^{14}C DATING AND STABLE CARBON ISOTOPES OF SOIL ORGANIC MATTER IN FOREST–SAVANNA BOUNDARY AREAS IN THE SOUTHERN BRAZILIAN AMAZON REGION

L. C. R. PESSENDA,[1] S. E. M. GOUVEIA,[1] RAMON ARAVENA,[2] B. M. GOMES,[3] RENE BOULET[4] and A. S. RIBEIRO[5]

ABSTRACT. This study, which was carried out in the southern Brazilian Amazon region (Rondônia state and Humaitá, Southern Amazon state), presents and discusses the significance of carbon isotope data measured in soil profiles collected across natural boundaries of forest to savanna vegetation. The main objective of this study was to evaluate the expansion-regression dynamics of these vegetation units in relation to climate changes during the Holocene. ^{14}C data from charcoal, soil organic matter (SOM) and its component humin fraction indicate that the organic matter in the studied soils is essentially Holocene in origin. ^{13}C data indicate that C_3 type plants were the dominant vegetation at all study areas in the early Holocene, and during the entire Holocene, in the forest sites of Central Rondônia state and in the forest site 50 km from the city of Humaitá. ^{13}C data also indicate that C_4 plants have influenced significantly the vegetation at the transitional forest and the Cerrado (wooded savanna) sites of Southern Rondônia state and the forest ecosystem located 20 km from the Humaitá city. These typical C_4 type isotopic signatures probably reflect a drier climate during the mid-Holocene. The ^{13}C records representing probably the last 3000 yr show an expansion of the forest, due to a climatic improvement, in areas previously occupied by savanna vegetation. These results and other published data for the Amazon region indicate that the areas representing today's forest-savanna boundaries have been determined by significant vegetation changes during the Holocene. The boundary between forest and savanna vegetation seems to be quite sensitive to climatic change and should be the focus of more extensive research to correlate climate and past vegetation dynamics in the Amazon region.

INTRODUCTION

Traditionally, the Amazon region has been regarded as an environmentally stable ecosystem through out most of the Quaternary (Schwabe 1969; Richards 1973). However, more recent evidence indicates that this region was affected by several dry episodes during the late Pleistocene (Van der Hammen 1972, 1974; Absy and Van der Hammen 1976; Absy *et al.* 1991; Sifeddine 1994) and in the Holocene (Absy 1980; Liu and Colinvaux 1988; Absy *et al.* 1991; Desjardins *et al.* 1996; Sanaiotti 1996; Pessenda *et al.* 1997a,b). These studies suggest that a significant and dynamic process of expansion-regression occurred between the tropical forest and savanna vegetation, with vegetation changes controlled primarily by paleoclimatic variations (Liu and Colinvaux 1988; Absy *et al.* 1991). The refuge theory in explanation of the high degree of biodiversity in tropical South America suggests that the modern situation resulted from differential species evolution in forest patches. These were isolated when continuous forest was replaced partially with savanna during dry periods of the Pleistocene and Holocene (Haffer 1969; Vanzolini 1970; Prance 1973). Consequently, the most likely hypothesis for the origin and the present distribution of the forest-savanna boundary, also called forest-savanna mosaic, in the Amazon region is paleoclimatic change (Desjardins *et al.* 1996).

One approach to study vegetation changes in the past is to evaluate the carbon isotopic composition (^{12}C, ^{13}C and ^{14}C) of soil organic matter (SOM). The stable carbon composition of SOM contains information regarding the occurrence of C_3 (forest) and/or C_4 (grasses) plant species in past plant communities, and their relative contribution to the net primary productivity by the plant community (Throughton, Stout and Rafter 1974; Stout, Rafter and Throughton 1975). $\delta^{13}C$ values of C_3 plant

[1]Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, 13400-970 Piracicaba, São Paulo, Brazil
[2]Waterloo Center for Groundwater Research, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
[3]Universidade de Rondônia, Campus de Ji-Parana, Rondônia, Brazil
[4]ORSTOM, Instituto de Geociencias, Universidade de São Paulo, 05508-900, SP, Brazil
[5]Instituto de Biologia, Universidade de Sergipe, Aracaju, Sergipe, Brazil

Proceedings of the 16th International ^{14}C Conference, edited by W. G. Mook and J. van der Plicht
RADIOCARBON, Vol. 40, No. 2, 1998, P. 1013–1022

species range from *ca.* –32‰ to –20‰, with a mean of –27‰, whereas $\delta^{13}C$ values of C_4 species range from –17‰ to –9‰, with a mean of –13‰. Thus, C_3 and C_4 plants have distinct $\delta^{13}C$ values and differ from each other by *ca.* 14‰ (Boutton 1991).

