

Effect of Land Use Change on the Carbon Cycle in Amazon Soils

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Susan E. Trumbore, Principal Investigator
Department of Earth System Science
University of California
Irvine, CA 92717-3100
714-856-6142 (phone); 714-856-6142 (FAX)
setrumbo@uci.edu

Eric A. Davidson, Co-Principal Investigator
The Woods Hole Research Center
P.O. Box 296
Woods Hole, MA 02543
508-540-9900 (phone); 508-540-9700 (FAX)

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The overall goal of this study was to provide a quantitative understanding of the cycling of carbon in the soils associated with deep-rooting Amazon forests. In particular, we wished to apply the understanding gained to answering two questions: 1) what changes will accompany the major land use change in this region, the conversion of forest to pasture? and 2) what is the role of carbon stored deeper than one meter depth in these soils? To construct carbon budgets for pasture and forest soils we combined: measurements of carbon stocks in above-ground vegetation, root biomass, detritus, and soil organic matter; rates of carbon inputs to soil and detrital layers using litterfall collection and sequential coring to estimate fine root turnover; ^{14}C analyses of fractionated SOM and soil CO_2 to estimate residence times; ^{13}C analyses to estimate C inputs to pasture soils from C-4 grasses; soil pCO_2 , volumetric water content, and radon gradients to estimate CO_2 production as a function of soil depth; soil respiration to estimate total C outputs; and a model of soil C dynamics that defines SOM fractions cycling on annual, decadal and millennial time scales.

The following manuscript has been submitted to *Nature* for review. As it succinctly summarizes the major results of our research, it serves as an excellent executive summary for our final technical report. Several other manuscripts are in preparation which describe in greater detail the methodologies and the results of our work. A list is appended of papers submitted and manuscripts in preparation. Also appended are a list of abstracts and copies of abstracts of papers presented or submitted for future presentation at professional meetings.

Please note that this project was carried out jointly with Dr. Daniel C. Nepstad, of The Woods Hole Research Center, (NAGW-2750; "Human Impacts on soil carbon dynamics of deep-rooted Amazonian forests"). We are coauthors on most of the papers and abstracts. Accordingly, this final report was prepared jointly, with equal participation of all of the PI's. A report of very similar substance will be submitted under separate cover for NAGW-2750.

Manuscripts submitted:

Nepstad, Carvalho, Davidson, Jipp, Lefebvre, Negreiros, Silva, Stone, Trumbore, and Vieira. The deep soil link between water and carbon cycles of Amazonian forests and pastures. *Nature*.

Nepstad, Jipp, Moutinho, Negreiros, and Vieira. The loss and recovery of forest health in seasonally-dry Amazonia: canopy seasonality, biomass and ants. In Rapport (Ed.) *Monitoring and Evaluation of Major Ecosystem Health*, NATO-ARS Series, Springer-Verlag, in press.

Manuscripts in preparation:

Davidson and Trumbore. Production of CO₂ in deep soils of the eastern Amazon. *Tellus*.

Trumbore, Davidson, and Nepstad. A below-ground budget of carbon cycling in forests and pastures of the eastern Amazon. *Global Biogeochemical Cycles*.

de Camargo, Martinelli, Trumbore, and Nepstad. Carbon turnover in forest and pasture soils of the eastern Amazon estimated from ¹³C and ¹⁴C. *Plant and Soil*.

Abstracts submitted and appended:

Camargo, P.B. de, S.E. Trumbore, E.A. Davidson, D.C. Nepstad, and L.A. Martinelli. $\Delta^{14}\text{C}$, $\delta^{13}\text{C}$ and C inventory differences between forest and pasture soils of eastern Amazonia. American Geophysical Union, San Francisco, CA, December 1993.

Camargo, P.B. de, L.A. Martinelli, S.E. Trumbore, E.A. Davidson, and D.C. Nepstad. Evaluation of C and N inventories, $\delta^{13}\text{C}$ and $\Delta^{14}\text{C}$ in deep soils from mature and regrowing forest (Capoeira), and pasture of eastern Amazonia. International Congress on Geochemistry, Berkeley, CA, May 1994.

Davidson, E.A. and S.E. Trumbore. Soil respiration and soil CO₂ concentration gradients in forests and pastures of the Amazon. American Society of Agronomy, Minneapolis, MN, November 1992.

Davidson, E.A., S.E. Trumbore, and D.C. Nepstad. Losses of carbon from pasture soils of the eastern Amazon estimated from measurements of isotopes, fluxes, and inventories. International Symposium: Soil Processes and Management Systems, Greenhouse Gas Emissions, and Carbon Sequestration, Columbus, OH, April 1993.

- Davidson, E.A., S.E. Trumbore, and D.C. Nepstad. Soil carbon dynamics in forests and pastures of the eastern Amazon. 1993 Annual Meeting, Ecological Society of America, Madison, WI, August 1993.
- Davidson, E.A., S.E. Trumbore, and D.C. Nepstad. Soil carbon dynamics in forests and pastures of the eastern Amazon. First GCTE Science Meeting, Woods Hole, MA, May 1994.
- Davidson, E.A., S.E. Trumbore, and D.C. Nepstad. Soil carbon dynamics in forests and pastures of the eastern Amazon. 1994 Annual Meeting, Ecological Society of America, Knoxville, TN, August 1994.
- Trumbore, S.E., E.A. Davidson, D.C. Nepstad, P.H. Jipp, and L.A. Martinelli. Production of CO₂ in pasture and mature forest soils of eastern Amazonia. American Geophysical Union, San Francisco, CA, December 1993.
- Trumbore, S.E. Recent applications of accelerator mass spectrometry ¹⁴C measurements to soil organic matter dynamics. ACS Symposium on Applications of Nuclear Chemistry, San Diego, CA, March 1994.

The Deep-Soil Link Between Water and Carbon Cycles
of Amazonian Forests and Pastures

D. C. Nepstad*¶, C. R. de Carvalho†; E. A. Davidson*, P. H. Jipp*§, P. A. Lefebvre*, G.
H. Negreiros*, E. D. da Silva†, T. A. Stone*, S. E. Trumbore‡, & S. Vieira*

*Woods Hole Research Center, Woods Hole, MA, 02543, USA.

†EMBRAPA-CPATU, C.P. 48, Belém, Pará, 66.001, Brazil

‡Department of Geosciences, University of California, Irvine, CA, 92717, USA

§Present address: Department of Environmental Studies, Duke University, Durham, NC, USA.

¶ To whom correspondence should be addressed.

