which we clip dead grass leaves and carefully gather leaf litter from the soil surface at 2-week intervals. Coarse litter production, including twigs and branches greater than one cm in diameter, is measured at the same interval using belt transects (1 x 50-m).

Ecosystem floor: Mass of the litter layer ("floor") of each ecosystem is measured monthly through destructive sampling of thirty 0.5-m2 plots. Decomposition of the ecosystem floor is estimated as the sum of litter production and the loss of mass from the floor. Decomposition is zero only if litter production is accompanied by an equal increase in mass of the ecosystem floor.

## Qualitative Interpretation of Isotopic Analyses

A few examples of our data illustrate the power of our approach. Near the soil surface, the Δ14C of the dense fraction of the SOM (i.e., mineral soil organic mater with density > 2.0 g/cc, which excludes all vascular plant material and charcoal) is about +150o/oo in the forest, but only about +30o/oo in the pasture (Table 1). Hence the surface soil of the forest must include a substantial portion of post-1960 carbon that bears the signature of elevated 14C levels. In contrast, the 17-yr old pasture must have lost most of the post-1960 that it once had, and the amount of new carbon added from pasture vegetation sources in the past 17 years must be small. Our inference from the 14C data, that little new carbon has been added to the pasture SOM, is corroborated by comparison of the 13C content of surface pasture and forest SOM. We assume that the pasture soil once had a 13C signature similar to the present forest soil (about -28o/oo) that reflects the Δ13C signature typical of forest plants with a C-3 type metabolism. The current Δ13C of the SOM near the surface in the pasture has declined only slightly, to about -25o/oo, indicating that about 80% of the C originated from C-3 plants and only about 20% of the C could have originated from C-4 pasture grasses that typically have Δ13C signatures of -15o/oo (Luiz Martinelli, Centro de Energia Nuclear na Agricultura (CENA), pers. comm.). For both forest and pasture soils, the Δ14C declines with depth and both show very old carbon predominating at 8 m depth.

The Δ14CO2 content also reveals an interesting story. At 35 cm depth in the pasture soil, the Δ14CO2 is only +140, indicating that a source of C older than 30 years (i.e., that was fixed before bomb testing) must be contributing to the CO2 within the soil to bring the Δ14CO2 value below modern levels of +150o/oo. If the pasture soil is not sequestering much modern carbon, as we concluded from the 14C and 13C signatures of the SOM, and if it is producing CO2 that originated from old carbon, then it is probably still losing soil carbon.

Below 1 m depth, both forest and pasture soils contain CO2 with a Δ14C value greater than +150o/oo. This can be true only if a source of carbon is being decomposed that was fixed 10-30 years ago, when the Δ14C of the atmosphere was above its current value of +150o/oo. We believe that the most likely source of this C is decomposition of coarse (>1 mm diameter) deep roots. In the forest,

Table 1. Comparison of the isotopic composition of soil $CO_2$ and soil organic matter (SOM) in one forest site and one pasture site at Fazenda Vitoria, Paragominas, Brazil. Data on $^{13}C$ are courtesy of Luis Martinelli, CENA, Piracicaba, Brazil.

| Depth (cm) | $\Delta^{14}CO_2$(°/oo) | | $\Delta^{14}C$ in SOM (°/oo) | | $\delta^{13}C$ in SOM (°/oo) | |
|---|---|---|---|---|---|---|
| | Forest | Pasture | Forest | Pasture | Forest | Pasture |
| 1 | | | 163 | 30 | -27.8 | -24.8 |
| 4 | | | 110 | 30 | | |
| 8 | | | 64 | 54 | | |
| 13 | | | 36 | -59 | | |
| 35 | 155 | 141 | -102 | -104 | | |
| 55 | | | -198 | -448 | -25.9 | -25.3 |
| 100 | 166 | 146 | -552 | -628 | -25.2 | -25.4 |
| 300 | 168 | 161 | -753 | -809 | -23.9 | -23.7 |
| 500 | 173 | 171 | | -736 | -23.3 | -23.6 |
| 800 | 171 | 173 | -739 | -796 | -24.8 | -23.4 |

roots would be expected to turnover regularly, with coarse roots having a longer residence time than fine roots. Pasture plants, however, do not produce many deep roots, so the probable source of the elevated 14C in the CO2 at depth in the pastures is decomposition of remaining roots of forest trees.

