The Holocene 11,2 (2001) pp. 250–254

Origin and dynamics of soil organic matter and vegetation changes during the Holocene in a forest-savanna transition zone, Brazilian Amazon region

L.C.R. Pessenda,[1] R. Boulet,[2] R. Aravena,[3] V. Rosolen,[4] S.E.M. Gouveia,[1] A.S. Ribeiro[1] and M. Lamotte[2]

([1] ^{14}C Laboratory, Centre for Nuclear Energy in Agriculture, University of São Paulo, Piracicaba SP, Postal Box 96, 13416-000, Brazil; [2] IRD, Institute of Geosciences, University of São Paulo, São Paulo SP, 01498-970, Brazil; [3] Department of Earth Sciences, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada; [4] Institute of Geosciences, University of São Paulo, São Paulo SP, 01498-970, Brazil)

Received 8 January 2000; revised manuscript accepted 11 July 2000

Abstract: Carbon isotope data on soil organic matter (SOM) were collected along an ecosystem transect 90 m in length that includes a tropical forest on the plateau, a transitional forest-savanna and savanna in a depression. Total organic carbon data show a significant increase in carbon content from sites representing forest ecosystem to sites representing savanna ecosystem. It was hypothesized that carbon accumulation in the depression is controlled by flooding conditions that slow down carbon decomposition and in part by carbon transport from the upper part of the transect (the savanna and the transition forest-savanna areas) into the depressions by water during the rainy season. The origin of the carbon was confirmed by using soil ^{13}C analysis. The savanna sites located in the depression showed $\delta^{13}C$ values between −19.5‰ and −22.5‰ indicating a mixture of C_3 and C_4 plants. The vegetation cover in the depression is predominantly C_3 grasses with $\delta^{13}C$ values of about −27‰ and −26‰. In the site under savanna located at an elevation slightly higher, the $\delta^{13}C$ value was more enriched (−16‰) showing the predominance of C_4 plants ($\delta^{13}C$ of −13.6‰). At the forest-savanna transition and in the forest ecosystem the $\delta^{13}C$ values were characteristic of C_3 plants (−25‰ and −28.1‰). ^{14}C and ^{13}C data indicate that the organic matter of mixed origin has been deposited for at least the last 7000 years in the savanna depressions. The ^{13}C pattern observed in the soil organic matter profiles indicate a predominance of C_3 plants in the early part of the Holocene. About 7000 to 4000 years ago, the data show the influence of C_4 plants, indicating forest regression associated with a drier climate than at present. The more recent ^{13}C records suggest forest expansion, and the return to a climate similar to the present.

A HOLOCENE RESEARCH REPORT

Key words: Carbon isotopes, soil organic matter, forest-savanna dynamics, palaeovegetation changes, Holocene, Brazilian Amazon region.

Introduction

About 80% of the Amazon basin is covered by deep lateritic soils. They are very old and characterized by relatively simple mineralogical composition (quartz, kaolinite, iron and aluminium oxides and hydroxides), with a very high diversity of organization and structures, constituted of solid, liquid and gaseous phases. The transfer of material by hydrological fluxes means that these soils are constantly changing due to the lateritic natural or human-influenced systems. The evaluation of the dynamics of such soil systems can be related to the present and to the past. The lateritic soils of the Amazon region support forest and savanna vegetation and are of fundamental importance in the bioclimatic equilibrium of the two ecosystems.

At the southern border of the sedimentary Amazon basin, under a humid tropical climate, the higher part of the landscape has large plateaus with topographic depressions. The soils are generally ferralitic, with hydromorphic characteristics in the depressions that

0959-6836(01)HL464RR

are flooded for at least 6–7 months during the rainy season. The present vegetation cover is represented by a patchwork of predominantly tropical forest and discontinuous natural savanna areas (Brasil, 1978).

This paper presents a study of the origin and dynamics of soil organic matter and vegetation changes which occurred during the late Pleistocene and Holocene, in a transition forest-savanna on lateritic soils in the southern Brazilian Amazon region. The research approach was based on measurement of the soil carbon content, determination of the $\delta^{13}C$ of soil organic matter, and radiocarbon dating of buried charcoal and samples from organic-rich horizons, collected in distinct soil locations covered by forest and savanna vegetation.

