HYDROMORPHIC SOIL, TOPOGRAPHIC DEPRESSION AND VEGETATION DEVELOPMENT HISTORY BY USING $\delta^{13}C$ AND ^{14}C IN RONDÔNIA STATE (SW BRAZILIAN AMAZON)

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RESUMO - $\delta^{13}C$ e ^{14}C obtidos da matéria orgânica do solo foram usados para diferenciar fases de flutuação da vegetação em transição floresta-savana. A região apresenta baixos platôs com depressões topográficas imperfeitamente drenadas na superfície. Na topossequência estudada foram analisados solos de cinco perfis localizados sob floresta (F), transição floresta-savana (S1), borda da depressão sob savana (S2) e centro da depressão sob savana (S3). Os valores de $\delta^{13}C$ e idades evidenciam que a ~ 200cm de profundidade**,** com idades entre ~ 12.000 e 10.000 A.P., valores de -27‰ a -27,7‰ indicam vegetação de floresta (C_3) em todos os perfis. Na profundidade de 100 cm, com idades entre ~ 6.000 e 5.000 A.P., houve enriquecimento de – 20,2‰ a -22,3‰, indicando regressão da floresta e expansão da savana. Valores entre -15,9 e -18,7‰ a 50-60 cm, estimado entre ~ 4.700 a 3.800 A.P., sugere máxima expansão da vegetação C_4 em resposta às condições climáticas mais secas, exceto no perfil S3 com valores mais empobrecidos (-20,9‰), sugerindo que na depressão, o desenvolvimento da hidromorfia possibilitou a presença de espécies de gramíneas C_3 e C_4 da savana em resposta as mudanças das condições ambientais.
Palavras-chave: Mudanças de vegetação, isótopos de carbono, contato floresta-savana, depressão topográfica, solo hidromórfico.

ABSTRACT - $\delta^{13}C$ and ^{14}C from Soil Organic Matter (SOM) were used to differentiate vegetation fluctuations in a contact forest-savannah. The study was carried out within a typical ecosystem of the SW Brazilian Amazon, characterized by lowered plateaus with waterlogged topographic depressions. The toposequence included five soil profiles located in forest (F), forest-savannah transition (FS), savannah (S1), savannah depression border (S2) and savannah in the depression (S3). The $\delta^{13}C$ values have shown that at ~200cm depth, with ages ~ 12,000 to 10,000 B.P., $\delta^{13}C$ values of - 27‰ to -27.7‰ indicate a homogeneous C_3 forest vegetation. At 100cm, as ~ 6000 to – 5000 B.P., an uniform enrichment of – 20.2‰ to -22.3‰ indicate a mixture of C_3 forest and C_4 savannah reflecting forest regression and savannah expansion. Higher $\delta^{13}C$ values (-15.9 to –18.7‰) at 50-60cm whose ages were estimated as ~4700 to – 3800 B.P. suggest a maximum expansion of C_4 savannah grass in response to drier climate conditions. More depleted ^{13}C value in S3 profile (-20.9‰) is attributable to a plant community consisting beside of C_4 savannah grass predominantly of C_3 savannah grass. Possibly due to an adaptive advantage of the C_3 photosynthetic pathway in response to changing environmental conditions, C3 grass emerged after the assumed initiation of depression formation at the time.
Keywords: Vegetation changes, carbon isotopes, forest-savannah border, topographic depression, hydromorphic soil.

INTRODUCTION

In SW Brazilian Amazon presently, submitted to a humid tropical climate, the landscape is characterized by lowered plateaus which developed seasonally flooded topographic depressions. Also mixed forest-savannah vegetation is characteristic feature of this landscape (Radambrasil, 1978).

Palynological and sedimentological data have evidenced that these two ecosystems changed under different paleoclimatic conditions. Due to alternations of dry and humid periods during the Quaternary, forest were replaced by savannah or savannah were replaced by forest under dry and humid periods, respectively, in different regions of the Amazon (Absy, 1993, Martin et al., 1993, Van der Hammen & Absy, 1994, Sifeddine et al., 2001, Maslin & Burns, 2001).

Also Soil Organic Matter (SOM) stable carbon isotopes values in different soil depths have demonstrated forest-savannah border fluctuations due to the past climatic changes.

