Carbon-13 variation with depth in soils of Brazil and climate change during the Quaternary

Received: 23 December 1994 / Accepted: 18 November 1995

Abstract Paleoecological and geomorphological studies indicate that, during the middle Holocene, there was a predominance of drier conditions with grassy savannas replacing forests across the South American continent. Modern savannas are composed mainly of C4 plants and soils developed under this type of vegetation show enrichment in 13C compared to soils under C3 vegetation cover. If soils contain stabilized organic matter formed in the middle Holocene, we hypothesize that former C4 vegetation would be evidenced by a large enrichment of 13C in soil organic matter (SOM). We investigate this possibility examining the depth variation of carbon isotopic composition in 21 soil profiles collected by different researchers at 14 different sites in Brazil. Of these, profiles from only three sites showed a marked increase of 13C with depth (9–10%, enrichment in δ13C difference between the surface soil and deepest depth); two sites showed intermediate enrichment (4–5%), and nine sites showed a small enrichment of approximately 2.5%. The majority of sites showing all-C3 derived SOM were in the Amazon region. Possible causes for the absence of a large 13C enrichment with depth are: (1) dominance of C3 rather than C4 grasses in mid-Holocene savannahs, (2) soil profiles did not preserve organic matter derived from mid-Holocene plants, (3) the retreat of forest areas did not occur on a regional scale, but was a much more localized phenomenon.

Key words Amazon · Vegetation change · Stable carbon isotope · Radiocarbon · Soil organic matter

Introduction

Soil organic matter (SOM) is a complex mixture of compounds from different pools, ranging from very labile compounds with very fast cycling times to refractory components that accumulate over millenia (Trumbore 1993). These attributes are susceptible to climate change, which can cause alterations in organic matter inputs and rates of decomposition (Jenkinson et al. 1991). The cumulative response of SOM behavior to past and future changes is a significant factor in the global carbon cycle (Prentice and Fung 1990; Tans et al. 1990; Jenkinson et al. 1991).

Paleoecological and geomorphological studies suggest the occurrence of severe climatic changes in the South American continent. It has been hypothesized that there were drier periods during the Pleistocene and Holocene than the present, when the tropical forest was replaced by savannah-like vegetation, with predominance of grasses (Van der Hammen 1974; Absy and Van der Hammen 1976; Absy 1980; Ab’Saber 1982; Bigarella and Andrade-Lima 1982; Leyden 1985; Markgraf 1989; Bush et al. 1990; Bush and Colinaux 1990; Markgraf 1991; Absy et al. 1991). The maximum in the proportion of grass pollen was found in the middle Holocene from ca. 6,000 to 4,000 years before present (BP) for several placed in South America (Absy 1980; Servant et al. 1989; Markgraf 1989; Absy et al. 1991; Ledru 1992, 1993; Servant et al. 1993), from 10,500 to 10,400 years BP for central Brazil (Servant et al. 1989, 1993; Ledru 1993), and ca. 13,000 years BP for eastern Amazonia (Absy et al. 1991).

If these grasses were of the C4 type, it may be possible to find a residual isotopic signal preserved in soil profiles. Depending on the degree of 13C enrichment in SOM with depth, two basic processes could explain the observed trends.
1. If the $^{13}$C enrichment with depth is small, the decomposition of organic matter, which favors $^{12}$C, is most likely the cause of the trend.

2. If the DC enrichment with depth is large, it is a stronger indication that the signal is due to the previous existence of $^{13}$C-enriched vegetation, probably C4 grasses.

We explore those possibilities through the analyses of the stable carbon isotope composition of 21 soil profiles collected at 14 sites in Brazil, encompassing different soil types and climatic conditions (Volkoff et al. 1982; Desjardins et al. 1991; Valencia 1993; Pessenda et al. 1995; Trumbore et al. 1995). Radiocarbon data for the organic matter from the same soil profiles provide an estimate of the minimum age of stabilized C4 organic matter.