As a naturally occurring radioisotope, ^{14}C has been used in the Amazon region as a useful tracer tool for the study of carbon dynamics in tropical soils and carbon cycling in forests and pastures (Trumbore 1993; Trumbore *et al.* 1995) and to provide information about soil chronology in paleoenvironmental studies in distinct regions of Brazil (Valencia 1993; Gomes 1995; Gouveia 1996; Pessenda *et al.* 1996b, 1997, 1998; Sanaiotti 1996). ^{14}C dating of charcoal present in soils has also been used in the Amazon region for chronological purposes (Soubies 1980; Saldarriaga and West 1986; Desjardins *et al.* 1996). The presence of charcoal has been linked to the occurrence of dry phases in the eastern Amazonia (Absy 1982; Absy *et al.* 1991; Van der Hammen 1982).

This paper is focuses on the applications of ^{14}C dating of SOM, humin fraction and charcoal samples collected in soils representative of forest-savanna boundary areas, located in the Southern Amazon region. This analysis is complemented by ^{13}C data from SOM that provide information about vegetation changes in the study region during the Holocene.

METHODS

Study Sites

The study sites are located in two regions: in the Rondônia state, northwestern part of Brazil, and Humaitá, southern part of Amazon state (Fig. 1). The four sampling sites in the Rondônia region are located close to the cities of Vilhena (12°42′S, 66°07′W), representing Cerrado vegetation, a wooded savanna (Ledru 1993), Pimenta Bueno a site supporting vegetation transitional between cerrado and natural forest (11°49′S, 61°10′W) and natural forest (11°46′S, 61°15′W), and Ariquemes (10°10′S, 62°49′W), under natural forest vegetation. The soil types from the study sites are given in Table 1. The distance between Vilhena and Pimenta Bueno is *ca.* 200 km and from Pimenta Bueno to Ariquemes *ca.* 400 km. In Pimenta Bueno, the distance between the forest transition and natural forest sites is *ca.* 40 km. The sampling sites in Humaitá (7°31′S, 63°2′W) region are located along the road BR 319, and form a transect ecotone including three distinct vegetation communities: a savanna (Campos de Humaitá), a savanna-forest transition (Campos de Humaitá-terra firme forest) and forest. Two sampling points are under savanna vegetation (those located at 5 and 17 km from Humaitá), one at 18 km from the city and supporting savanna-forest transition and two under forest vegetation at 20 km and 50 km distance. The soil types from the study sites are given in Table 1.

Sampling and Analytical Aspects

Soil samples were collected from excavations located in areas under distinct vegetation communities. Soil sampling involved the collection up to 10 kg of material at 10-cm intervals to a maximum depth of 200 cm. Samples were dried at 60°C to constant weight and root and plant remains were discarded by hand-picking. Any remaining plant debris was removed by flotation in HCl 0.01M, the soil was then redried to constant weight and sieved. The prepared soil fraction <0.200 mm (total soil) and the humin fraction were used for ^{13}C and ^{14}C analyses. Charcoal samples were also collected whenever available for carbon isotope analysis. A detailed description of the chemical treatment for soil and charcoal samples is given in Pessenda *et al.* (1996a,b).

The grain size analyses were carried out at the Soil Science Department of the Escola Superior de Agricultura "Luiz de Queiros". The ^{14}C analyses of SOM and some humin and charcoal 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 measurement of ^{14}C in small humin fraction and charcoal samples was carried out using the AMS technique at the Isotrace laboratory of the University of Toronto. ^{13}C analysis and the determination of carbon contents in soil samples were carried out at the Environmental Isotopes Laboratory, University of Waterloo, Ontario, Canada. ^{14}C data are reported as percent modern carbon (pMC) and as conventional ^{14}C yr BP. The ^{13}C data is expressed (in δ notation) as per mil and relative to the PDB standard.