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Deforestation and logging degrade more forest in eastern and southern Amazonia than in any other region of the world¹⁻³. This forest alteration affects regional hydrology⁴⁻¹⁰ and the global carbon cycle¹¹⁻¹³ but our current understanding of these effects is limited by incomplete knowledge of tropical forest ecosystems. It is widely agreed that roots are concentrated near the soil surface in moist tropical forests¹⁴⁻¹⁷, but this generalization incorrectly implies that deep roots are unimportant in water and C budgets. Our results indicate that half of the closed-canopy forests of Brazilian Amazonia occur where rainfall is highly seasonal, and these forests rely on deeply penetrating roots to extract soil water. Pasture vegetation extracts less water from deep soil than the forest it replaces, thus increasing rates of drainage and decreasing rates of evapotranspiration. Deep roots are also a source of modern carbon deep in the soil. The soils of the eastern Amazon contain more carbon below 1 m depth than is present in above-ground biomass. As much as 25% of this deep soil C could have annual to decadal turnover times and may be lost to the atmosphere following deforestation.

We compared the importance of deep roots in a mature, evergreen forest with an adjacent man-made pasture, the most common type of vegetation on deforested land in Amazonia. The study site is near the town of Paragominas, in the Brazilian state of Pará, with a seasonal rainfall pattern and deeply-weathered, kaolinitic soils that are typical for large portions of Amazonia (Fig. 1, ref. 18). Root distribution, soil water extraction and soil carbon dynamics were studied using deep auger holes and shafts in each ecosystem and the phenology and water status of the leaf canopies were measured. We estimated the geographical distribution of deeply-rooting forests using satellite imagery, rainfall data and field measurements.

Roots were most abundant near the soil surface in the forest and pasture, as expected, but they were also found at depth (Fig. 2A). Root systems extended to 18 m depth in one shaft excavated in the forest. Fine root biomass was not significantly

different between forest and pasture (Fig. 2A). However, pasture plants experienced less drought stress than forest plants during the severe 1992 dry season measured as pre-sunrise xylem pressure potential (XPP_{pre}) of canopy leaves (Fig. 3A). Water vapor flux from green leaf surfaces was also higher in the pasture late in the dry season, where mean leaf resistance at mid-day was $2.1 \pm 0.3 \text{ s cm}^{-1}$ vs. 17.0 ± 3.32 in the forest. Drought stress in pasture vegetation was low because pasture plants reduce their leaf area during the dry season more than forest plants (Fig. 3B), thereby depleting soil moisture through transpiration less than the forest. Dominant plant species of the pasture, such as the grass, *Hyparrhenia* and the shrub, *Rolandra*, avoid drought by shedding leaves at mild drought stress while forest trees such as *Lecythis* and *Tetragastris* tolerate low XPP, and retain their leaves. This conclusion is supported by measurements of XPP at the leaf turgor loss point, which ranges from -3.2 to -1.5 MPa among forest species and from -1.6 to -1.0 MPa among pasture species.

Changes in soil moisture content are consistent with these observations of canopy behavior. During the 6-month dry seasons of 1991 and 1992, the soil moisture stored from 1 to 8 m declined more in the forest ($498 \pm 10 \text{ mm}$) than in the pasture ($318 \pm 28 \text{ mm}$) (Fig. 2B) because of greater water extraction in the forest. Given a smaller soil water deficit at the end of the dry season, the pasture soils recharge more rapidly in the wet season and the potential for discharge via deep seepage or as runoff is greater than in the forest. This change in recharge and seepage resulting from land-use change has important implications for local and regional hydrology.

The amount of water that leaves each ecosystem as vapor (evapotranspiration, ET) can be estimated for the dry season by adding the reduction in moisture stored in the soil to the amount of water that entered the soil as rainfall. During the 6-month dry seasons of 1991 and 1992, average daily rainfall was 0.94

mm, forest ET was 4.0 mm, and pasture ET was 3.1 mm. In the last and driest half of the 1991 dry season period, when daily rainfall averaged 0.80 mm, daily forest ET continued relatively high at 3.2 mm whereas daily pasture ET declined to 1.7 mm. These dry-season reductions in ET associated with forest conversion to pasture correspond to a 16% reduction in latent heat transfer, and are particularly important in Amazonia because of the tight link between ET and regional climate⁵⁻¹⁰. Reduced ET resulting from a decrease in water uptake from deep soil is not included in existing climate models of Amazonia, and could exacerbate the rainfall decline and air temperature increase already predicted as a result of forest conversion to pasture in the region.

Another line of evidence indicating the activity of roots deep in the soil profile is the isotopic composition of soil CO₂ and organic matter. The $\Delta^{14}\text{C}$ of SOM declines with depth as expected (Fig. 2D), indicating that the proportion of very old C increases with depth. However, the $\Delta^{14}\text{CO}_2$ remains at or above modern atmospheric levels (Fig 2E), indicating that the CO₂ is produced primarily from root respiration and from microbial decay of carbon fixed by plants within the last 30 years.

One of the implications of this deep input of soil C is that land-use change affecting root activity could also modify deep soil C stocks. The pasture soil has lost about 1.6 kg C m⁻² from the top 1 m (Fig. 2C) and changes could also have occurred at depth but be obscured by relatively large spatial heterogeneity of soil C. Other studies have shown both increases and decreases in soil C following conversion of forest to pasture¹⁹⁻²¹. Soil C inventories seldom include analyses below 1 m depth, probably because soil C concentrations decline roughly exponentially with depth and the C present in deep soils is often assumed to be inert. When integrated over a large volume, however, the soil C inventory below 1 m depth exceeds that above 1 m depth (Fig. 2C) and soil C from 0 to 8 m depth (30 kg m⁻²) is double that of the

above-ground biomass (15 kg m^{-2}). Although small changes in soil C concentration at depth are difficult to quantify reliably, the large stocks of soil C in deep soils and high concentrations of CO_2 at depth (Fig. 2E) indicate that changes in soil C and root stocks in deep soils deserve more careful study. Based on ^{14}C data, we estimate that about 10-25% of the total C in SOM between 1 and 8 m, about $2\text{-}5 \text{ kg m}^{-2}$, may be turning over on annual to decadal time scales.

Amazonian forests that depend on deeply penetrating roots to maintain evergreen canopies represent an area larger in size than Western Europe, including about half of the region's closed-canopy forests and three-fourths of the closed forest that has already been cleared (Fig. 1). The water and carbon cycles of this vast tropical forest are closely linked deep in the soil, and are modified by human land-use practices. Determination of these modifications will require accurate ecosystem models that include a better understanding of the extent and function of deep roots.

Figure Legends:

Figure 1. Major forest types and dry season rainfall of Brazilian Amazonia.