**Methods**

Locations of soil profiles are shown in Fig. 1. A total of 21 soil profiles at 14 sites, encompassing different climate regimes and soil types were collected (Table 1). Of these sites 7 were located in the Amazon basin, which is characterized by high temperature and heavy rainfall (Fig. 1). Three other profiles were also collected in areas of high average temperatures: Juacema, Nhecolândia and Salitre. The first one is located in the northeast region of Brazil, which is mainly characterized by low rainfall (Fig. 1). The Nhecolândia profile was collected in the Brazilian Pantanal, one of the largest floodplains in the world, and the Salitre profile was collected in the southernmost region of Brazil (Fig. 1). In areas of lower average temperatures, six profiles in four different places (São Roque, Piracicaba, Londrina and Tunas) were collected (Fig. 1). Soil types differed among places (Table 1). The most common soil types in Brazil, Latossolo and Podzolico, which are equivalent to ultisols and oxisols in the American classification system, were present at most sampling sites (Table 1). Soils classified as Terra Roxa Estruturada (equivalent to alfisols) were present at two sites, and finally Cambissolo and Areia Quartzoza, both equivalent to inceptisols, were present at one site each. In all sampling sites the vegetation was the primary forest characteristic of each region.

Details of soil sampling and soil characteristics can be found elsewhere (Cerri 1979; Volkoff et al. 1982; Soubies and Chauvel 1985; Martins et al. 1991; Higa 1989; Rocha 1990; Valencia 1993; Pessenda et al. 1996; Trumbore et al. 1995). Analysis of carbon isotopic composition, expressed as $\delta^{13}$C, were not always carried out by the same authors that collected soil samples. (A list of those authors can be found in Table 1.) Radiocarbon ages, expressed as years before present (years BP), were available for profiles located at Piracicaba, Londrina, Altamira, Salitre, Nhecolândia and Para-Rives and are shown in Table 1.

![Fig. 1](image-url)
Table 1 Sites of soil sampling (numbers in parentheses indicate the number of profiles collected at each site) following by soil type according to the Brazilian classification system; soil texture; mean annual temperature, rainfall and climate type

| Code – Site       | Brazilian classification         | Texture     | Mean annual temperature | Mean annual rainfall | Climate             | References                      |
|-------------------|----------------------------------|-------------|-------------------------|----------------------|---------------------|---------------------------------|
| Man – Manaus (1)  | Latossolo Amarelo                | Clay        | 27°C                    | 2100 mm              | Trop. humid         | a                               |
| Alt – Altamira (2)| Terra Roxa Estruturada           | Clay        | 27°C                    | 1650 mm              | Trop. humid         | b                               |
| Cpo – Capitólio Poço (1) | Latossolo Podzolizado  | Silty-clay  | 27°C                    | 2500 mm              | Trop. humid         | c                               |
| Par – Paragominas (3) | Latossolo Amarelo              | Clay        | 27°C                    | 1750 mm              | Trop. humid         | d                               |
| Ori – Oriente Novo (1) | Latossolo Vermelho-Amarelo      | Silty-clay  | 25°C                    | 2200 mm              | Trop. humid         | e                               |
| Dom – S. Domingos (1) | Podzólico Vermelho-Amarelo      | Silty-clay  | 25°C                    | 2300 mm              | Trop. humid         | f                               |
| Ten – Terra Nova (1) | Cambissolo                      | Silty-clay  | 25°C                    | 300–1000 mm          | Trop. semi-arid      | g                               |
| Jua – Juacema (1)  | Latossolo                        | Silty-clay  | 25°C                    | 1280 mm              | Trop. humid         | h                               |
| Pan – Nhecolândia (1)| Area Quartoza                   | Sandy       | 25°C                    | 1700 mm              | Subtropical         | i                               |
| Sal – Salitre (2) | Latossolo Vermelho-Amarelo      | Clay        | 24°C                    | 1200 mm              | Subtropical         | j                               |
| Sro – São Roque (1)| Podzólico                        | Sandy-clay  | 21°C                    | 1200 mm              | Subtropical         | k                               |
| Pir – Piracicaba (2)| Latossolo Vermelho-Amarelo      | Clay        | 20°C                    | 1200 mm              | Subtropical         | l                               |
| Lon – Londrina (2) | Terra Roxa Estruturada           | Clay        | 19°C                    | 1200 mm              | Subtropical         | m                               |
| Tun – Tunas (1)    | Latossolo Podzolizado            | Silty-clay  | 18°C                    | 1400 mm              | Temperate           | n                               |