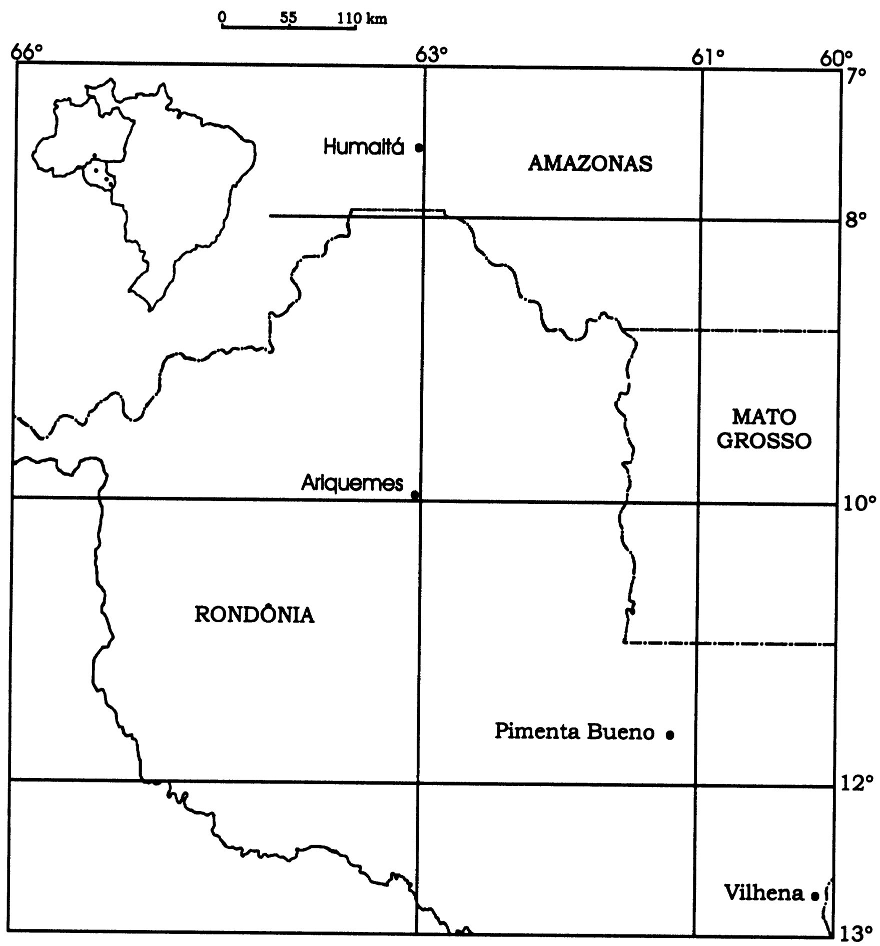

Fig. 1. Location of study sites

RESULTS AND DISCUSSION

Soil Properties

The total organic carbon contents of Rondônia and Humaitá soils are presented in Table 2. In general, the Humaitá soils record lower carbon contents than the Rondônia soils. The highest values (between 2.0 and 3.5%) in both regions are observed in the shallow part of the soil. The profiles show a decrease of carbon concentration with depth reaching values as low as 0.05% at the deepest sampling interval. The profiles of carbon content observed at the study sites were similar to results

https://doi.org/10.1017/S0033822200018981 Published online by Cambridge University Press

TABLE 1. Soil Types of the Study Regions

	Rondônia				Humaitá				
	Forest Ariquemes	Forest P. Bueno	Forest Transition P. Bueno	Cerrado Vilhena	Forest (50 km*)	Forest (20 km*)	Forest transition (18 km*)	Savanna (17 km*)	Savanna (5 km*)
Brazilian Classification	Podzólico Vermelho-Amarelo	Latossolo Amarelo	Latossolo Vermelho Escuro	Latossolo Vermelho-Amarelo	Podzólico Vermelho-Amarelo	Cambissolo Álico	Cambissolo Álico	Litossolo	Plintossolo
Soil Taxonomy (USDA)	Ultisol	Oxisol	Oxisol	Oxisol	Ultisol	Dystropept	Dystropept	Troporthent	Tropaquept

*Distance from the city of Humaitá

TABLE 2. Percentage of Total Organic Carbon of Soil Samples from Rondônia and Humaitá

Sample horizon (cm)	Rondônia				Humaitá				
	Forest Ariquemes	Forest P. Bueno	Forest Transition	Cerrado	Forest (50 km*)	Forest (20 km*)	Forest Transition (18 km*)	Savanna (17 km*)	Savanna (5 km*)
0–10	1.8	2.6	2.4	3.5	--	2.1	0.9	2.1	1.3
10–20	1.5	2.1	1.6	1.9	1.3	1.8	0.8	--	--
20–30	1.2	2.8	1.1	1.7	0.9	1.5	0.6	0.8	0.5
30–40	0.7	1.2	1.1	1.2	--	--	--	--	--
40–50	0.6	1.1	0.8	1.2	0.6	0.9	1.0	0.6	0.2
50–60	--†	1.5	0.8	--	--	0.8	0.4	0.4	--
60–70	--	0.9	0.6	--	0.5	0.8	0.3	0.2	0.2
70–80	0.9	0.8	0.5	1.0	--	0.6	0.3	--	--
80–90	--	0.6	0.4	--	0.4	0.6	0.2	0.2	0.2
90–100	0.5	0.4	0.2	1.0	--	0.5	0.2	0.2	--
100–110	--	0.4	0.7	--	0.4	0.5	0.2	0.1	0.1
110–120	--	0.3	0.9	--	--	--	--	--	--
120–130	-	0.4	--	--	0.3	0.4	0.1	0.1	0.1
130–140	0.3	0.5	0.9	0.7	--	0.4	0.1	0.1	--
140–150	--	0.5	--	--	0.2	0.3	0.1	0.1	0.2
150–160	--	0.5	--	--	--	0.3	0.1	0.1	--
160–170	0.3	0.5	1.0	0.8	0.2	0.3	0.1	0.1	0.1
170–180	--	0.4	0.5	--	--	0.3	0.1	0.05	--
180–190	--	0.4	--	--	0.2	0.3	0.1	0.05	0.1
190–200	--	0.3	0.3	0.8	0.2	--	--	--	0.1