## Modelling Quantitative Estimates of C Pool Sizes and Transfer Rates

In the examples above, we give only qualitative interpretations of the important fractions of SOM and sources of CO2. By itself, a measure of Δ14C ofSOM or CO2 usually indicates qualitatively which age class must be present, but several quantitative combinations of age classes could yield the same integrated Δ14C value. A more quantitative interpretation of SOM 14C data requires an understanding of the partitioning of carbon among labile and refractory soil pools. The 14C content of rapidly cycling components reflects the changes in atmospheric 14C content over the past thirty years, while more refractory components are affected very little by bomb 14C. By using other information to help constrain the sizes and 14C contents of some pools, the dynamic makeup of the soil carbon can be determined more unambiguously.

To find the most probable combination of young, intermediate, and old carbon that produces the observed Δ14C, we use a model that is constrained by other measurements and some assumptions. Following the examples of Jenkinson and Raynor (1977), Parton et al. (1987), and Van Breemen and Feijtel (1990), our model defines three operationally distinct fractions of soil organic matter with active (annual), slow (decadal) and passive (centennial - millennial) residence times. We also divide the soil into five depth increments and we model the three fractions for each depth increment (Fig. 2).

For the forest soil model, we assume that SOM is at steady state. While this may not be true, (there is no prima facie reason why tropical forest soils should necessarily reach steady state), the rate of possible C accumulation is probably very small relative to the error terms of input data and uncertainties of estimates resulting from other assumptions of the model. The steady state assumption greatly simplifies the model, so we adopt it at present. However, the work we are now doing lays the groundwork for us to return to the study sites before we retire from scientific research