The determination of SOM stable carbon isotopes compositions ($\delta^{13}C$) represents one of the well-established methods to distinguish different plant communities through time. Together with the ^{14}C radiometric datings it represents a suitable approach to reconstruct vegetation changes due to the prevailing climatic conditions within Amazon during different Quaternary time intervals (Desjardins et al., 1996, Gouveia et al., 1997, Pessenda et al., 1998a,b, Pessenda et al., 2001, Freitas et al., 2001, Sanaiotti et al., 2002).

On the other hand, beside mentioned climatic changes also other abiotic and biotic factors e.g. geomorphic conditions, water balance, animal interventions (e.g. termites), inter-species competition and, particularly in modern times, human activities (burning or clearing) can affect forest-savanna dynamics (Eden & McGregor, 1992, Boutton, 1996, Youta Happi, 1998, Eschenbrenner et al., 2000, Biedenbender et al., 2004, Bush et al., 2008).

The objective of this study was to evaluate changes in forest-savannah border related to the opening of topographic depression and the development of waterlogged soil in the surface of flat plateaus typical by using soil data, $\delta^{13}C$ and ^{14}C radiometric dating in a representative toposequence of the landscape. Previously, in the same study area, Pessenda et al. (2001) attributed the variations of isotopic signature in analysed soil samples to erosion, deposition and mixture of organic matter in depressed area. However, our study provides additional information based on chemistry and mineralogy of soils, and the possibility that changes in SOM are related to the development of hydromorphic conditions (Gleysol or Gleissolo in Brazilian classification) in former well-drained soil (Plinthosol or Plintossolo in Brazilian classification) responsible to determine the limits of the occurrence of C_3 and C_4 vegetation. Normally, the formation and the evolution of topographic depression in plateau can be attributed to the release and exportation of chemical elements from soil and soil solutions (Suguio, 1969, Filizola and Boulet, 1996), and the persistence of the loss of material results in enlargement and deepening of these areas, becoming periodically or permanently waterlogged (Millot, 1977, Phillips, 2005). The goal is to obtain the better understanding between forest-savannah dynamics in relation to the transformation of soil cover in a toposequence, characterizing a distinct hydromorphic environment when compared with the well-drained soil in around it.

MATERIALS AND METHODS

Landscape settings

The studied transect is located near km 70 of BR319 federal highway (8°18’S e 68°48’W), between the cities of Porto Velho (Rondônia State) and Humaitá (Amazonas State) in SW Brazilian Amazon, within the Madeira and Solimões hydrographic basins. The geological substrate is represented by the Solimões Formation (Pliocene- Pleistocene sediments) which is widespread through the Amazon area. This formation is composed of fine-grained sandstones with ferruginous-clayey matrix and/or cement interbedded by clayey layers, variously coloured by iron hydroxides and oxides. Quartz, mica, kaolinite and feldspar are the main siliceous minerals. These deposits are related to the Andean orogenesis which gave rise to extended and confined fluvial and lacustrine environments, where these sediments were deposited (Sampaio & Northfleet, 1973).

The regional relief is dominantly characterized by low elevated plateaus. Their surfaces are flat with maximum altitude of about 250 m, including depressed areas, both closed and/or connected with superficial drainage network (Rosolen & Herpin, 2008). Radambrasil (1978) 1/1,000,000 scale soil maps were used as reference basis for distinguishing poorly drained soils surrounded by well-drained soils within the regional landscape. According to ISSS Working Group (1998), these soils are classifiable as Gleysol and Ferralsol, respectively. The soil spatial distribution in an elementary watershed was made through nineteen auger pit transects disposed in radial organization from drainage axe to upslope. Drainage axe is represented by temporary waterlogged soil (Gleysol) developed in the topographic depression, subjected to rising groundwater. Upslope is represented by well-drained soil (Ferralsol) composed by superficial soft horizons (*solum*) above mottled horizon (plinthite) (Rosolen & Herpin, 2008). The horizons of soils are distributed along slope correlated with topographic features. Soil depth and physical-chemical composition are presented in Table 1a-e.