Study site

The study area is located in the southern border of the Amazon Sedimentary Basin (Figure 1), at km 79 of BR 319 (8°10′S; 63°51′W), Amazonas state, between the cities of Porto Velho (Rondonia state) and Humaitá (Amazonas state). The mean annual precipitation is about 2500 mm and the mean temperature is 25°C. Maximum precipitation occurs during the summer season (October–March) and the drier period is around June–August. Extensive flat areas and elevations of 200 and 250 m characterize the region. The soil cover is developed on sedimentary rocks of the Solimões formation, from Late Pliocene to early Pleistocene, constituted of continental sandy-clayey sediments (Sampaio and Northfleet, 1973). The vegetation cover is represented by natural tropical forest interspersed with savanna.

A trench 3 m deep and 90 m long was studied in the vegetation transition, with the forest on the plateau (point A) 2 m higher than the savanna (point E) in the depression (Figure 1). The soils according to FAO classification are Ferralitic Cambissol on part of the plateau (0–35 m), Plintic Gleysols in the savanna and the border of the depression (35–62 m) and Humic Plintic Gleysols (72–90 m) at the centre of the depression (Rosolen *et al.*, 1998). The vegetation cover is tropical forest at point A, a transition forest-savanna at point B and savanna from points C to E. Some of dominant plants in the forest ecosystem are *Eschweilera* sp., *Ischnosiphon* sp., *Miconia* sp. 1, *Miconia* sp. 2, *Brosimum* sp., *Cecropia* sp. 1. Predominant grass species at point C is *Andropogus* sp. (C_4 plant) and *Panicum parvifolium LAM* (C_3) at points D and E, both interspersed with trees, mainly *Curatella americana*, *Miconia* sp. and *Cassia* sp.

Material and methods

The sampling collection from soil surface to 290 cm depth was made in five locations (points A, B, C, D and E) of the trench (Figure 1).

Soil samples were dried at 60°C to constant weight, and root and plant remains were discarded by handpicking. Any remaining plant debris was removed by flotation in HCl 0.01 M, dried to constant weight and sieved. The soil fraction less than 0.200 mm were used for $\delta^{13}C$ analyses. Charcoal fragments were collected directly from the trench wall, from 5 cm to about 60 cm depth, in distinct vertical positions. A detailed description of the chemical treatment for soil and charcoal samples can be found in Pessenda *et al.* (1996a; 1996c). In the depression (location E), two samples of a rich organic horizon were collected at 0–10 cm and 20–30 cm depths. A sample mass of 20 g was treated with HCl 4% v/v for two hours at 80°C, following washings with distilled water until pH around 6.

The grain-size analysis was carried out at the Soil Science Department of the Escola Superior de Agricultura 'Luiz de Queiroz'. The ^{14}C analyses on large charcoal fragments and rich organic horizon samples were carried out at the Radiocarbon Laboratory, Centro de Energia Nuclear na Agricultura (CENA), following the standard procedure for liquid scintillation counting (Pessenda and Camargo, 1991). The ^{14}C analysis of small charcoal fragments was carried out at the Isotrace laboratory of the University of Toronto, employing the AMS technique. Radiocarbon data are reported as radiocarbon ages as years BP.

The $\delta^{13}C$ analysis and total organic carbon on soil samples were carried out at the Environmental Isotope Laboratory, University of Waterloo, using a Carlo Erba Analyzer attached to an Optima mass spectrometer. $^{13}C/^{12}C$ data are expressed in δ (‰) units relative to the PDB standard, and organic carbon is expressed as percentage of dry soil.

Results and discussion

Chronology

Radiocarbon dating was mainly carried out on pieces of charcoal found in the 50–60 cm soil horizon collected in the transect interval between 40 and 60 m. The radiocarbon dates range between 3810 and 4770 years BP. Radiocarbon analysis performed in the rich organic sediment found in the depression area (location E) produced dates of modern at 0–10 cm depth and 1650 years BP