a Volkoff et al. (1982) soil description and δ13C analysis
b Rocha (1990) soil description
c Desjardins et al. (1991) δ13C analysis
d Valencia (1993) δ13C analysis
e Martins et al. (1986) soil description

gominas and these analyses were conducted by Valencia (1993) for the first three profiles, and by Pessenda et al. (1996), Victoria et al. (1995), and Trumbore et al. (1995) for the last three profiles, respectively.

Results and discussion

The contemporary vegetation cover of all sites was primary forest (C3 plant type), and the δ13C of the surface soil organic matter varies from −28.5 to 26.0‰. In order to make the comparison among different profiles easier, the depth variability of the carbon isotopic composition in each profile was expressed as the difference of the δ13C of a soil depth in relation to the δ13C value of the most superficial sampling depth. We call this difference Δ13C, defined as:

\[ Δ^{13}C = δ^{13}C_{\text{surface}} - δ^{13}C_{\text{depth}} \]

where δ13C_surface is the value of the surface soil and δ13C_depth is the value at a given depth. Δ13C values were mostly positive, reflecting the fact that δ13C values increased with depth in nearly all soil profiles.

Results were grouped according to the Δ13C values. Figure 2A and B shows profiles with the smallest Δ13C values. The profiles with the highest Δ13C are shown in Fig. 2D and profiles with intermediate to small values of Δ13C are grouped in Fig. 2C.

Most of the soil profiles with the smallest Δ13C values (Fig. 2A and 2B) are from the Amazon Basin (Fig. 1). In these profiles the highest Δ13C value was 3.5‰, but most of the values were smaller than 2.5‰, which indicates that the major cause of 13C enrichment with depth was probably fractionation during decomposition of SOM. The only exception to this pattern was the depth variability observed in the Terra Nova profile, where the Δ13C value reached almost 8.5‰ near the bottom (Fig. 2D). Profiles from Piracicaba and Londrina showed similar 13C enrichment (Fig. 1). The profile Lon-1 at Londrina reached a Δ13C value of 11.5‰ at the bottom (Fig. 2D). In such cases the most likely cause for this large 13C enrichment with depth is the existence of prior C4 vegetation (Dzurac et al. 1985; Mondenesi et al. 1986; Schwartz et al. 1987; Volkoff and Cerri 1987; Martin et al. 1990; Desjardins et al. 1991; McPherson et al. 1993; Wang et al. 1993; Mariotti and Peterschmitt 1994; Victoria et al. 1995). Both profiles of Salitre, Nhecolândia, and Tunas had intermediate Δ13C values varying approximately from 4.0 to 6.0‰ (Fig. 2C). The Nhecolândia profile came from the Brazilian Pantanal, a large floodplain, highly dynamic in terms of geomorphology (Adamoli 1982), with a landscape that alternates high land forested areas with low land areas of savannah. This dynamism is reflected in the Δ13C values, with a maximum of almost 6‰ at 100 cm depth, suggesting the replacement of the forest by a C4 savannah, and a decrease to almost 0.5‰ at 170 cm depth, indicating the dominance of a C3 vegetation type again (Victoria et al. 1995). The profiles from Tunas and Salitre (Sal-1 and Sal-2) show Δ13C increasing from 4.0 to 6.0‰, within the upper 30 cm. Below, Δ13C values were constant to the bottom of the profiles. According to Pessenda et al. (1995) the cause of the increase of Δ13C with depth at these sites is fractionation of isotopes during decomposition and not a past vegetation change. However, palynological evidence of a past vegetation change in favor of grasses that may have been C4 (Ledru 1993), and the Δ13C value of 4.0–6.0‰, suggest that paleovegetation change cannot be ruled out as an explanation.