*Distance from the city of Humaitá
†Samples not analyzed

obtained from most Amazonian oxisols (Volkoff and Cerri 1988; Desjardins *et al.* 1996). However, throughout its depth profile the Cerrado soil (wooded savanna) has a higher carbon content than recorded by forest soils, and this is not in agreement with previous published work. Sanches *et al.* (1982) show that soils under tropical forest vegetation generally have higher C contents in their uppermost layers than soils under tropical savanna vegetation; Desjardins *et al.* (1996) obtained the same general pattern for oxisols collected in Roraima, northern Brazilian Amazon region. In those instances, the lower C content for the savanna soil was correlated with lower clay content and smaller litter inputs. No relationship was observed between clay content and organic carbon in the Rondônia and Humaitá soils (Gomes 1995; Gouveia 1996). The highest soil clay content (54–78%) was found in the forest transition site at Pimenta Bueno, that presented lower C concentration than the Cerrado site (soil clay content of 36–57%) at Rondônia. Furthermore, the lowest total C content for the four soil profiles of the Rondônia region was observed in the forest soil at Ariquemes (Table 2). It is possible that higher carbon contents measured in the Cerrado soil profile at Rondônia region could be due to the presence of charcoal fragments that were observed in this profile. In the Humaitá region, the shallow layers of the savanna soils record carbon contents that are similar or slightly higher than those of forest soils (Table 2). However, this is probably due to peat formation, since each site is located in a depression that is completely flooded during at least six months in the year. Clay contents for the Humaitá soils tend to be quite similar (26–50%) but with the exception of the savanna site 17 km from Humaitá that shows values of up to 64% (Gouveia 1996).

Radiocarbon Dates

The ^{14}C data from the Rondônia and Humaitá sites are given in Tables 3 and 4. The measurements from Rondônia are derived from the total SOM and some charcoal samples. In the case of the Humaitá soils, SOM and/or the humin fraction were dated. These data show clearly the influence of bomb ^{14}C penetration in the first 20 cm at least in both regions. The age profiles from the SOM at the Rondônia sites range between 1590 and 3020 yr BP for the 90–100-cm interval, increasing to values of 3310 and 3550 yr BP at the deepest (190–200 cm) sampling interval. It seems that translocation of recent (post-bomb) carbon down the soil profile is most pronounced at the forest site in Pimenta Bueno, which also shows the youngest age for the 90–100-cm depth interval.

The charcoal data reveal significantly higher ages when compared to the stratigraphically identical SOM samples. At the forest site in Pimenta Bueno, charcoal gives a date of 2050 yr BP at a depth of 55 cm compared to an age of only 1590 yr BP for the SOM in the 90–100 cm interval. An age difference of almost 3000 yr BP is observed between charcoal and SOM collected at 90–100 cm depth in the Cerrado profile. The largest age difference is observed in the forest transition between charcoal (7000 BP, 155 cm) and the SOM (3310 and 3550 BP, 190–200 cm) at the forest site in Pimenta Bueno and Cerrado, respectively. The ^{14}C data clearly document the effect of translocation of shallow, more recent carbon down the soil profile, which is reflected on the SOM dates. The trend of ^{14}C age increase with soil depth and the occurrence of charcoal ^{14}C ages that are significantly older than those recorded by the soil total soil fraction have been reported from other sites and soils in Brazil (Valencia 1993; Gomes 1995; Gouveia 1996; Pessenda *et al.* 1996a,b).

The Humaitá SOM records much older dates than that in the Rondônia soils (Tables 3 and 4). For example, the deepest samples collected from the Rondônia region *ca.* 3,550 yr BP compared with a range of 6530–10,860 yr BP at similar depth in the Humaitá soils. Furthermore, it would appear that the savanna soils have preserved carbon that is much older than the forest soils at Humaitá. The preservation of older carbon in soils has been correlated to its clay content and the rates of organic matter decomposition (Scharpenseel and Becker-Heidmann 1989). However, no clear differences are observed in the clay content between savanna and forest soils at our study sites (Gomes 1995; Gou-

TABLE 3. ^{14}C Dating of Total Soil and Charcoal Samples from Rondônia Sites in Relation to Soil Depth

Sample Horizon (cm)	*Forest-Ariquemes* ^{14}C pMC	BP	$\delta^{13}C$ (‰)	*Forest-P. Bueno* ^{14}C pMC	BP	$\delta^{13}C$ (‰)	^{14}C (BP)
0–5	125.0 ± 0.9	Modern	−29.5	113.9 ± 0.8	Modern	−28.9	--
15–20	108.4 ± 0.8	Modern	−28.2	108.4 ± 0.8	Modern	−28.1	--
20–30	96.9 ± 0.7	250 ± 60	−27.7	108.5 ± 0.8	Modern	−27.7	540 ± 100†
30–40	--*	--	−26.9	--	--	−27.4	--
40–50	--	--	−26.3	--	--	−28.2	--
70–80	--	--	−26.4	--	--	--	--
90–100	73.6 ± 0.6	2460 ± 70	−26.9	82.1 ± 0.7	1590 ± 70	−25.0	5930 ± 130†
155†	--	--	--	--	--	--	--
160–170	66.6 ± 0.7	3270 ± 90	−26.3	--	--	--	--
190–200	--	--	--	66.2 ± 0.6	3310 ± 80	−24.1	--