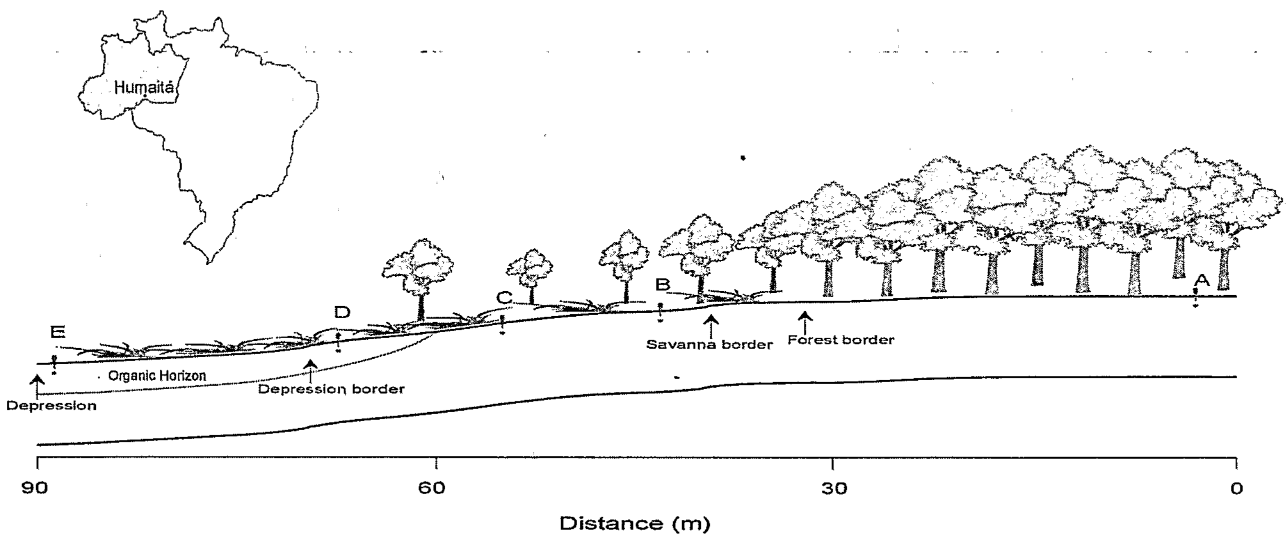

Figure 1 Map of Brazil showing the sampling location and the vegetation transect including the sampling points: into the forest (A), in the savanna border (B), in the savanna (C), in the middle of slope in the savanna (D) and in the middle of a depression, also under savanna vegetation (E).

Table 1 Radiocarbon dating of buried charcoal fragments and soil organic horizon in relation to lateral distance in the trench and soil depth

	Depth (cm)	Lateral distance (m)	^{14}C age (years BP)
Charcoal	45	40	4510 ± 90
Charcoal	50	46.5	4110 ± 60
Charcoal	50	48.3	4770 ± 270
Charcoal	50	60	3810 ± 80
Organic horizon	0–10	85	Modern
Organic horizon	20–30	85	1650 ± 50

at 20–30 cm depth (Table 1). A generalized age-depth profile for soils (humin fraction) based on 32 radiocarbon dates in the study area, which are in very good agreement with more than 50 humin/charcoal radiocarbon dates in distinct soil depth profiles from other sites in Brazilian Amazonas, can be represented by an age of 5000–6000 years for the 90–100 cm soil horizon and 10 000–12 000 years for the 190–200 cm soil depth (Freitas, 1999; Gouveia *et al.*, 1997; 1999; Gouveia and Pessenda, 2000; Pessenda *et al.*, 1996a; 1996b; 1998a; 1998b; 1998c).

Grain-size and carbon profiles

The soils are clayey in the entire profile. The carbon data show the typical profiles of decreasing carbon content with depth (Figure 2). The shallow soil horizons (0–10 cm) show carbon content of 1.9–3.1% in the sites representative of forest ecosystem (A, B). Slightly higher carbon content is observed at similar depths in the sites (C, D) representing the savanna ecosystem. These values are typical for soils in savanna and forested ecosystem in the southern and northern part of the Amazon basin (Desjardins *et al.*, 1996; Gouveia *et al.*, 1997; Pessenda *et al.*, 1998a; 1998c). However, a significant increase to carbon values as high as 10% is observed in location E, also under savanna vegetation. Site E is located in a depression, therefore the higher carbon content, that is also observed in the carbon content-depth profiles, may be associated with a better preservation of the organic matter due to the fact that these areas are flooded for at least six months during the rainy season. It is well known that decomposition of organic matter underwater, maybe with reducing conditions, is much slower than under oxidizing conditions that prevail in the non-flooded area. Furthermore, carbon transport of organic matter from the relatively higher savanna and forested areas (elevation of up to about 2 m above the depression) can also contribute to carbon accumulation in the depression. The hypothesis of the origin of the organic matter will be evaluated using the $\delta^{13}C$ data.