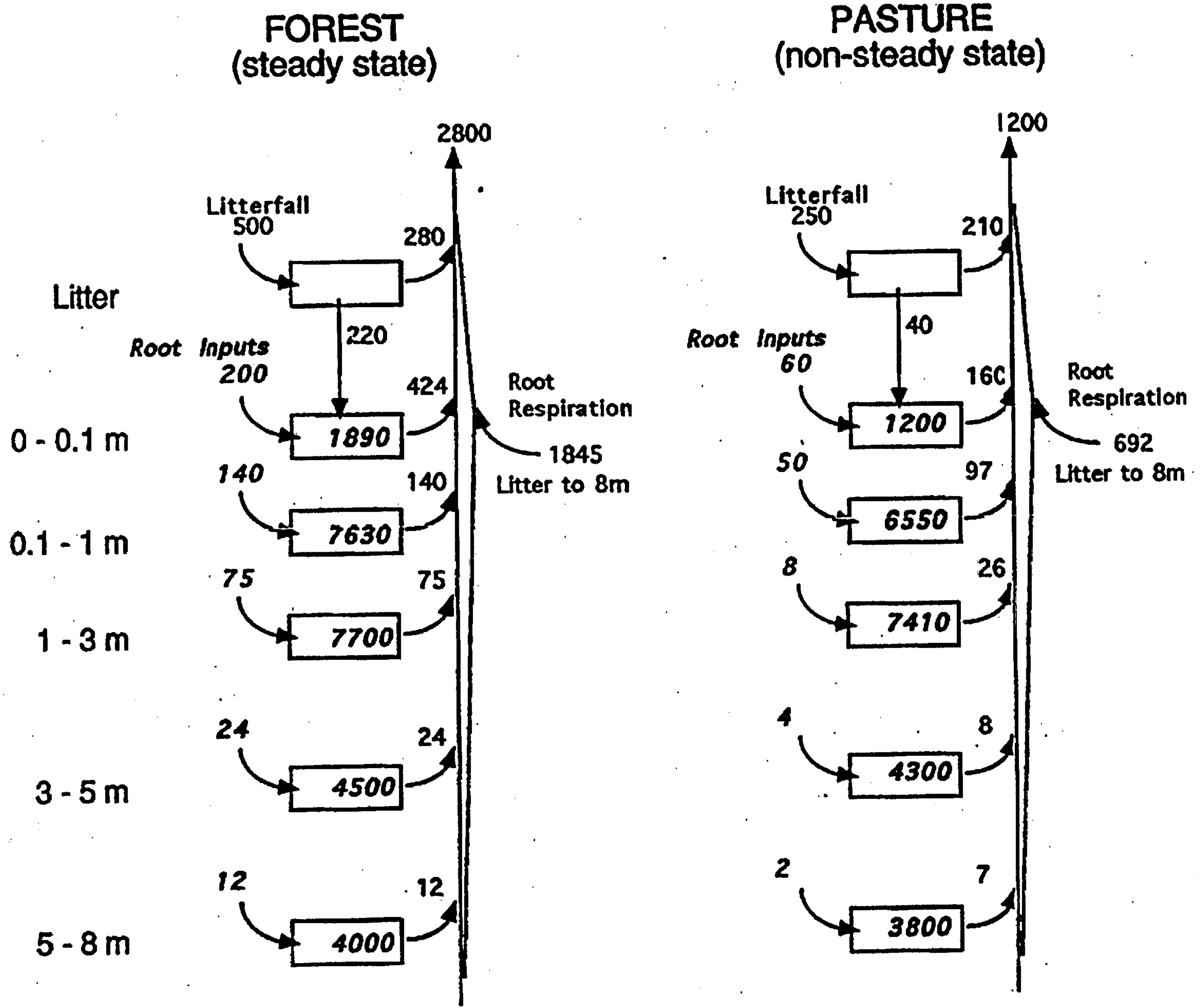


Figure 2. Preliminary modeling results based on wet season field measurements in Fazenda Victoria, Paragominas, Brazil. Fluxes are given in gC/m2/a ; reservoirs are in gC m-2. Values used in the Figure are calculated using the model.

(maybe in the year 2020), analyze the isotopic signature of the SOM, and calculate rates of C accumulation without the steady state assumption in our model.

For the present, the model is further constrained by measured inputs and outputs of C. Litterfall is measured at each forest and pasture plot. We assume that litter inputs are only important in the upper 10 cm of soil and that nearly all inputs to the deep soil are from fine root turnover. Input of C to the soil via turnover of roots are estimated by assuming that the input is equal to the annual production of fine roots (<1 mm diameter) measured by sequential coring. The sequential coring samples are currently being processed, so for calculations in this proposal, we assume that peak fine root biomass, measured near the end of the wet season, provides a reasonable estimate of annual C input to the soil from roots.

Outputs of C occur mainly as the production of CO2. We assume that leaching losses of DOC are negligible. Production of CO2 occurs via root respiration and microbial decomposition of SOM. Total production of CO2 is measured by CO2 flux measurements in flux chambers at the soil surface, using aLiCor CO2 analyzer. To partition the CO2 production measured at the soil surface into production rates at each depth increment, we also calculate CO2 production as a function of depth. We remove syringe samples of soil gases from stainless steel tubes inserted horizontally 2 m into the soil pit wall at 0.35, 0.55, 1.0, 3.0, 5.0, and 8.0 m depth (in some cases we have found that a 2 m tube is not long enough to avoid effects of exchange of gases acrossthe soil pit wall; however, we can correct for this artifact, using concentration profiles and estimates of diffusivity). The syringe samples are analyzed for concentrations of CO2 and 222Rn (Fig. 3). Knowing the rate of 222Rn production from decay of 226Ra and the profile of 222Rn concentrations within the soil, we estimate the effective diffusivity of gases within each depth increment of the soil (Dorr and Munnich, 1990). Using this estimate of effective diffusivity and the profile of pCO2, we calculate production of CO2 as a function of depth. If SOM is assumed to be at steady state (which is clearly not valid for the pasture, but it may be nearly valid for the forest), then the difference between total CO2 production and total C inputs to the soil provides an estimate of root respiration.