Table 2 summarizes the radiocarbon ages of soil profiles for those where such data were available. The 14C
Fig. 2 Variation of $\Delta^{13}C$ values in relation to soil depth: A, B sites with smallest $\Delta^{13}C$ values; C sites with intermediate $\Delta^{13}C$ values, and D sites with highest $\Delta^{13}C$ values. Site abbreviations are given in Table 1.

Ages reported represent the average “age” of a carbon atom in SOM, and certainly represent a mixture of both older and younger material. For samples from deep in the soil, the radiocarbon age may be taken as a minimum age for stabilized organic matter. For instance, although the $^{14}C$ age of organic matter at 100 cm depth in Para-gominas soils is about 14,000 years BP, it was estimated by Trumbore et al. (1995) that this average age represents a mixture of 10% modern carbon with 90% radiocarbon-free carbon (i.e., 90% with average age >40,000 years BP).

One of the most widely accepted climatic changes in the past is the drought that occurred in the middle Holocene (Servant et al. 1993). Pollen records from Salitre (Ledru 1993) and Southern Serra dos Carajás, near Altamira (Absy et al. 1991) show sharp increase in grass species. The Piracicaba, Londrina and Terra Nova profiles clearly show a sharp increase in $\Delta^{13}C$ (Fig. 2C). The deepest dated depths (170–180 cm) in the Piracicaba and Londrina profiles reach ages of ca. 3600 years BP and ca. 9300 years BP. These soils were presumably subjected to paleoclimatic and paleovegetation changes associated with the mid-Holocene. In Salitre the deepest dated depth (190–200 cm) is almost 7000 years BP, which means that these profiles also experienced the middle Holocene drought. However, the increase of $\Delta^{13}C$ with depth was not as sharp as in the Piracicaba and Londrina profiles, making it difficult to establish the cause for this increase. No other profiles showed the effects of the middle Holocene dryness in their carbon isotopic composition. In addition, seven other profiles collected in several areas of the Amazon region down to 4 m depth show no significant variation in carbon stable isotopic composition (Sanaiti, unpublished work). As modern savannah soils clearly show the presence of C4 grasses in their SOM (Dzurec et al. 1985; Mondenesi et al. 1982; Schwartz et al. 1987; Volkoff and Cerri 1987; Martin et al. 1990; Desjardins et al. 1991; McPherson et al. 1993; Wang et al. 1993; Mariotti and Peterschmitt 1994), the apparent absence of C4 signal in majority of the profiles is intriguing.

There are several hypothesis that can explain the lack of a C4 signal.

Soil depth (cm)
The lack of signal would be consistent with dominance by C3 rather than C4 grasses. The same hypothesis was raised by Guillet et al. (1988), who found a similar situation in the tropical region of Colombia. However, judging by the modern savannas of the region, this is unlikely.

2. The retreat of forest areas was not on a regional scale, but was a much more localized phenomenon.

3. The C4 plants were not present long enough to leave their isotopic imprint on stabilized soil organic matter.

The refuge theory for the high degree of biodiversity in tropical South America suggests that the high diversity resulted from differential species evolution in forest patches that were isolated when forests were replaced with grassy savannas during the Pleistocene and Holocene, and remained isolated until a new climatic change provoked the return of an intact continuous forest (Haffer 1969; Vanzolini 1970; Prance 1973, 1982; Brown 1974).

If the findings of this study are confirmed in further analysis, it would be a strong indication that extensive areas of grass never existed in the Amazon, especially during the Holocene. In view of refuge theory this would have strong implications for interpretations of species evolution of the Amazon rain forest.