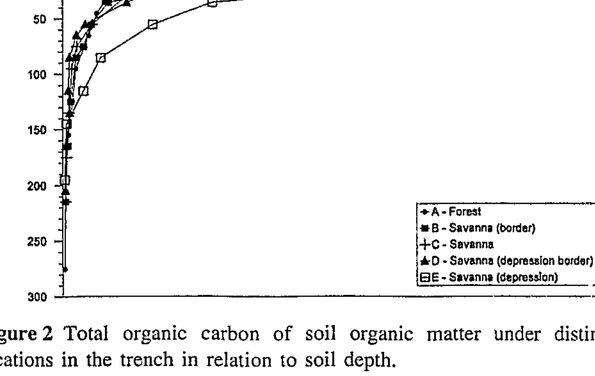

Figure 2 Total organic carbon of soil organic matter under distinct locations in the trench in relation to soil depth.

$\delta^{13}C$ data

A significant carbon isotopic difference is observed in the shallow soil horizon (0–10 cm) between the sites representing the forested and the savanna areas (Figure 3). The data at site C show a $\delta^{13}C$ value of –16‰ compared to values of –28.1‰ and –25‰ for the forested areas (sites A and B). This pattern is related to the predominance of C_4 plants in the savanna vegetation, represented by the predominant *Andropogun* sp. with a $\delta^{13}C$ of about –13.6‰. These plants are much more enriched in ^{13}C than the C_3 plants that form the forest. This is a well-documented pattern in the Amazon region (Desjardins *et al.*, 1996; Gouveia *et al.*, 1997; Pessenda *et al.*, 1998a; 1998b; 1998c).

However, at sites D and E that are also under savanna vegetation, the trend of $\delta^{13}C$ is related to values typical of a mixture of C_3 and C_4 plants. Site D, located in the beginning of the depression, has a $\delta^{13}C$ value of –19.5‰, while site E located in the middle of the depression has a $\delta^{13}C$ value of –22.5‰. Both sites are covered by the C_3 grass *Panicum parvifolium* LAM with a $\delta^{13}C$ of –27‰. In such a situation we could expect more depleted ^{13}C values in the shallow soil horizon in both sites. The more enriched values found can probably be associated with transport of organic matter from the savanna areas located in the higher part of the transect (C) which are characterized by $\delta^{13}C$ values of –13.5‰ and –16‰ (C_4 grass). Therefore, the ^{13}C data support the hypothesis, based on carbon content, that part of the organic matter preserved in the depression areas was transported into these areas from the higher locations of the transect represented by location C, probably during periods of intense rains. The amount of precipitation in the study area is around 2500 mm. It is important to point out that hydromorphic soils found in the savanna areas studied are also formed in depressions in the forested areas (Rosolen *et al.*, 1998).

Based on the $\delta^{13}C$ depth profiles and ^{14}C data (Figure 3), it is possible to postulate that significant vegetation changes have occurred in the study area during the Holocene. These profiles show $\delta^{13}C$ values around –26‰ in the lower part of the profiles in all sites indicating that during this time (10 000–12 000 years; Gouveia *et al.*, 1997; Pessenda *et al.*, 1998a; 1998b; 1998c), the study area was covered by forest vegetation. A significant change toward more enriched $\delta^{13}C$ values is observed at sites A, B, C and D reaching values as high as –14‰ in the 20–30 cm soil horizon interval. This trend, which starts in the organic matter preserved approximately at the 120–130 cm depth interval, is a clear indication of a major influence of C_4 plants during the time represented in the soil horizon between 130 and 30 cm, reaching a maximum in the 20–30 cm soil interval. However, the ^{13}C enrichment trend is not so pronounced at site E, reaching only values around –21‰ in the soil interval 130–30 cm, indicating that most of the organic matter deposited during the time represented by this soil horizon was a mixture of C_3 and C_4 plants similar to the present conditions. Radiocarbon dates obtained in soils in the same region (Pessenda *et al.*, 1998a; 1998b; 1998c) and the data obtained in the study (Table 1), show that at least this organic matter was deposited during the last 7000 years. Based on soil ^{13}C data, similar vegetation changes during the same period had also been documented in the northern (Roraima state) and southern (Rondonia state) Amazon region (Desjardins *et al.*, 1996; Pessenda *et al.*, 1998a), as well as through pollen analyses of lake sediments in Carajás, central-northern (Pará state) Amazon region (Sifeddine, 1994).