We have pCO2 profiles and CO2 flux measurements from February and May, 1992, which were the beginning and end of the wet

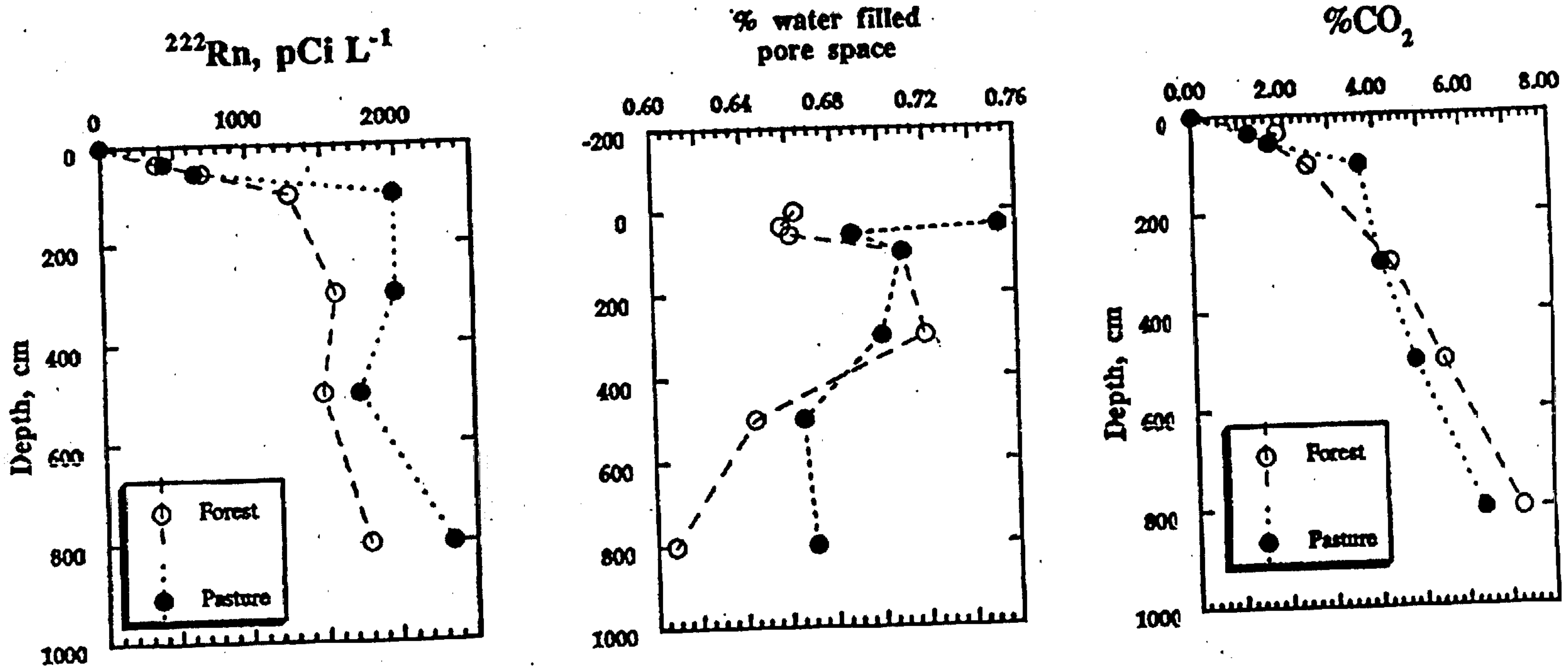


Figure 3. Depth profiles of measured $^{222}$Rn, water-filled pore space, and p$CO_2$ in one forest and one pasture site.

season, respectively. We will obtain more measurements in November, 1992, which is near the end of the dry season, which may necessitate lowering the annual estimates of CO2 production. Because the estimates of CO2 production play a key role in this model, we would prefer to have monthly estimates, so that the full seasonal variation can be included in our annual budgets. There were no significant diel effects on CO2 fluxes during the wet season -- we shall also measure diel effects in the dry season.