Sample Horizon (cm)	*Forest Transition* ^{14}C pMC	BP	$\delta^{13}C$ (‰)	*Cerrado* ^{14}C pMC	BP	$\delta^{13}C$ (‰)
0–5	123.0 ± 0.8	Modern	−28.1	130.5 ± 0.9	Modern	−21.1
15–20	108.5 ± 0.9	Modern	−24.5	124.4 ± 0.9	Modern	−15.0
20–30	98.1 ± 0.7	160 ± 60	−20.6	93.5 ± 0.7	530 ± 65	−14.8
30–40	--*	--	−19.1	--	--	−14.2
40–50	--	--	−18.8	--	--	−14.4
70–80	78.2 ± 0.6	1970 ± 60	--	--	--	−15.9
90–100	73.8 ± 0.6	2440 ± 70	−21.7	68.6 ± 0.6	3020 ± 70	−18.6
155†	38.3 ± 0.7	7000 ± 130*	--	--	--	--
160–170	--	--	−27.9	--	--	−19.6
190–200	--	--	−30.6	64.3 ± 0.5	3550 ± 70	−18.3

*Samples not analyzed

veia 1996). It is possible that highest litter inputs (younger material) in the forested soils, as a consequence of its highest biomass, and the decomposition of recent materials as tree roots at the deepest part of the profiles, in comparison with the savanna vegetation, can explain the youngest dates observed in the forest soils.

The ages of the humin fraction samples are much older than those of the corresponding SOM in the Humaitá soils, with an difference up to 2000 yr BP. These data indicate the presence of carbon that was deposited during late Glacial and early Holocene time. ^{14}C dates covering the Holocene have also been obtained from charcoal and humin samples taken from soil profiles representing surface to 200-cm depth, at distinct sites and soils in Brazil and including one site in the northern part of the Amazon region (Valencia 1993; Pessenda *et al.* 1996a,b).

^{13}C Results and Paleoclimatic Interpretation

This section presents a short discussion of the ^{13}C data presented in Tables 3 and 4. A detailed interpretation of the ^{13}C profiles is reported elsewhere (Pessenda *et al.* 1997, 1998). The $\delta^{13}C$ at the forest sites in both study regions ranges from −29.5‰ and −27‰ for the shallow soil horizon to −26.3‰ and −24‰ in the deeper (160–200 cm) part of the soil profile. This isotopic enrichment pattern is probably due to the progressive decomposition of soil organic matter (Nadelhoffer and Fry 1988; Becker-Heidmann and Scharpenseel 1992) and these isotopic signatures are typical for soil organic matter generated by C_3 vegetation type (Cerri *et al.* 1985; Boutton 1991; Desjardins *et al.*

TABLE 4. Radiocarbon Dating of Total Soil (SOM) and Humin Samples from Humaitá Sites in Relation to Soil Depth

Samples		Total soil		Humin	
Horizon (cm)	pMC	Age (BP)	$\delta^{13}C$ (‰)	pMC	Age (BP)
Forest (50 km*)					
10–20	111.1 ± 0.9	Modern	−29.4	--	--
20–30	95.6 ± 0.7	360 ± 60.0	−27.9	--	--
90–100	55.3 ± 0.5	4760 ± 70.0	−27.3	--	--
190–200	45.3 ± 0.4	6530 ± 80	−24.8	--	--
Forest (20 km*)					
0–10	109.6 ± 0.8	Modern	−26.7	--	--
20–30	102.1 ± 1.0	Modern	−22.0	--	--
90–100	74.6 ± 0.6	2360 ± 60	−20.7	53.4 ± 3.5	5040 ± 530
180–190	46.6 ± 0.5	6130 ± 90	−24.0	36.2 ± 1.9	8170 ± 430
Forest Transition (18 km*)					
0–10	113.9 ± 0.1	Modern	−18.4	--	--
20–30	96.3 ± 0.7	310 ± 60	−16.1	--	--
90–100	64.1 ± 1.1	3570 ± 130	−21.4	47.6 ± 1.5	5960 ± 260
180–190	--†	--	−24.5	39.6 ± 0.4	7380 ± 70
Savanna (17 km*)					
0–10	115.8 ± 0.9	Modern	−15.0	--	--
20–30	92.3 ± 0.7	640 ± 60	−14.7	--	--
90–100	--	--	−19.9	50.0 ± 1.5	5570 ± 240
140–150	--	--	−26.4	26.1 ± 0.4	10,790 ± 80
180–190	--	--	−22.5	22.2 ± 0.3	12,080 ± 90
Savanna (5 km*)					
0–10	107.5 ± 0.8	Modern	−15.5	--	--
20–30	91.9 ± 0.7	680 ± 60	−13.7	--	--
90–100	44.9 ± 0.6	6440 ± 110	−20.0	--	--
190–200	26.2 ± 0.4	10860 ± 90	−24.7	--	--

*Distance from the city of Humaitá
†Samples not analyzed

1991; Pessenda *et al.* 1996b). These results indicate that during the time represented by this record, the C_3 type vegetation has been predominant in the regions of forest vegetation in Pimenta Bueno and Ariquemes, Rondônia, and at the forest sites in the Humaitá region.