Evergreen forests in areas of pronounced seasonal drought (36% of the region) may depend on deep soil water extraction and, therefore, have water and C cycles similar to those described for the Paragominas study site (2°59'S, 47°31'W). Precipitation at the study site is highly seasonal (1750 mm annual average, <250 mm falls from July to November), and typical of the eastern and southern portions of the Basin, where most deforestation is occurring. Savannas and deciduous forests (14%) were separated from evergreen forests (75%) based on seasonal patterns of canopy greenness (as seen from satellites) and a vegetation map. Evergreen forests include areas that did not display a seasonal depression of the Normalized Difference Vegetation Index²² during the dry seasons of the period 1986-88. Maximum monthly values were used to minimize the effects of clouds and smoke. Areas cleared for agriculture and seasonally flooded land (i.e., pixels with the spectral signature of water) are adapted from Stone et al.²³. Dry season rainfall refers to the average driest 3-month period of the year²⁴. Seventy-five percent of the 212 weather stations used had ≥8 years of rainfall data. Interpolation of rainfall data was conducted using IDRISI. Shaft excavations to 8 m depth at wetter sites (Trombetas, 1°41'S, 56°26'W) and at drier sites (Santana de Araguaia, 9°33'S, 50°33'W) reveal root distributions similar to those at Paragominas. At Santana de Araguaia, annual rainfall is 1500 mm and daily rainfall is <0.5 mm during the driest 3 months. Annual rainfall at Trombetas is 2200 mm and >1.5 mm d⁻¹ during the driest 3 months, indicating that the deep-rooting phenomenon extends into areas that we classified as not depending on deep soil water.

Figure 2A-F. Vertical profiles of root, water and C parameters to 8 m soil depth in adjacent mature forest and man-made pasture near Paragominas, eastern Amazonia. Points are means and bars are one standard error of measurements in 3 soil shafts per ecosystem, except for fine root biomass, where $n=36$ auger soil samples in the forest and $n=24$ in the pasture. (A) Live fine root biomass (diameter ≤ 1 mm). (B) Average soil water reduction during the 6-month dry seasons of 1991 and 1992. (C) Soil C stocks (not including root C). (D) $\Delta^{14}\text{C}$ of soil organic matter excluding root C. (E) $\Delta^{14}\text{CO}_2$ of the soil atmosphere. (F) Concentration of CO_2 in the soil atmosphere. The forest was cleared at the pasture site in 1969, planted with the grasses *Panicum maximum* and later *Brachiaria humidicola*, and was heavily grazed intermittently to the present. Woody shrubs and treelets now dominate the site and it supports little grazing. Live fine root biomass (<1 mm diameter) was estimated for 1.5-kg samples taken from auger holes lined with plastic tubing to prevent contamination of deep samples. Roots were cleaned through flotation sieving and sorted manually. Time domain reflectometry (TDR) sensors were installed at the surface and horizontally into the shaft walls at one meter intervals and biweekly readings were converted to volumetric soil water²⁵. Stainless steel tubes (1.8 m long, 0.32 cm diameter) were inserted horizontally into the sides of the shaft for soil atmosphere sampling. Errors in estimate of CO_2 concentrations due to diffusion through the shaft wall were determined to be $<10\%$. Evacuated stainless steel canisters (0.5 l) were also filled for later analysis of $^{14}\text{CO}_2$ by accelerator mass spectrometric determination. ^{14}C results are reported as $\Delta^{14}\text{C}$, the deviation (in parts per thousand) in the $^{14}\text{C}/^{12}\text{C}$ ratio of the sample (corrected for variations in $^{13}\text{C}/^{12}\text{C}$) compared to the absolute standard (oxalic acid in 1950). Using the $\Delta^{14}\text{C}$ notation, zero represents the 1950 atmospheric $^{14}\text{CO}_2$ content, positive values reflect the influence of ^{14}C derived from aboveground thermonuclear weapons testing, and negative values indicate that significant portions of the C have been isolated from

exchange with atmospheric CO₂ long enough for ¹⁴C to decay radioactively (half-life = 5730 years). All ¹⁴C analyses were performed at the Center for Accelerator Mass Spectrometry (AMS), Lawrence Livermore National Laboratory using established methods²⁶⁻²⁸. The Δ¹⁴C values of about -850‰ for soil organic matter (SOM) at 5 to 8 m (2D) indicate that most, but not all, of the C is very old. Assuming that the old C is essentially radiocarbon dead (-1000‰), the remaining modern fraction (+143 to +200‰) would be 12% to 13% of the total carbon present in SOM at 8 m

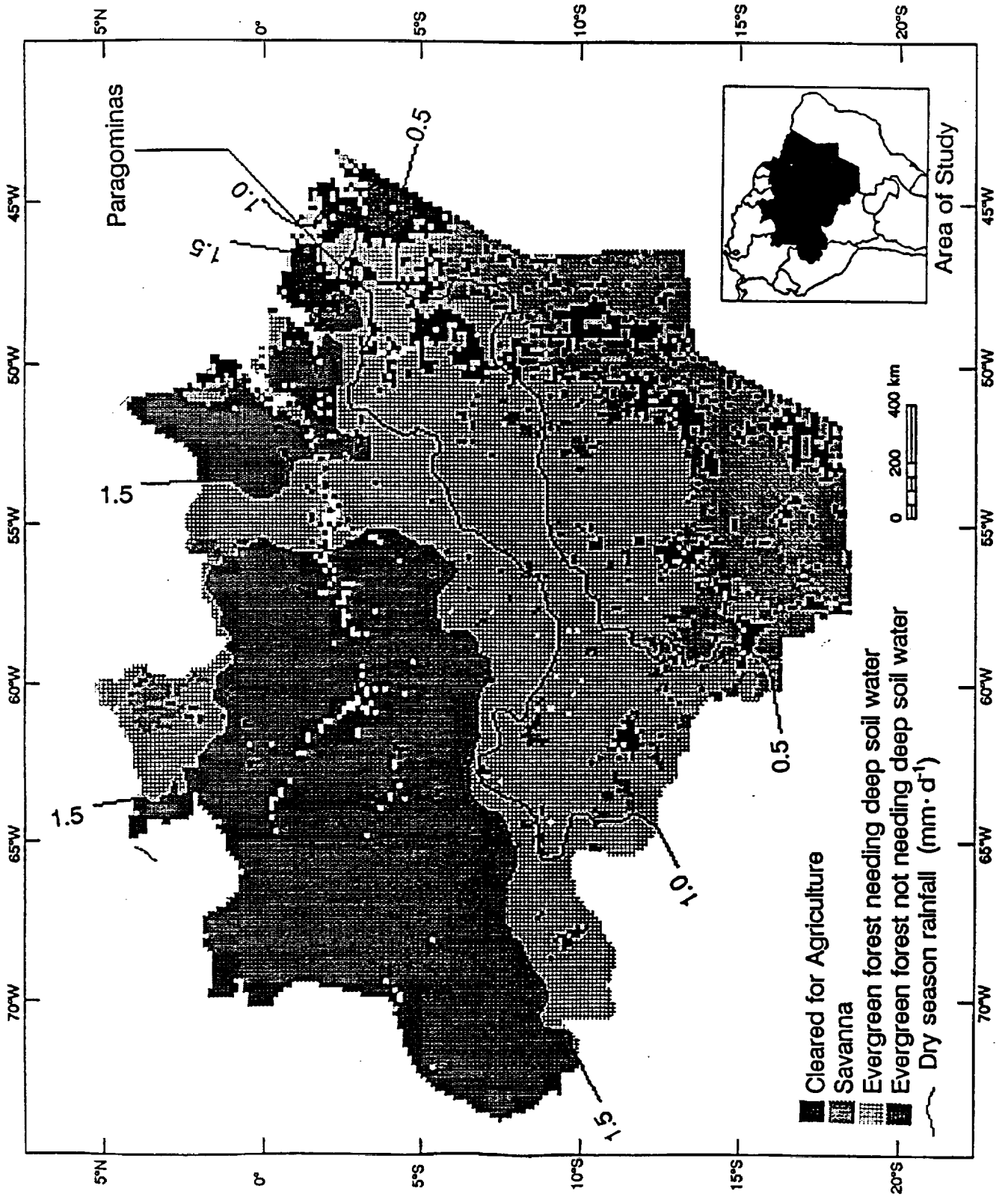
$$(([-850+1000]/1000)/[1+(143/1000)])=0.13.)$$