Acknowledgements We would like to thank J. Hedges, S. Wilhelm, M. McClain, and Eric Davidson for comments on the manuscript. Financial support was provided by Conselho Nacional de Pesquisa e Desenvolvimento and Fundação de Amparo à Pesquisa do Estado de São Paulo.

References

Abr 1982) The paleoclimate and paleoecology of tropical Amazonia. In: Prance GT (ed) Biological diversification in the tropics. Columbia University Press, New York, pp 41–59

Abys ML (1980) Dados sobre as mudanças do clima e da vegetação da Amazônia durante o Quaternário. Acta Amazonica 10:929–932

Abys ML, Van der Hammen T (1976) Some paleo-ecological data from Rondónia, southern part of Amazonian Basin. Acta Amazonica 6:293–299

Abys ML, Cleef A, Fournier M, Martin L, Servant M, Sifeddine A, Ferreira da Silva M, Soubies F, Sugüio K, Turcq B, Van der Hammen T (1991) Mise en évidence de quatre phases d’ouverture de la forêt dense dans le sud-est de l’Amazonie au cours des 60 000 dernières années. Première comparaison avec d’autres régions tropicales. CR Acad Sci Paris Sér II 312:673–678

Andera Lima D 1982) Paleoenvironmental changes in Brazil. In: Prance GT (ed) Biological diversification in the tropics. Columbia University Press, New York pp 27–40

Boulet R, Pessenda LCR, Telles ECC, Melfi AJ (1995) Zoogeography of the area of origin and its use in the study of the Cerrado. Discussão sobre o conceito “Complexo Pantanal”. In: Proceedings of Congresso Brasileiro de Botânica. Sociedade Brasileira de Botânica, Teresina, Brazil, pp 109–119

Bigarella JJ, Andrade-Lima D (1982) Paleoenvironmental changes in Brazil. In: Prance GT (ed) Biological diversification in the tropics. Columbia University Press, New York, pp 27–40

Boulet R, Pessenda LCR, Telles ECC, Melfi AJ (1995) Zoogeography of the area of origin and its use in the study of the Cerrado. Discussão sobre o conceito “Complexo Pantanal”. In: Proceedings of Congresso Brasileiro de Botânica. Sociedade Brasileira de Botânica, Teresina, Brazil, pp 109–119

Brown KS Jr (1974) Quaternary refugia in tropical America: evidence for race formation in Heliconius butterflies. Proc R Soc Lond B 187:369–378

Bush M, Colinvaux PA (1990) A pollen record of a complete glacial cycle from lowland Panama. J Veg Sci 1:105–118

Bush MB, Colinvaux PA, Wiemann C, Piperno DR, Liu KB (1990) Late Pleistocene temperature depression and vegetation change in Ecuadorian Amazonia. Quat Res 34:330–347

Cerri C (1979) Alterações e pedogênese em áreas graníticas situadas sob diferentes condições bioclimáticas encontradas no Brasil. Master Thesis, University of São Paulo

Desjardins Th, Volkoff B, Arend F, Cerri C (1991) Distributions de carbone total et de l’isotope 14C dans des sols ferralsitiques du Brésil. Sci Sol 29:175–187

Dzouc RS, Boutton TW, Caldwell MM, Smith BN (1985) Carbon isotope ratios of soil organic matter and their use in assessing community composition changes in Curlew Valley, Utah. Oecologia 66:17–24

Guillet B, Faire P, Mariotti A, Khobzi J (1988) The 14C dates and C3/C4 ratio of soil organic matter as a means of studying the past vegetation in intertropical regions: examples from Colombia (South America). Palaeoecol Palaeoecol Palaeoecol 65:15–51

Haffer J (1969) Speciation in Amazonian forest birds. Science 165:131–137

Higa NT (1989) Caracterização das fases sólida e líquida de solos e arenas derivados do granito sob floresta tropical Amazônica (Terra Nova do Norte – MT). PhD Thesis, Universidade de São Paulo