The $\delta^{13}C$ values for the soil representing the savanna sites in the Humaitá region show substantially enriched (less negative) $\delta^{13}C$ values, when compared with the forest sites. This difference reflects the influence of C_4 plants in these ecosystems. The shallow soil horizons range between −15‰ and −21‰. It is worthy of note that significantly more depleted $\delta^{13}C$ values (−22 and −26.4‰) are observed in the deepest part of the soil profiles from the savanna sites, compared to the shallow horizons. They are similar to corresponding depth intervals at the forest sites. If the ^{14}C data obtained for the savanna profiles is considered representative of the SOM chronology, then it can be postulated that during the late Pleistocene (*ca.* 12,000 yr BP) and early Holocene (*ca.* 10,000 yr BP) forest vegetation covered the study area. With the exception of the Cerrado site, the Rondônia data show the same pattern. These results are in agreement with other studies that document the occurrence of a fully developed tropical forest in the southern zone of South America, between 10,000 and 9500 yr BP and 8000 yr BP (Absy *et al.* 1991; Van der Hammen 1991; Servant *et al.* 1993).

https://doi.org/10.1017/S0033822200018981 Published online by Cambridge University Press

Another significant feature of the ^{13}C data is the relative ^{13}C enrichment observed in the middle part of the soil profile from the forest site 20 km from Humaitá and at the forest transition and Cerrado sites in the Rondônia region. This suggests a major influence of C_4 plants during the time represented by this soil interval, although the pattern is not evident in the soil profile sampled from the forest site 50 km from Humaitá. ^{14}C dating of the humin fractions in the 90–100 cm layers from the forest and forest transition sites gives values *ca.* 5000–6000 yr BP, which corresponds to the mid-Holocene. A charcoal date from the Rondônia Cerrado site also supports the presence of mid-Holocene carbon in the middle part of that soil profiles. Palynological data indicate that several dry periods occurred in the central Amazon area and in other regions of South America during the Holocene (Absy 1982; Van der Hammen 1982; Absy *et al.* 1991). Therefore, the ^{13}C data recorded in this study suggest a regression of some present-day forest areas and the predominance of savanna vegetation associated with a dry phase during the mid-Holocene. In view of the 200 km distance between the Cerrado and the forest transition site, it is obvious that these vegetation changes affected large areas of the Amazon Basin. Similar ^{13}C profiles have been reported in other areas and as representative of the transition of forest to savanna (Desjardins *et al.* 1996; Sanaiotti 1996) suggesting regional-scale changes in vegetation communities in the Amazon Basin during the Holocene.

Conclusion

The ^{14}C data show that significantly older dates are obtained from the humin fraction and charcoal samples in comparison with total SOM. It seems that the savanna soils have preserved older carbon than the forest sites. Clay contents are not significantly different and therefore this pattern could be related to a higher input of organic matter at the forest sites compared to the savanna sites. The soil chronologies for the two study regions indicate that the soil profiles contain carbon deposited during the late Glacial and early Holocene.

The ^{13}C and ^{14}C data obtained for soils sampled along the transects in the Rondônia state and in the Humaitá region show that significant vegetation changes occurred during the period represented by the development of these profiles. During the early Holocene, forest vegetation covered the present-day forest and forest transition sites and also areas in the Humaitá region that now support savanna vegetation. No significant changes during the remaining portion of Holocene are evident from the isotopic record at the forest sites in Rondônia and in the forest at 50 km from Humaitá. On the other hand, significant changes are observed during the mid-Holocene in forest transition and in Cerrado ecosystem soil profiles, located in the southern part of Rondônia state, and in the vegetation transect forest-savanna including the forest site located 20 km from Humaitá city. These latter soil profiles show the influence of C_4 plants, suggesting drier conditions compared with present day climatic conditions in the Amazon region. The evidence is for a regression of the forest in the areas represented by these soil profiles. The more recent portion of the ^{13}C records indicate expansion of the forest into the forest transition in Rondônia and in the Humaitá region. This study shows that there was a vegetation change in the transition areas between forest and savanna vegetation located in the southern part of the Brazilian Amazon region, more distinct in the central-southern part of Rondônia state and the Humaitá region, southern part of the Amazonas state, probably related to the climate changes during the mid-Holocene. These boundary areas seem to be particularly sensitive to climatic change and should be the focus of more extensive research dealing with climate and past vegetation dynamics in the Amazon region.