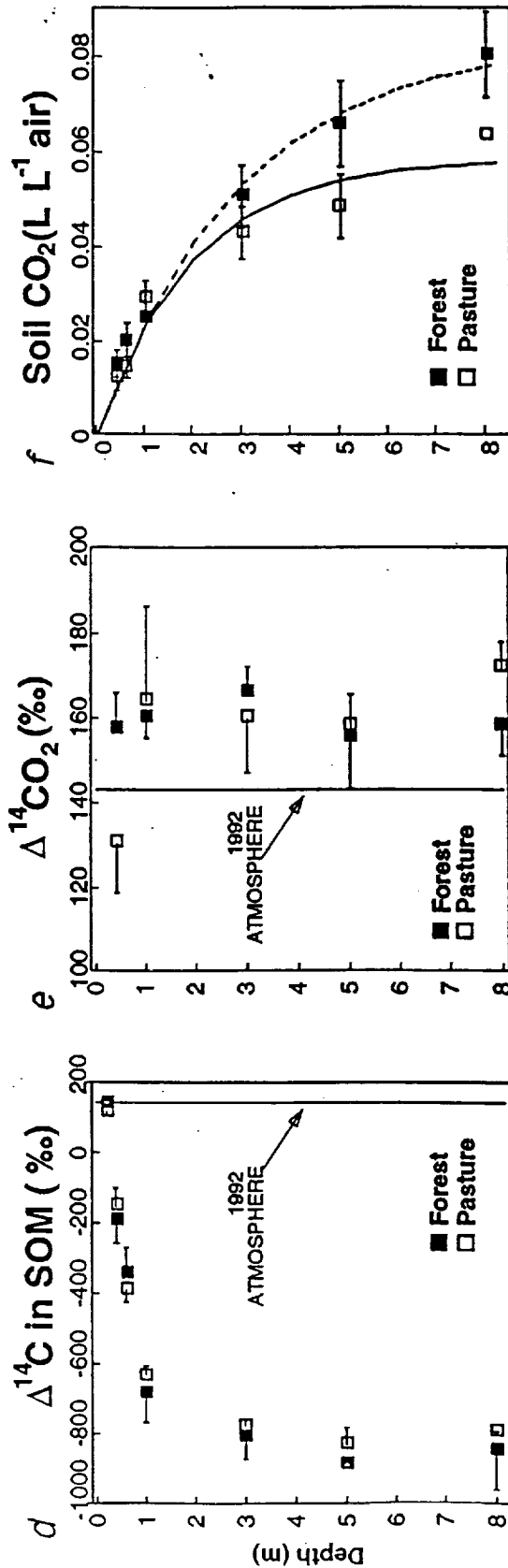
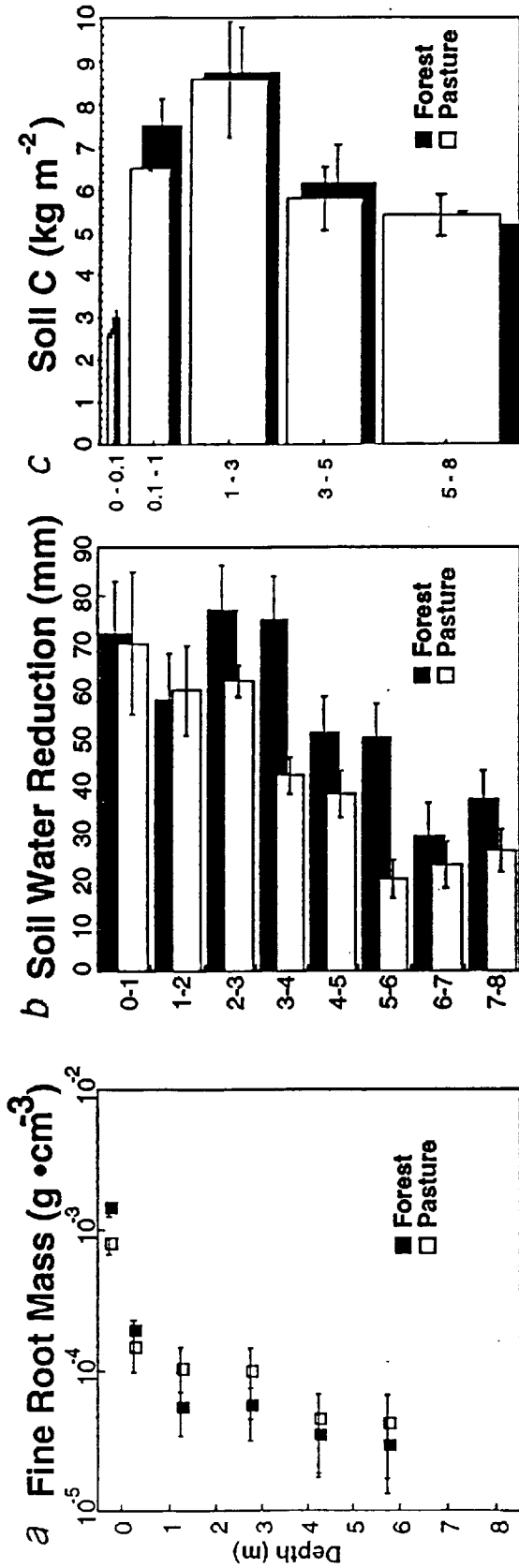
Figure 3. Seasonal trends of leaf canopy drought stress, leaf area and rainfall in adjacent mature forest and pasture, eastern Amazonia. Points are means and bars are one standard error. (A) Pre-sunrise xylem pressure potential (XPP_{pre}) of eight common species in the forest and pasture. Lower (more negative) numbers signify greater drought stress. (B) Percent of maximum leaf area for the same plant species that were used for xylem pressure potential measurements, based on monthly observations of tagged branches ($n=20$ branches per species). (C) Daily rainfall. Seasonal patterns of leaf dynamics, XPP_{pre} and leaf resistance to vapor flux (r) were measured in canopies of the forest and pasture. XPP_{pre} was measured for common plant species in both the forest (5 trees, 2 lianas, 1 palm) and pasture (3 shrubs, 2 grasses, 2 lianas, 1 palm) at monthly intervals. Three leaves from each of 3 individuals per species were measured during a three-day period using a pressure chamber²⁹. Leaves were collected prior to sun-rise and measured within one hour. Leaf resistance to vapor flux was measured for the same individuals at the peak of the 1992 dry season (September) using a transient state porometer (LiCor 700). Two leaves were measured from each plant between 930 and 1100 hs and again between 1300 and 1500 hs. Measurements were made within 60 s of harvest.