Once we have estimates of inputs and outputs of C for the forest soil, we have the necessary constraints to use the 14C data in a time dependent model to partition the soil C into active, slow, and passive pools. The amount of carbon in each of these pools was varied until the observed Δ14C signatures of SOM and CO2 were reproduced.

Most of the carbon in the top 1 m is in the active (annual) and slow pool (decadal), whereas most of the carbon at depth is in the passive (millennial) pool (Table 2). A very long residence time had to be used for the passive pool at depth because the very low Δ14C values indicate that most of the SOM there is essentially radiocarbon-free. The reason that this finding does not contradict our finding that CO2 production at depth is strongly influenced by more modern carbon (probably decomposition of coarse roots) is that the rate of CO2 production at depth is very small relative to the SOM inventory. About 90% of the C at 8 m is very old, but decomposition of the remaining 10% strongly influences the Δ14CO2 signature.

Using this "best fit" model for forest soil C fraction sizes and residence times, we then reran the model for the pasture site, cutting C inputs in 1975 (the date that the site was converted from forest to pasture) to 40% of forest C inputs in the top 1 m of soil and 10% below 1 m (Fig. 2). These values are consistent with differences in fine root biomass at these depths between the forest and pasture sites. The model was then used to calculate CO2 production from decomposition of SOM in the pasture. We assumed no change in the apportionment of new carbon among the three soil C fractions or in their decay constants. As inputs rates are the only parameter that changed, the inventory of carbon in the model declines with time until, eventually, a new, lower steady state would be reached if the site were maintained as a degraded pasture (of course, secondary succession would probably begin before such a new steady state were reached). The rate of decline in soil C

Table 2. Partitioning of forest soil organic matter into active, slow, and passive fractions.

| Depth | Active | | Slow | | Passive | |
|---|---|---|---|---|---|---|
| (cm) | % of total | Residence time (yrs) | % of total | Residence time (yrs) | % of total | Residence time (yrs) |
| 0-10 | 23 | 1 | 60 | 40 | 17 | 3500 |
| 10-100 | 1.5 | 3 | 67.5 | 50 | 31 | 50000 |
| 100-300 | 3 | 5 | 17 | 50 | 80 | 50000 |
| 300-500 | 4 | 5 | 5 | 50 | 91 | 50000 |
| 500-800 | 3 | 10 | 7 | 50 | 90 | 50000 |

Table 3. Comparison of modeled and observed $\Delta^{14}C$ of soil $CO_2$ and soil organic matter (SOM).

| Depth (cm) | $\Delta^{14}CO_2$ (°/oo) | | $\Delta^{14}C$ in SOM (°/oo) | |
|---|---|---|---|---|
| | Modelled | Observed | Modelled | Observed |
| Forest: | | | | |
| 0-10 | +162 | no data | +89 | +102 |
| 10-100 | +159 | +155 | -162 | -160 |
| 100-300 | +183 | +166 | -658 | -650 |
| 300-500 | +106 | +170 | -760 | -750 |
| 500-800 | +213 | +170 | -757 | -740 |
| Pasture: | | | | |
| 0-10 | +160 | no data | +46 | +45 |
| 10-100 | +137 | +140 | -228 | -275 |
| 100-300 | +143 | +153 | -727 | -720 |
| 300-500 | +181 | +166 | -819 | -810 |
| 500-800 | +196 | +189 | -801 | -800 |

depends on the residence time of the SOM pool; annual cycling pools respond almost instantaneously, while decadal pools are still losing C after 17 years.