ACKNOWLEDGMENTS

We thank Mr. Paulo A. Cardia, owner of Fazenda Barra do Prata, Mr. Eric Stone, INCRA's Superintendent in Humaitá, and Major Eduardo Santos de Carvalho, commandant of 54° Batalhão da Infantaria da Selva (BIS), for their support during the fieldwork. We also thank Dr. Kazimiers Rozanski, Faculty of Physics and Nuclear Techniques, Krakow, Poland, for linguistic improvement and stimulating discussions, M. V. L. Cruz, R. Roveratti and C. Bonini for sample preparation and ^{14}C analyses and R.Drimmie, Head of Environmental Isotopes Laboratory of University of Waterloo, Canada, for ^{13}C analyses. We gratefully acknowledge financial support from São Paulo Foundation for Research (FAPESP), grants no. 94/1272-1, 95/3037-2 and 96/1447-1 and CNPq grant no. 522179/94-0 and 522923/96-8 and to PRONEX no. 41.96.0938.00 to L. C. R. Pessenda and a CNPq fellowship to S. E. M. Gouveia.

REFERENCES

Absy, M. L. 1980 Dados sobre as mudanças do clima e da vegetação da Amazonia durante o Quaternário. *Acta Amazonica* 10: 929–932.

____1982 Quaternary palynological studies in the Amazon Basin. *In* Prance, G. T., ed., *Biological Diversification in the Tropics*. New York, Columbia University Press: 67–73.

Absy, M. L., Cleef, A. L. M., Fournier, M., Martin, L., Servant, M., Sifeddine, A., Da Silva, M. F., Soubies, F., Suguio, K., Turcq, B. and 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. *Compte Rendus de l'Académie des Sciences*, 2nd Series, 312: 673–678.

Absy, M. L. and Van der Hammen, T. 1976 Some paleoecological data from Rondonia, southern part of the Amazon Basin. *Acta Amazonica* 6(3): 293–299.

Becker-Heidmann, P. and Scharpenseel, H. W. 1989 Carbon isotope dynamics in some tropical soils. *In* Long, A., Kra, R. S. and Srdoč, D., eds., Proceedings of the 13th International ^{14}C Conference. *Radiocarbon* 31(3): 672–679.

____1992 The use of natural ^{14}C and ^{13}C in soils for studies on global climate change. *In* Long, A. and Kra, R. S., eds., Proceedings of the 14th International ^{14}C Conference. *Radiocarbon* 34(4): 535–540.

Boutton, T. W. 1991 Stable carbon isotopes ratios of natural materials: II Atmospheric, terrestrial, marine and freshwater environments. *In* Coleman, D. C. and Fry, B., eds., *Carbon Isotope Techniques*. San Diego, Academic Press: 173–185.

Cerri, C. C., Feller, C., Balesdent, J., Victoria, R. and Plenecassagne, A. 1985 Application du traçage isotopique naturel en ^{13}C, a l'étude de la dynamique de la matière organique dans les sols. *Comptes Rendus de l'Académie des Sciences*, 2nd Series 300(9): 423–426.

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 revealed by stable ratios of soil organic matter. *Oecologia* 108: 749–756.

Desjardins, T., Volkoff, B., Andreux, F. and Cerri, C. C. 1991 Distribution du carbone total et de l'isotope ^{13}C dans des sols ferrallitiques du Brésil. *Science du Sol* 29: 175–187.

Gomes, B. M. 1995 (ms.) Estudo paleoambiental no estado de Rondonia utilizando datação por ^{14}C e razão $^{13}C/^{12}C$ da matéria orgânica do solo. Master's Thesis, CENA, University of São Paulo: 100 p.

Gouveia, S. E. M. 1996 (ms.) Estudos das alterações de paleovegetações na Amazonia central utilizando a datação radiocarbônica e razão $^{13}C/^{12}C$ da matéria orgânica do solo. Master's Thesis, CENA, University of São Paulo: 75 p.

Haffer, J. 1969 Speciation in Amazoniam forest birds. *Science* 165: 131–137.

Ledru, M. P. 1993 Late Quaternary environmental and climatic changes in Central Brazil. *Quaternary Research* 39: 90–98.

Liu, K. B. and Colinvaux, P. A. 1988 A 5200-year history of Amazon rain forest. *Journal of Biogeography* 15: 231–248.

Nadelhoffer, K. J. and Fry, B. 1988 Controls on natural nitrogen-15 and carbon-13 abundance in forest soil organic matter. *Soil Science Society of America Journal* 52: 1633–1640.

Pessenda, L. C. R., Aravena, R., Melfi, A. J., Telles, E. C. C., Boulet, R., Valencia, E. P. E. and Tomazello, M. 1996a Carbon isotopes (^{13}C,^{14}C) in soil to evaluate changes during the Holocene in Central Brazil. *Radiocarbon* 38(2): 191–201.

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

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

Pessenda, L. C. R., Gouveia, S. E. M., Gomes, M. B. M., Aravena, R., Boulet, R. and Ribeiro, A. 1997 Studies of palaeovegetation changes in the central Amazon by carbon isotopes of soil organic matter. *In* Murphy, P., ed., *Proceedings of the International Simposium on Isotope Techniques in the Study of Past and Current Environmental Changes in the Hydrosphere and Atmosphere*. Vienna, IAEA: in press.