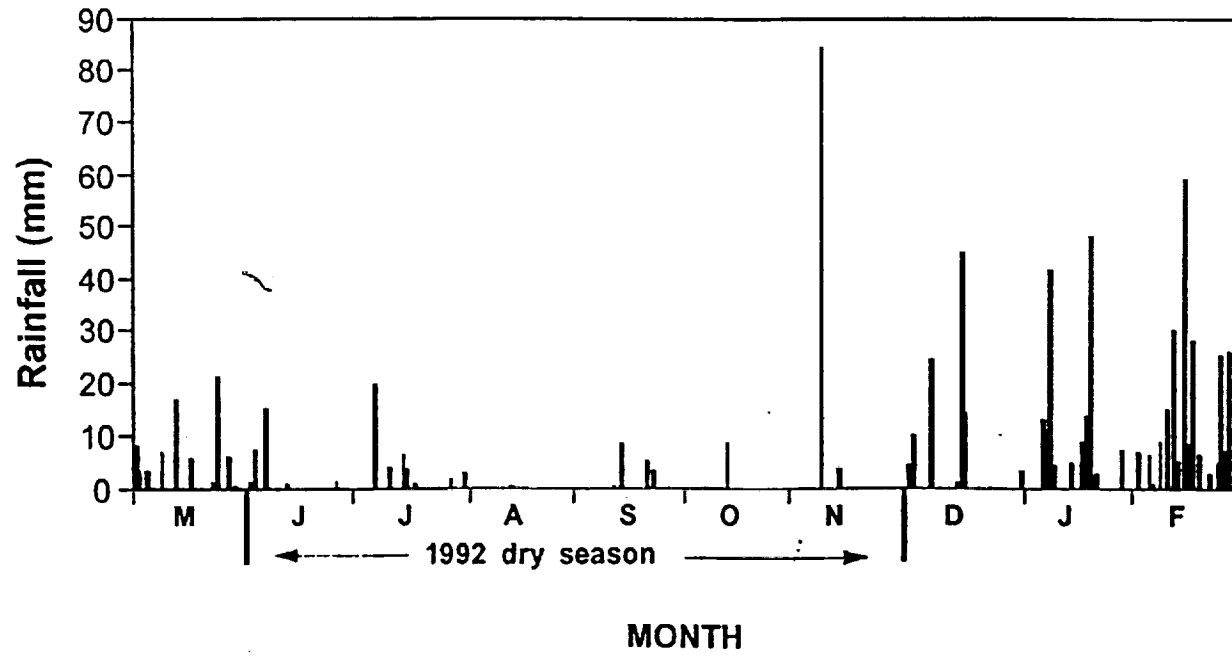
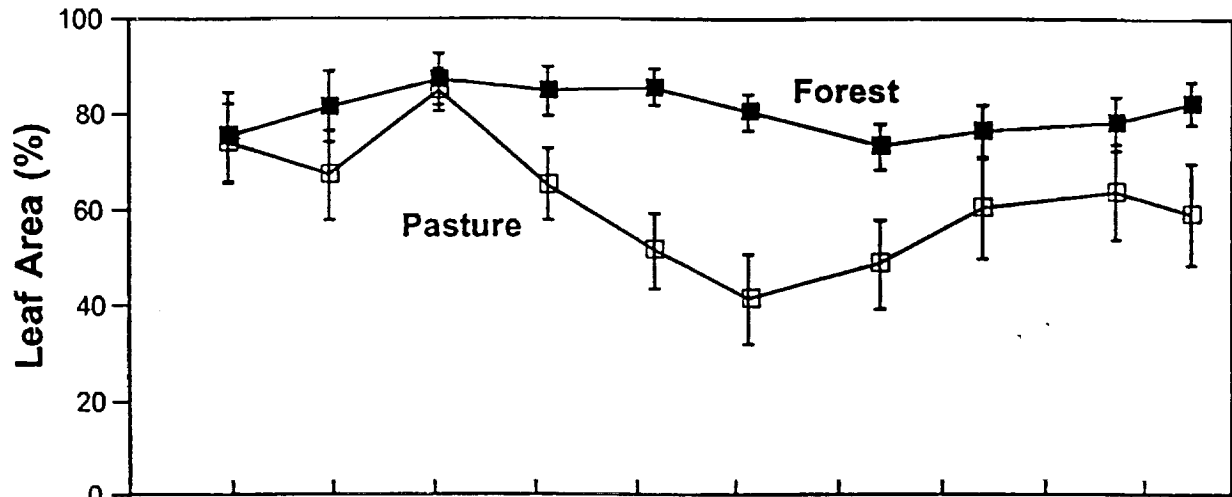
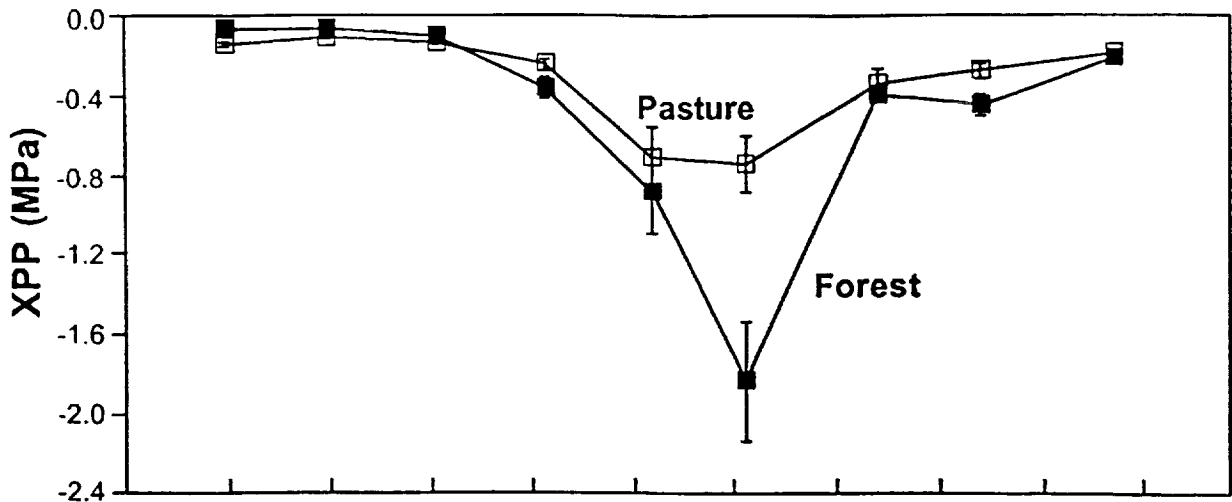
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$\Delta^{14}\text{C}$, $\delta^{13}\text{C}$ and C Inventory Differences Between Forest and Pasture in Soils of Eastern Amazonia.