It is important to highlight that the ^{13}C pattern observed in the soil organic matter profiles in the study area was also measured in a series of soil profiles collected in a 200 km transect that included the study site. This transect is located between the cities of Humaitá (121 km north of the study site) and Porto Velho (79 km south of the study site). Data from this transect indicate that the savanna vegetation was present at least about 30 km south

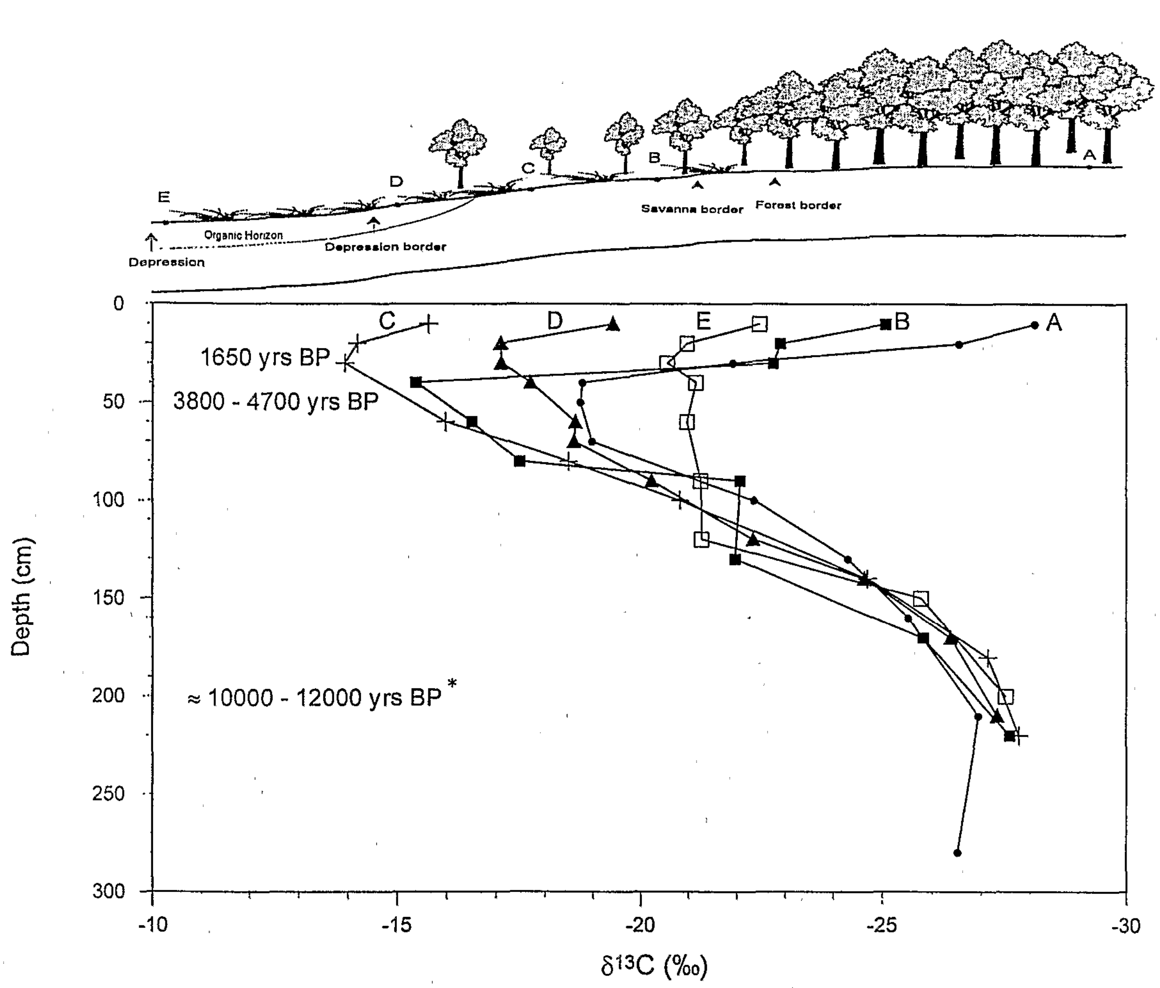

Figure 3 $\delta^{13}C$ values of soil organic matter under distinct locations in the trench in relation to soil depth. The radiocarbon datings were obtained from soil organic horizon and buried charcoal samples. *Average values obtained from soil (humin) samples in the horizon 190–200 cm in the Amazon region (Gouveia *et al.*, 1997; Pessenda *et al.*, 1998b; 1998c).

and 100 km north of the study site, during the stage of forest regression between about 8000 and 4000 years ago (Freitas *et al.*, 2001). Although there is no information about palaeovegetation changes along an east–west axis for the study site, the finding of carbon transport into the depression areas in the forest-savanna transition region has important implications for carbon exchange between the different ecosystems and carbon fluxes in the Amazon basin.

Conclusions

This paper shows a complex relationship during the last 10000 years between vegetation changes and carbon dynamics in a plateau-depression landscape that is part of the main ecosystems (forest and savanna) in the Amazon Basin. The data show a significant increase in soil carbon content from more elevated sites representative of forest ecosystem (1.9–3.1%) to higher values in sites representing savanna ecosystem. The differences were mainly observed in the site located in a depression, where the organic matter was deposited and shows carbon values high as 10% of soil dry matter. Part of this organic matter was probably transported by water during rainy periods from the savanna site covered by C_4 grass vegetation, located in the higher part of the ecosystem transect. The preservation of organic matter in the depression could be associated with flooding that occurs for at least six months of the year.