Jenkinson DS, Adams DE, Wild A (1991) Model estimates of CO2 emissions from soil in response to global warming. Nature 351:304–306

Table 2 Radicarbon ages (years BP) of soil organic matter along some soil profiles

| Depth (cm) | Altamira Alt-2 | Paragominas Par-1 | Nhecolândia Sal-2 | Salitre Sal-2 | Piracicaba Pir-2 | Londrina Lon-2 |
|-----------|----------------|------------------|-------------------|--------------|-----------------|---------------|
| 0–10      | modern          | modern            | modern             | 240          | modern           | modern        |
| 20–30     | modern          | modern            | modern             | 240          | modern           | modern        |
| 30–40     | modern          | modern            | modern             | 240          | modern           | modern        |
| 40–50     | 1440            | 4850              | 639               | 3700         | 3260            | 5450          |
| 50–60     | 3640            | 14190             | 2002              | 5550         | 3640            | 9340          |
| 60–70     | 2790            | 1483              | 2002              | 5550         | 3640            | 9340          |
| 70–80     | 3640            | 14190             | 2002              | 5550         | 3640            | 9340          |
| 80–90     | 1440            | 4850              | 639               | 3700         | 3260            | 5450          |
| 90–100    | modern          | modern            | modern             | 240          | modern           | modern        |
| 100–110   | 1440            | 4850              | 639               | 3700         | 3260            | 5450          |
| 110–120   | 3640            | 14190             | 2002              | 5550         | 3640            | 9340          |
| 120–130   | 4800            | 1483              | 2002              | 5550         | 3640            | 9340          |
| 130–140   | modern          | modern            | modern             | 240          | modern           | modern        |
| 140–150   | 2002            | 5550              | 3640              | 9340         | 3260            | 5450          |
| 150–160   | 4800            | 1483              | 2002              | 5550         | 3640            | 9340          |
| 160–170   | modern          | modern            | modern             | 240          | modern           | modern        |
| 170–180   | 4390            | 2002              | 5550              | 3640         | 9340            | 3260          |
| 180–190   | modern          | modern            | modern             | 240          | modern           | modern        |
| 190–200   | 6940            | 3640              | 9340              | 3260         | 5450            | 3260          |
| 200–300   | 22470           |                   |                   |              |                 | 3260          |

ab Valencia (1993); b Trumbore et al. (1995); c Victoria et al. (1995); d Boulet et al. (1995)
Ledru MP (1992) Modifications de la végétation du Brésil Central entre la dernière époque glaciaire et l’interglaciaire actuel. CR Acad Sci Paris Ser II 314:117–123

Ledru MP (1993) Late Quaternary environmental and climatic changes in central Brazil. Quat Res 39:90–98

Leyden BW (1985) Late Quaternary aridity and holocene moisture fluctuations in the Lake Valencia basin, Venezuela. Ecology 66:279–289

Mariotti A, Petershmitt E (1994) Forest savanna ecotone dynamics in India as revealed by carbon isotope ratios of soil organic matter. Oecologia 97:475–480

Markgraf V (1989) Paleoclimates in Central and South America since 18,000 BP based on pollen and lake-level records. Quat Sci Rev 8:1–24

Markgraf V (1991) Younger Dryas in southern South America? Boreas 20:63–69

Martin A, Mariotti A, Balesdent J, Lavelle P, Vuattoux V (1990) Estimate of organic matter turnover rate in savanna soil by 13C natural abundance measurements. Soil Biol Biochem 22:517–523

Martins PFS, Cerri CC, Volkoff B, Andreux F, Chauvel A (1991) Consequences of clearing and tillage on the soil of a natural Amazonian ecosystem. For Ecol Manage 38:273–282

McPherson GR, Boutton TW, Midwood AJ (1993) Stable carbon isotope analysis of soil organic matter illustrates vegetation change at the grassland/woodland boundary in southeastern Arizona, USA. Oecologia 93:95–101