P B de Camargo (Centro de Energia Nuclear na Agricultura, CP 96, Piracicaba, SP, cep13400, Brazil; Internet: pcamargo@halo.ps.uci.edu)

S E Trumbore (Dept. of Geosciences, University of California, Irvine, CA 92717-3100; 714-856-6142; Internet: trumbore@bro.ps.uci.edu)

E A Davidson and D C Nepstad (The Woods Hole Research Center, Woods Hole, MA 02543)

L A Martinelli (Centro de Energia Nuclear na Agricultura, CP 96, Piracicaba, cep13400, SP, Brazil)

Soil carbon inventory, natural ^{13}C abundance, natural ^{14}C activity and their changes as a consequence of conversion forest to pasture in an eastern amazonia oxisol were studied. Measurements of the 0-10cm soil layer shows differences in C content (3.1 vs 2.7% C in forest and pasture, respectively), $\delta^{13}\text{C}$ (-27.5 vs -24.5‰) and $\Delta^{14}\text{C}$ (+135 vs +107‰) in density >2.0g/cc fraction. These results indicate that the amount of C is less in pasture than forest and only 20% of the SOM from the pasture has been added since the change of vegetation (1975). Higher positive value of $\Delta^{14}\text{C}$ in the forest indicate that turnover of soil carbon in this layer is rapid. In addition, the amount of new carbon from pasture vegetation sources since 1975 is smaller. The values of $\delta^{13}\text{C}$ increase and $\Delta^{14}\text{C}$ decrease with the depth in the soil profile, but we see no difference between forest and pasture, probably because the deep pastures profiles remain the characteristics of the primary forest before vegetation change. Other samples of soil the surface (0-30cm) from a 600m transect extending from degraded pasture through "capoeira" (secondary forest) to primary forest were measured. The $\delta^{13}\text{C}$ of SOM in the pasture soil has increase to -20‰ in 14 years, indicating that between 20-50% of the SOM has been added from grasses. The small difference in $\delta^{13}\text{C}$ between capoeira and forest may be explained by the rapid turnover of the organic matter. The result from comparison of forest and pasture in this transect corroborate those from the first comparison, with the conclusion that little new carbon has been added to the pasture soils. We are running $\Delta^{14}\text{C}$ analyses of this transect now.

1. 1993 Fall Meeting
2. 013102574
3. (a) P B de Camargo
Dept. of Geosciences
University of California
Irvine, CA 92717-3100

(b) Tel. 714-856-6142

(c) Fax 714-725-3256
4. A (Atmosphere)
5. (a) A08 (Land Use
Change in Tropical
Regions...)

(b) 0315 (Biosphere-
atmosphere interactions)
0330 (Geochemical
Cycles)
6. N/A
7. 0%
8. check for \$30 enclosed.
9. C (contributed)
10. Schedule with Trumbore
(same field site)
11. Yes

EVALUATION OF C AND N INVENTORIES, $\delta^{13}\text{C}$ AND $\Delta^{14}\text{C}$ IN DEEP SOILS FROM MATURE AND REGROWING FOREST (CAPOEIRA), AND PASTURE OF EASTERN AMAZONIA.

CAMARGO P.B.DE*, Martinelli L.A., Pessenda L.C.R.,
Centro de Energia Nuclear na Agricultura, CP 96,
Piracicaba, SP 13400-970, Brazil; TRUMBORE S. E.,
Dept. of Geosciences, University of California, Irvine,
CA 92717-3100; Davidson E.A., and Nepstad D.C., The
Woods Hole Research Center, Woods Hole, MA 02543.

To better understand how tropical forest clearing, pasture management, and forest regrowth affect deep soil C cycling we investigate: C and N inventories to estimate below-ground C and C/N dynamics, $\delta^{13}\text{C}$ analysis to calculate C inputs to pasture soils from C-4 grasses and $\Delta^{14}\text{C}$ analyses of soil CO_2 to estimate residence times of soil organic matter.

Much of the eastern Amazon Basin, including our study area in Paragominas, Para, is characterized by deep oxisols (more than 8m). This region experience a significant dry season, although most of its forests retain leaf canopies continuously. Deep rooting of trees in mature forests support evapotranspiration during the dry season and impact C and N inputs at depth.

Measurements of the 0-8 m soil layer show that C and N decrease from the surface (2.00 - 0.15%) to 3m (0.20 - 0.01%) respectively, then remain constant to the bottom. The C/N ratio varies between 10 to 20 and usually increases below 2m. There are no significant differences below 2m between the three ecosystems.

In the upper 10cm the bulk density increases from mature forest and "capoeira", to pasture (0.96, 1.07, 1.24g/cc) respectively. Below that, bulk density is roughly constant (1.3±0.5g/cc). Large bulk density at the surface in pastures is due to compaction because of loss of organic matter and physical disturbance.

The $\delta^{13}\text{C}$ values in the upper 10cm are -27.3, -26.7, -24.4‰, for forest, "capoeira" and pasture. These results indicate that only 20% of the SOM from pasture has been added since the change of vegetation (1969). The influence of C-4 vegetation can be seen in pastures to a depth of 25cm, but not below. The values of $\delta^{13}\text{C}$ increase with the depth (by 1 to 4‰) in the soil profile. No difference is observed at depth among mature, regrowing forest and pasture, probably because the deep pasture and "capoeira" profiles retain the characteristics of the primary forest before vegetation change. This increase could reflect fractionation due to decomposition or movement of organic matter down the profile.