Pessenda, L. C. R., Valencia, E. P. E., Camargo, P. B., Telles, E. C. C., Martinelli, L. A., Cerri, C. C., Aravena, R. and Rozanski, K. 1996b Natural radiocarbon measurements in Brazilian soils developed on basic rocks. *Radiocarbon* 38(2): 203–208.

Prance, G. T. 1973 Phytogeographic support for the theory of Pleistocene forest refuges in the Amazon Basin, based on evidence from distribution patterns in Caryocaraceae, Chrysolalanaceae, Dichapetalaceae and Lecythidaceae. *Acta Amazonica* 3: 5–28.

Richards, P. W. 1973 The tropical rain forest. *Scientific American* 229: 58–68.

Saldarriaga, J. G. and West, D. C. 1986 Holocene fires in the northern Amazon basin. *Quaternary Research* 26: 358–366.

Sanaiotti, T. (ms.) 1996 The woody flora and soils of seven Brazilian Amazonian dry savanna areas. PhD.Thesis, University of Stirling, Scotland: 148 p.

Sanches, P. A., Gichuru, M. P. and Katz, L. B. 1982 Organic matter in major soils of the tropical and temperate regions. *In* Non symbiotic nitrogen fixation and organic matter in the tropics. *12th International Congress of Soil Sciences*, New Delhi: 99–114.

Schwartz, D., Mariotti, A., Lanfranchi, R. and Guillet, B. 1986 $^{13}C/^{12}C$ ratios of soil organic matter as indicators of ecosystem changes in tropical regions. *Geoderma* 39: 97–103.

Schwabe, G. H. 1969 Towards an ecological characterization of the South American continent. Fittkau, E. J., Illies, J., Klinge, H., Schwabe, G. H. and Sioli, H., eds., *Biogeography and Ecology in South America*. The Hague, Dr. W. Junk: 1: 113–116.

Servant, M., Maley, J., Turcq, B., Absy, M. L., Brenac, P., Fournier, M. and Ledru, M. P. 1993 Tropical forest changes during the late Quaternary in African and South American lowlands. *Global and Planetary Changes* 7: 25–40.

Sifeddine, A., Bertrand, Ph., Fournier, M., Martin, L., Servant, M., Soubies, F., Suguio, K. and Turcq, B. 1994 La sédimentation organique lacustre en milieu tropical humide (Carajas, Amazonie orientale, Brésil): Relation avec les changements climatique des 60000 dernièrs années. *Bulletin de la Sociéte Geologique de France* 165(6): 613–621.

Soubies, F. 1980 Existence d'une phase sèche en Amazonie brésilienne datée par la présence de charbons dans le sols (6000–3000 ans B.P.). *Cahiers ORSTOM, Série Géologie* 11(1): 133–148.

Stout, J. D., Rafter, T. A. and Throughton, J. H. 1975 The possible significance of isotopic ratios in paleoecology. *In* Suggate, R. P. and Creewell, M. M. eds., *Quaternary Studies*. Wellington, Royal Society of New Zealand: 279–286.

Throughton, J. H., Stout, J. D. and Rafter, T. 1974 Long term stability of plant communities. *Carnegie Institute of Washington Yearbook* 73: 838–845.

Trumbore, S. E. 1993 Comparison of carbon dynamics in tropical and temperate soils using radiocarbon measurements. *Global Biogeochemical Cycles* 7(2): 275–290.

Trumbore, S. E., Davidson, E. A., de Camargo, P. B., Nepstad, D. C. and Martinelli, L. A. 1995 Belowground cycling of carbon in forests and pastures of Eastern Amazonia. *Global Biogeochemical Cycles* 9: 515–528.

Valencia, E. P. E. 1993 (ms.) Datação por ^{14}C e razão $^{13}C/^{12}C$ de solos sob climas tropical e subtropical do Brasil. Master's Thesis. CENA, University of São Paulo: 91 p.

Van der Hammen, T. 1972 Changes in vegetation and climate in the Amazon Basin and surrounding areas during the Pleistocene. *Geologie en Mijnbouw* 51: 641–643.

____1974 The Pleistocene changes of vegetation and climate in tropical South America. *Journal of Biogeography* 1: 3–26.

____1982 Paleoecology of tropical South America. *In* Prance, G. T., ed., *Biological Diversification in the Tropics*. New York, Columbia University Press: 60–66.

____1991 Palaeoecological background: Neotropics. *Climate Change* 19: 37–47.

Vanzolini, P. E. 1970 Zoologia sistemática, geografia e a origem das especies. *Instituto de Geografia São Paulo* 3: 1–56.

Volkoff, B. B. and Cerri, C. C. 1988 L'humus des sols du Brésil. Nature et relations avec l'environnement. *Cahiers ORSTOM, Série pédologie* 24: 83–95.