The hypothesis of the origin of the organic matter was confirmed by using ^{13}C data of soil samples and vegetation. In the savanna site represented by site C, the $\delta^{13}C$ of –16‰ shows the predominance of C_4 plants in this area. In the savanna sites, located in the beginning and middle of depression and covered by C_3 grass (−27‰), the $\delta^{13}C$ values of –19.5‰ to –22.5‰ reflect the contribution of organic matter from C_4 plants probably transported from the areas represented by site C. At the savanna border and forest ecosystems the $\delta^{13}C$ values were characteristic of C_3 plants (–25‰ and –28.1‰).

The ^{14}C data indicate that the organic matter of a mixed origin of C_3 and C_4 plants has been deposited for at least the last 7000 years in the depression areas in the ecosystem transect. The ^{13}C pattern observed in the soil organic matter profiles indicate a predominance of C_3 plants in the vegetation in the study area in the early part of the Holocene. About 7000 to 4000 years ago, the data show the influence of C_4 plants, indicating forest regression associated with a drier climate than the present. The more recent portion of ^{13}C records indicates the expansion of the forest, and probably the return to a climate similar to the present.

This study shows that significant vegetation changes occurred in the transition area between forest and savanna vegetation, located in the km 79 of BR-319, southern Amazon State, Brazilian Amazon region. This paper confirms and supports a previous hypothesis (Pessenda *et al.*, 1998a; 1998b; 1998c) that these types of boundary area are particularly sensitive to climatic changes and should be the focus of more extensive research, dealing with climate and past vegetation dynamics in the Amazon region.

Acknowledgements

We gratefully acknowledge financial support from São Paulo Foundation For Research (FAPESP) grant no. 97/11733-4 and

PRONEX/FINEP no. 41.96.0938.00. We also thank M.V.L. Cruz for sample preparation and ^{14}C analyses and R. Drimmie, Head of Environmental Isotopes Laboratory of the University of Waterloo, Canada, for the ^{13}C and carbon analyses.

References

Brasil, Ministério das Minas e Energia 1978: *Projeto Radambrasil.* Folha SB 20 Purus. Rio de Janeiro, *Levantamento de Recursos Naturais* 17, 566 pp.

Desjardins, T., Carneiro Filho, A., Mariotti, A., Chauvel, A. and **Girardin, C.** 1996: Changes of the forest-savanna boundary in Brazilian Amazonia during the Holocene as revealed by soil organic carbon isotope ratios. *Oecologia* 108, 749–56.