The few $\Delta^{14}\text{C}$ data that we have now, show higher positive values in the surface of forest and pasture (+149 and +130‰) and indicate that turnover of soil C in this layer is rapid (less than 30 years). $\Delta^{14}\text{C}$ values decrease with depth quickly in the first meter to -700‰ and -630‰ in forest and pasture and remain between -750 and -800 at greater depth in both profiles.

Our observations, together with CO_2 flux in the soil will be used to construct models with predict changes in C and C isotopes accompanying forest-pasture vegetation change.

*Current address: Depart. of Geosciences

1. Plinio B. de Camargo
Department of Geosciences
University of California, Irvine
Irvine, CA 92717-3100

2. Tel: 714-7253516
Fax: 714-7253256

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FAX Abstracts Cannot Be Accepted!**Soil Respiration and Soil CO₂ Concentration Gradients in Forests and Pastures of the Amazon. E.A. DAVIDSON* and S.E. TRUMBORE, Woods Hole Research Center and Univ. of California, Irvine.**

Conversion of forests to pastures is thought to result in net release of soil carbon to the atmosphere and to change the dynamics of carbon cycling. We are studying the cycling of soil-C in primary forest sites and in degraded pastures in the Brazilian state of Pará. Mean flux of CO₂ from the soil surface was 0.29 and 0.14 g C m⁻² h⁻¹ in forests and pastures respectively. Concentrations of CO₂ increased with depth at all sites; [CO₂] at 5 m depth averaged 6.5% and 4.8% in forests and pastures, respectively. Deep roots are common in forests of this region and are the probable source of CO₂ at depth. These data indicate that more carbon cycles through the forest soil than the pasture soil, both at depth and near the surface. We are also measuring the ¹⁴C content of soil-C and of CO₂ in soil atmospheres to estimate age and rates of turnover of soil carbon.

E.A. Davidson, 508-540-9900

Mailing Address of Corresponding Author:

Title and name
Department
University or other organization
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Dr. Eric A. Davidson

Woods Hole Research Center
P.O. Box 296
Woods Hole, MA 02543
USA

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International Symposium: Soil Processes and Management Systems, Greenhouse Gas Emissions, and Carbon Sequestration, Columbus, OH, April 1993
Losses of Carbon from Pasture Soils of the Eastern Amazon Estimated from Measurements of Isotopes, Fluxes, and Inventories

Eric A. Davidson¹, Susan E. Trumbore², and Daniel C. Nepstad¹

¹The Woods Hole Research Center
and

²The University of California, Irvine.

The effects of clearing tropical forests on stores of soil carbon are poorly understood because of a dearth of comparative information on below-ground C budgets of tropical forests and the ecosystems that are replacing them. We are studying cycling of soil-C in primary forest sites and in degraded pastures in the Brazilian state of Pará. Our measurements include ¹⁴C analysis of soil CO₂ and fractionated SOM to estimate residence times, ¹⁴C analysis to estimate C inputs to pasture soils from C-4 grasses, sequential coring to estimate fine root biomass production, litterfall collection and forest inventories to estimate above ground C dynamics, soil pCO₂, and radon gradients to estimate CO₂ production at depth, soil respiration to estimate total C outputs, and a model of soil C dynamics that defines SOM fractions cycling on annual, decadal, and millennial time scales. The ¹⁴C and ¹³C data from a pasture cleared in 1975 show not only that much of the labile forest SOM has been lost, but also that little new C has been added to the SOM from pasture vegetation. Mean flux of CO₂ from the soil surface was 0.29 and 0.14 g C m⁻² h⁻¹ in forests and pastures respectively. Concentrations of CO₂ increased with depth at all sites; pCO₂ at 5 m depth averaged 6.5% and 4.8% in forests and pastures, respectively. Deep roots are common in forests of this region and are the probable source of CO₂ at depth. These data indicate that more carbon cycles through the forest soil than the pasture soil, both at depth and near the surface. Most of the C turnover in forest and pasture soils occurs near the surface, but most of the long-term C storage occurs below 1 m. Constraining our model with the field measurements listed, our preliminary estimate of the cumulative C loss from the pasture soil is 2.7 kg C m⁻² (about 10% of the forest soil C inventory), and it is still losing about 0.09 kg C m⁻² yr⁻¹. About one-third of the total C lost was from soil below 1 m depth. Although this magnitude of soil-C loss is significant as a source of atmospheric CO₂, spatial heterogeneity of soil C would make a decline of only 10% of the soil C stocks difficult to measure using traditional inventory measurements.

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DAVIDSON, ERIC A., DANIEL C. NEPSTAD, AND SUSAN E. TRUMBORE. The Woods Hole
Research Center, Woods Hole, MA, 02543, USA and the University of California, Irvine, CA,
92717, USA. Soil carbon dynamics in pastures and forests of the eastern Amazon.

There is a dearth of information on below-ground C budgets of tropical forests and the ecosystems that
are replacing them. Mean flux of CO₂ from the soil surface was 0.29 and 0.14 g C m⁻² h⁻¹ in primary
forests and degraded pastures, respectively, near Paragominas, Brazil. Litterfall and fine root inputs
were about two times greater in forests than pastures. The ¹⁴C and ¹³C contents of SOM and CO₂ in a
pasture cleared in 1975 show that much of the labile forest SOM has been lost and little new C has
been added by pasture vegetation. A preliminary estimate of the cumulative net C loss from the
pasture soil is 2.7 kg C m⁻² (about 10% of the forest soil C inventory), and it is still losing about 0.09 kg
C m⁻² yr⁻¹. Most of the soil C turnover occurs near the surface, but most of the long-term C storage
occurs below 1 m in these oxisols. About 10% of the soil C at depth has a mean residence time of
years to decades and is input by the deep roots of trees in this seasonally droughty region. Grasses
have fewer deep roots, and about 1/3 of the total C lost from pasture soil was from below 1 m depth.

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EXAMPLE:

MURPHY, PETER G. and REBECCA R. SHARITZ. Michigan State University, East
Lansing, MI, 48824, USA and Savannah River Ecology Laboratory, Aiken,
SC, 29801, USA. Long-term recovery of northern hardwood forest
following gamma irradiation.

A northern Wisconsin hardwood forest was exposed to 3300 hours of point-
source gamma irradiation from 3 May to 16 October, 1972. Cumulative ...