Mondenesi MC, Matsui E, Volkoff B (1986) Relação 13C/12C nos horizontes humíferos superficiais e nos horizontes escuros profundos dos solos de campo e mata da região de Campos do Jordão, São Paulo, Brasil. In: Regional coloquio on soil organic matter studies. Centro de Energia Nuclear na Agricultura, Piracicaba, Brazil, pp 155–160

Pessenda LCR, Aravena R, Melfi AJ, Telles ECC, Boulet R, Valencia EPE, Tomazello M (1995) The use of carbon isotopes (13C, 14C) in soil to evaluate vegetation changes during the Holocene in Central Brazil. Radiocarbon 38

Prance GT (1973) Phylogeographic support for the theory of Pleistocene forest refuges in the Amazon Basin, based on evidence from distribution patterns in Caryocaraceae, Chrysophyllumaceae, Dichapetalaceae and Lecythidaceae. Acta Amazonica 3:5–28

Prance GT (1982) Forest refuges: evidence from woody angiosperms. In: Prance GT (ed) Biological diversification in the tropics. Columbia University Press, New York, pp 137–158

Prentice KC, Fung IY (1990) The sensitivity of terrestrial carbon storage to climate change. Nature 346:48–51

Rocha GC (1990) Características e dinâmica de coberturas pedológicas sobre rochas básicas nas regiões norte e sul do Brasil. Ph D Thesis, University of São Paulo

Schwartz D, Mariotti A, Lanfranchi R, Guillette B (1987) 13C/12C ratios of soil organic matter as indicator of vegetation changes in the Congo. Geoderma 39:97–103

Servant M, Fournier M, Soubies F, Sugui K, Turcq B (1989) Sècheresse holocène au Brésil (18–20° latitude Sud). Implications plaéometeorologiques. CR Acad Sci Paris Sér II 309:153–156

Servant M, Maley J, Turcq B, Absy ML, Brenac P, Fournier M, Ledru MP (1993) Tropical forest changes during the Late Quaternary in African and South American lowlands. Paleogeogr Paleoclimatol Paleocool 7:1–16

Tans PT, Fung IY, Takahashi T (1990) Observational constraints on the global atmospheric CO2 budget. Science 247:1431–1438

Trumbore S (1993) Comparison of carbon dynamics in tropical and temperate soils using radiocarbon measurements. Global Biogeochem Cycles 7:275–290

Trumbore SE, Davidson EA, Camargo PB, Nepstad DC, Martinelli LA (1995) Below-ground cycling of carbon in forests and pastures of eastern Amazonia. Global Biogeochem Cycles 9:515–528

Valencia EPE (1993) Datação por 14C e razão 13C/12C de solos sob climas tropical e subtropical do Brasil. Master Thesis, University of São Paulo

Van der Hammen T (1974) The Pleistocene changes of vegetation and climate in tropical South America. J Biogeogr 1:3–26

Vanzolini PE (1970) Zoologia sistêmática geografia e a origem das espécies. Inst Geogr Sao Paulo 3:1–56

Victoria RL, Fernández FA, Martinelli LA, Piccolo MC, Camargo PB, Trumbore S (1995) Past vegetation changes in the Brazilian Pantanal arboreal-grassy savannah ecotone by using carbon isotopes in the soil organic matter. Global Change Biol 1:165–171

Volkoff B, Cerri CC (1987) Carbon isotopic fractionation in subtropical Brazilian grassland soils. Comparison with tropical forest soil. Plant Soil 102:27–31

Volkoff B, Matsui E, Cerri CC (1982) Discriminação isotópica do carbono nos húmuses de latossolos e podzol na região amazônica do Brasil. In: Colóquio regional sobre matéria orgânica do solo. Piracicaba, pp 147–153

Wang Y, Cerling TE, Effand WR (1993) Stable isotope ratios of soil carbonate and soil organic matter as indicators of forest invasion of prairie near Ames, Iowa. Oecologia 95:365–369