Freitas, H.A., Pessenda, L.C.R., Aravena, R., Gouveia, S.E.M., Ribeiro, A.S. and **Boulet, R.** 2001: Lake Quaternary vegetation dynamic record in southern Amazon inferred from carbon isotopes in soil organic matter. *Quaternary Research*, in press.

Gouveia, S.E.M. and **Pessenda, L.C.R.** 2000: Datation par le ^{14}C de charbons inclus dans le sol pour l'étude du rôle de la remontée bologique de matière et du colluvionnment dans la formation de latosols de l'état de São Paulo, Brésil. *C. R. Acad. Sci. Paris* 330, 133–38.

Pessenda, L.C.R., Aravena, R., Boulet, R., Roveratti, R. and **Gomes, B.M.** 1997: Dinâmica de vegetações durante o Quaternário recente no sul do Amazonas, indicada pelos isótopos do carbono do solo. *Geochimica Brasiliensis* 11, 355–67.

Gouveia, S.E.M., Pessenda, L.C.R., Boulet, R., Aravena, R. and **Scheel-Ybert, R.** 1999: Isótopos do carbono dos carvões e da matéria orgânica do solo em estudos de mudança de vegetação e clima no Quaternário e da taxa de formação de solos do estado de São Paulo. *Anais da Academia Brasileira de Ciências* 71(4–11), 969–80.

Pessenda, L.C.R. and **Camargo, P.B.** 1991: Datação. radiocarbônica de amostras de interesse arqueológico e geológico por espectrometria de cintilação líquida de baixa radiação de fundo. *Química Nova* 14(2), 98–103.

Pessenda, L.C.R., Aravena, R., Melfi, A.J. and **Boulet, R.** 1996a: The use of carbon isotopes (^{13}C, ^{14}C) in soil to evaluate vegetation changes during the Holocene in central Brazil. *Radiocarbon* 38, 191–201.

Pessenda, L.C.R., Gomes, B.M., Aravena, R., Ribeiro, A.S., Boulet, R. and **Gouveia, S.E.M.** 1998a: The carbon isotope record in soils along a forest-cerrado ecosystem transect: implications for vegetation changes in the Rondonia state, southwestern Brazilian Amazon region. *The Holocene* 8, 599–604.

Pessenda, L.C.R., Gouveia, S.E.M., Aravena, R., Gomes, B.M.; Boulet, R. and **Ribeiro, A.S.** 1998b: Radiocarbon dating and stable carbon isotopes of soil organic matter in forest-savanna boundary areas in the southern Brazilian Amazon forest. *Radiocarbon* 40, 1013–22.

Pessenda, L.C.R., Gouveia, S.E.M., Gomes, B.M., Aravena, R., Boulet, R. and **Ribeiro, A.S.** 1998c: Studies of palaeovegetation changes in the central Amazon by carbon isotopes (^{12}C, ^{13}C, ^{14}C) of soil organic matter. In *Proceedings of the Symposium on Isotope Techniques in the Study of Past and Current Environmental Changes in the Hydrosphere and the Atmosphere*, IAEA-SM-349/46, Vienna, Austria, 645–52.

Pessenda, L.C.R., Valencia, E.P.E., Martinelli, L.A. and **Cerri, C.C.** 1996b: ^{14}C measurements in tropical soil developed on basic rocks. *Radiocarbon* 38, 203–208.

Rosolen, V., Fritisch, E., Boulet, R., Melfi, A.J., Lamotte, M., Grimaldi, M., Eschenbrenner, V. and **Magat, Ph.** 1998: Soil differentiation in a toposequence characteristic of the low plateaux landscapes of the southern part of upper Amazon basin (Solimões sediments, Brazil). World Congress of Soil Science, France.

Sampaio, A. and **Northfleet, A.** 1973: Estratigráfica correlação das bacias sedimentares brasileiras. *Ann. 27 Congresso Sociedade Brasileira de Geologia, Aracaju, Brasil* 3, 189–206.

Sifeddine, A., Frohlich, F., Fournier, M., Martin, L., Servant, M., Soubiès, F., Turcq, B., Suguio, K. and **Volkmer-Ribeiro, C.** 1994. La sédimentation lacustre indicateur de changements des paléoenvironnements au cours des 30000 derniérs années (Carajás, Amazonie, Brésil). *C. R. Acad. Sci. Paris* 318(II), 1645–52.