SOIL CARBON DYNAMICS IN FORESTS AND PASTURES OF THE EASTERN
AMAZONE.A. Davidson¹, S.E. Trumbore², and D.C. Nepstad¹¹The Woods Hole Research Center, Woods Hole, MA, USA²University of California, Irvine, CA, USA

Studies of above-ground processes in tropical forests have revealed the importance of forests in regional hydrologic cycles. In the eastern Amazon, where evergreen forests are maintained by deep rooting systems, deep roots are an important link between the hydrologic and carbon cycles because roots extract water and also are sources of carbon deep in the soil profile. Soil C inventories seldom include analyses below 1m depth, probably because soil C concentrations decline roughly exponentially with depth and the C present in deep soils is assumed to be inert. When integrated over a large volume, however, the soil C inventory below 1m depth is $>20 \text{ kg C m}^{-2}$ at Paragominas in the Brazilian state of Pará, which is greater than the inventory of the top 1m of soil (10 kg C m^{-2}) and the above ground biomass of the primary forest (15 kg C m^{-2}). The $\Delta^{14}\text{C}$ of soil organic matter (SOM) measured at 8 m depth is -850‰ , which indicates that most, but not all of the deep soil C is very old. We estimate that about 10-25% of the total C in SOM between 1 and 8m (about $2\text{-}5 \text{ kg C m}^{-2}$) cycles on annual to decadal time scales. Modern isotopic signatures of soil CO_2 at depth support this estimate. Hence, this pool of modern soil C deep in the soil could be lost if land-use change affects rooting depths and soil C inputs.

According to our soil C inventories, degraded and abandoned pasture soils have lost 1.6 kg C m^{-2} in the top 1m of soil relative to the forest soil. Spatial heterogeneity and analytical limitations preclude detection of soil C loss below 1m using standard inventory approaches. Instead, we are completing a below-ground C budget, using estimates of fine root production from sequential coring, estimates of CO_2 production from profiles of CO_2 concentration and gaseous diffusivity, surface fluxes of CO_2 , and isotopic analyses of SOM and CO_2 . This budget allows us to constrain a model of residence times of soil C pools and address the impact on soil C dynamics of land use changes that affect rooting distribution.

August 1994
Knoxville, TN, July 1994

Nepstad et al. NAGW - 2750
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DAVIDSON, ERIC A., SUSAN E. TRUMBORE, and DANIEL C. NEPSTAD. The Woods Hole Research Center, Woods Hole, MA, 02543, USA, and University of California, Irvine, CA, 92717, USA. Soil carbon dynamics in forests and pastures of the eastern Amazon.

Roots of the seasonally dry eastern Amazon are evergreen because they extract water with deep roots. Roots are also sources of carbon deep in the soil profile. The soil C inventory below 1 m depth is >20 kg C m⁻² at Paragominas, Brazil, which is greater than the inventory of the top 1 m of soil (10 kg C m⁻²) and the above-ground forest biomass (15 kg C m⁻²). The Δ¹⁴C of soil organic matter (SOM) at 8 m depth is -850‰, which indicates that most, but not all, of the deep soil C is very old. About 2-5 kg m⁻² between 1 and 8 m depth (10-25% of the total C in SOM) cycles on decadal time scales. Soil ¹⁴CO₂ measurements support this estimate. Modern C deep in the soil could be lost if land-use change affects rooting depths and soil C inputs. Degraded and abandoned pasture soils have lost 1.6 kg C m⁻² in the top 1 m of soil relative to the forest soil. Loss of soil C below 1 m cannot be reliably detected with standard inventory analyses, but a complete below-ground C budget constrains a model of residence times of soil C pools and permits estimation of the effects of land use change and root inputs on soil C dynamics.

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American Geophysical Union, San Francisco, CA, December 1993

Production of CO₂ in Pasture and Mature Forest Soils of Eastern Amazonia

S E Trumbore (Dept. of Geosciences, University of California, Irvine, CA 92717-3100; 714-856-6142; Internet: trumbore@bro.ps.uci.edu)

E A Davidson and D C Nepstad (The Woods Hole Research Center, Woods Hole, MA 02543)

P Jipp (Dept. of Forestry, Duke University, Durham, NC 27706)

L A Martinelli (Centro de Energia Nuclear na Agricultura, DP 96, Piracicaba, SP, Brazil)

Mean CO₂ fluxes from the soil surface of primary forests and degraded pastures measured near Paragominas, Para, Brazil, in 1992-93 were 0.29 and 0.14 g C m⁻² hr⁻¹, respectively. Little diel or seasonal variation in soil CO₂ flux was observed in the primary forest, though wet season (December-May) fluxes from pasture soils were slightly greater than those in the dry season (June-November). To understand the differences between forest and pasture carbon fluxes, we have combined measurements of the CO₂ content of the soil atmosphere (to 8 m depth) with estimates of soil gas effective diffusivity to determine the rate of CO₂ production as a function of depth in the soil profile. Soil atmosphere CO₂ concentrations increase dramatically with depth in both forest and pasture soils, to values of 8 - 10% CO₂ at 8m. We use a model based on measured values of bulk density and volumetric soil water content to estimate effective diffusivity (D_{eff}) of soil gases as a function of soil depth. The model-derived D_{eff} values are tested against observed production rates and depth profiles of ²²²Rn in the soil atmosphere. CO₂ production as a function of depth is then calculated directly from D_{eff} and the change in concentration with depth of soil atmosphere CO₂. Additional information available from these sites in the form of annual turnover of fine root biomass allows us to estimate the relative contributions of root respiration and soil organic matter decomposition to the CO₂ flux in each depth interval. The ¹⁴C content of the CO₂ produced at depths of >3m in both forest and pasture soils shows that the CO₂ at these depths which is derived from decomposition of organic matter reflects the isotopic composition of plant carbon which was fixed from the atmosphere between 1960 and 1990.

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(c) Fax 714-725-3256
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**RECENT APPLICATIONS OF ACCELERATOR MASS
SPECTROMETRY ^{14}C MEASUREMENTS TO SOIL ORGANIC
MATTER DYNAMICS**

Susan E. Trumbore, Department of Geosciences, University of California, Irvine, CA 92717-3100 and Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, CA 94550.

The recent application of Accelerator Mass Spectrometry (AMS) to measure cosmogenic isotopes, with its advantages of small sample size (1 mg of carbon) and high throughput (50-100 samples/day), has motivated research using ^{14}C as a tracer for carbon cycling in soil, sedimentary and dissolved organic matter. ^{14}C may be used in several ways to understand the soil carbon cycle: (1) the observed increase in ^{14}C in soil organic matter since 1960 (due to the incorporation of carbon labelled with ^{14}C created by atmospheric testing of nuclear weapons) indicates the amount of carbon turning over on decadal and shorter timescales in soils; (2) ^{14}C measurements of fractionated organic matter may be used to identify extremely refractory components; and (3) the ^{14}C content of decomposing organic matter (measured as the ^{14}C content of soil CO_2 or CH_4) is a sensitive indicator of the turnover time of more rapidly cycling carbon. This talk will emphasize recent work relating the turnover and accumulation of soil organic matter to soil forming factors, such as climate, vegetation, parent material, and time.