This simple model for the conversion of forest to pasture does well at reproducing the 1992 observed 14C contents of both SOM and respired CO2, as well as reproducing the changes in surface 13C values (Table 3). The model was then used to calculate CO2 production from decomposition of SOM in the pasture. As in the steady state (forest) model, C losses are calculated as the decomposition rate times the inventory, but in the pasture, losses exceed inputs. The model calculates that the pasture soil has lost 2.7 kg C m-2 since 1975 and is currently losing 85 g C m-2 yr-1. Of course these are a very preliminary estimates; we have proposed to NASA several new measurements that we believe would help to further constrain the model. Among the constraints predicted by the model but as yet unmeasured are the 13C content of CO2 resulting from soil decomposition (we have plans for these measurements in collaboration with Luis Martinelli at the Centro de Energia Nuclear naAgricultura (CENA), Piracicaba, Brazil). Losses of carbon and the isotopic content of respired carbon during long-term laboratory incubations of soils,currently being conducted by Elizabeth Holland and Alan Townsend at NCAR, should also be predicted by the model.

A loss of 2.7 kg C m-2 is about 10% of the forest soil carbon inventory. This is a significant amount of carbon if it applies generally to forest-pasture conversions in the area, but it is probably too small to be reliably detected bystandard soil C inventory analyses. Most soil C inventories, including our own,that include sampling to 8 m would have an error term of at least 10%. In addition to the usual problems of appropriate depths, changing erosional surfaces, and soil compaction that beset inventory analyses, differences of only a few hundredths of a percent of C concentration can have a large effect on inventory estimates when applied to very deep soils. Although many assumptions are built into our modelling estimates of soil C loss, we have confidence that they are realistic because the model is constrained by several directly measured parameters, including the very compelling data on soil C isotopes.

## Regional Studies

One objective of our NASA-funded research is to help develop a basis for assessing the regional variation in Amazon forest soil carbon dynamics. We are approaching this study by developing a Basin-wide GIS database with NDVI seasonality, drought intensity, and soils data layers, through more detailed evaluation of Landsat imagery, and through field measurements.

High resolution Satellite Data We have selected and purchased two Landsat TM scenes of the region immediately to the west of Paragominas from INPE. The imagery was chosen to see if any subtle differences in canopy reflectivity could be found that might be associated with the presence orabsence of the deep root phenomenon. The dates of the imagery are May and August 1991: the end of the rainy season and the middle of the dry season. Both images were relatively free of clouds. To date these images have been radiometrically corrected using a bulk atmospheric correction and a subset or portion of the images have been geographically co-registered.

Earlier imagery of the region from other projects have also been pulled together. These include Landsat MSS data from August 6, 1981 and Landsat TM data from September 1 1988 and from July 17, 1986.

Three different transforms of the 1991 data, first, into the Normalized Difference Vegetation Index (NDVI), second, into the Moisture Stress Index (Rock) MSI indexes and third into the tasselled cap transform of brightness, greenness and wetness. Wetness has been described by Cohen as more accurately describing stand maturity which, in the Pacific Northwest US, is shown in imagery as variations in the amounts of shadow in the canopy. This was thought to show promise in Amazonia as well because a typical undisturbed tropical moist forest as seen in TM imagery typically has a salt and pepper appearance due, presumably,to canopy emergent with fully illuminated tops (the salt) and an immediately west adjacent shadow (the pepper).

We have found intensification of a newer type of forestry activity which may make the search for regions immediately adjacent to Paragominas with differing phenology related to deep roots more problematic. Specifically, there are in the new imagery vast areas that have been perturbed by selective logging. We have found that the amount of selective logging affects an area about the same as land newly cleared for pasture and fields. The amount of selective logging in a test region of 2,500 km sq in 1991 (3.2%) was about double what was seen in imagery of the same region five yearsearlier (1.4%). Also, selective logging in 1991 was more widely geographically distributed than it was in 1986 with more logging occurring farther away from the urban center of Paragominas than before. The features of selective logging visible in the 1986 imagery were not apparent in the same locations in 1991 imagery. We found that little land selectively logged, perhaps 10%, is converted to pasture and that there was virtually no overlap between sites logged in 1986 and sites logged in 1991. At this point, it is unclear how long the visual clues of selective logging remain apparent in the satellite imagery from following years. This could be explored with an improved time series of TM or SPOT data but this is outside the realm of this research.

Consequently, we do not know now from satellite which areas in this region have been disturbed by selective logging and are therefore unable to say whether changes in phenology of canopy reflectivity are due to differences in rooting depth or due to recent land use history. We will continue to try to isolate stands that are known from ground work to be free of the effects of selective logging to pursue our understanding of the finer scale features of canopy phenology.

Low Resolution Satellite Data We currently have two varieties of GVI (Global Vegetation Index) data for the globe. This data, at 15 km resolution allows biweekly or monthly examination of the greenness index (NDVI) at continental or global scales. To date we have used this data in this research to create seasonality regions in Amazonia that are defined by the variation in the greenness index over the course of a year created by averaging three or 5 year GVI data sets together. We will, upon receipt from Sam Goward of the Univ. of Maryland of a third GVI data set, develop a similar map based on his soon to be released 9 year inter-calibrated GVI data set.

We will integrate in the GIS, the GVI data sets that show basin-wide canopy seasonality with precipitation data bases. One such data base has been obtained from Elson Dias (collaborator at Embrapa-Cpatu) and another is a subset of a global precipitation data base from NOAA. We should then be able to show on a point by point (15 km by 15 km) basis for the entire Basin the correlation between rainfall patterns and canopy phenology. Where the canopy phenology follows monthly rainfall pattern we hypothesize that the deep rooting phenomenon does not occur. When canopy vigor remains high despite sesaonal declines in rainfall, we hypothesize that the deep rooting phenomenon is occuring.

Field Work: We predict that the effective rooting depth of Amazon forests varies partially as a function of soil texture. In coarse soils with low water holding capacity, forests may be unable to support a deep root system, and should exhibit greater leaf shedding in response to seasonal drought. We have therefore initiated a study to compare the profiles of fine roots on adjacent sand and clay soils. On the two study sites we visited (Rio Capim, 80 km west of Fazenda Vitoria, and Porto Trombetas, 1500 km NW of Paragominas), we discovered that sandy soils are never more than 8 m above the water table. In soil samples extracted with long-handled augers, and protected from contamination by shallow soil with PVC liners, roots were encountered to 8 m depth on both sand and clay soils on both of these sites. If this pattern holds for other regions, then the deciduous forests of Amazônia may be restricted to areas where hardpans prevent vertical penetration of roots, and not to areas of sandy soil as we had predicted.

## Future Research

In the coming year, we intend to conduct soil respiration and pCO2 measurements near the end of the dry season (November). We will also continue to process our samples for isotopic analyses and for root biomass.

We have submitted a new joint grant proposal to fill some gaps that we have identified in our carbon model and to expand our studies to secondary forests and managed pastures. Briefly, we have proposed four new foci: A) New measurements, including monthly measurements of soil respiration and litter leaching, aging of roots by size class, and direct measurements of root respiration, that would further constrain and improve our preliminary estimates of the C budgets of the primary forest and pasture sites already being studied; B) Expansion of our study to include investigation of the rates of C sequestration in secondary forests, which are an important and growing component of the landscape; C) Expansion of our study to include both actively managed "reformed" pastures and minimally managed degraded pastures; and D) Regional studies of lower sampling intensity that permit comparison of the C dynamics we observe in eastern Amazonia to the C dynamics in other parts of Amazonia where annual precipitation and seasonal distribution of precipitation vary.