The vegetation cover is mainly characterized by open tropical forest with natural savannah patches which are considered as remnants of Quaternary drier time intervals vegetations. The forest ecosystem is dominated by *Eschweilera* sp., *Ischnosiphon* sp., *Miconia* sp., *Brosimum* sp., and *Cecropia* sp. The grass prevailing in the forest–savanna transition and savanna is *Andropogum* sp. (C_4). *Panicum parvifolium LAM* (C_3) represents the dominant grass in the depressed area, interspersed by trees like *Curatella americana*, *Miconia* sp. and *Cassia* sp. (Pessenda et al., 2001).

The climate is characterized by 2,250 mm mean annual rainfall, with a short dry period from June to August with an average precipitation lower than 40mm/month and a mean annual temperature of 24°C.

Sampling

The study was carried out on a representative toposequence located in a forest-savannah transition. Along the toposequence 90 m length, an approximately 3 m deep trench was dug. The height difference between the highest part of the plateau covered by forest and the centre of the depression occupied by savannah was of 2 m. Soil samples in 5 profiles, including all soil horizons, were collected: Upslope, forest (F) (0m), forest-savannah transition (FS) (43m), savannah (S1) (55m). Downslope, savannah depression border (S2) (67m) and centre of savannah depression (S3) (90m). In all profiles, samples for $\delta^{13}C$ analyses were collected from each 10 cm between 0 to 60cm. Below this depth until ~ 250 cm, samples were taken in a mottled soil matrix, considering the proportion of red, yellow and grey colours.

^{14}C datings were presented in two others papers in the same area by Gouveia et al (1997) and Pessenda et al. (2001). The datings were done in charcoal fragments less than 5 mm of diameter, collected in the middle of the toposequence between 50-60 cm soil depth in the profiles S1 and S2. Two samples were taken from organic matter rich horizons in the depression center (S3) between 0-10 cm and 20-30 cm depth. The charcoals (50-60 cm depth) indicated ages changeable from 3,810 – 4,770 yr B.P. The organic matter rich horizons, at 20-30 cm and 0-10 cm depth, indicated ages from ~1,650 yr B.P. until today (less than 300 years), respectively (Pessenda et al., 2001). From 90-100 cm and 190-200 cm of depth, Gouveia et al. (1997) reported ages from ~5,000-6,000 yr B.P and ~10,000-12,000 yr B.P., respectively.

Laboratory methods

For total organic carbon (Figure 1), and $\delta^{13}C$ analyses (Figure 2), soil samples were dried at about 50°C until a constant weight. Root and other plant residues were removed by handpicking. Any remnant plant material was removed by floating in 0.01 M HCl and subsequently wet-sieved at 210μm. $\delta^{13}C$ isotopes and total organic carbon were determined by using a Carlo Erba Analyser attached to an Optima Mass Spectrometer (Environmental Isotope Laboratory, University of Waterloo, Canada). The $\delta^{13}C$ results are expressed in δ (‰) units according to the international PDB standard. The analytical uncertainties averaged 0,3‰. Total organic carbon contents are expressed as percentage of dry soil. ^{14}C datings on charcoal fragments were carried out at the Isotrace Laboratory of University of Toronto (Canada) employing the AMS technique. Radiocarbon data are reported as radiocarbon ages as years B.P. (Pessenda et al., 2001).

Exchangeable cations were determined according to van Raij et al. (1987). Values of pH were measured in water by using a pH bench Meter. Grain size analysis was carried out after oxidation by H_2O_2, and soil dispersion with NaOH and $Na_4P_2O_7$ treatments according to Embrapa, 1997. X-ray diffraction (XRD) on clay fractions was made with a SIEMENS D5000 diffractometer (Cu-Ka radiation, 40 kV, 30 mA, scanning rate of 1°2θ minute^{-1}).

RESULTS AND DISCUSSION

Chemical, textural and mineralogical characterizations of soils

Results of chemical and grain size analyses of the five soil profiles (F, FS, S1, S2 and S3) are shown in the Table 1a-e. Summarized, chemical analyses showed low pH values ranging from pH 4.6 – 5.4 at all profiles and all depths. Also minor values for all bases (K, Mg, Ca, Na) accompanied by a low percentage base saturation (BS) were measured. Grain size characteristics in the profiles F, FS and S1 showed higher silt and clay contents, where clay represents the dominant grain size fraction. In the profiles S2 and S3 the proportion of clay in relation to silt and sand fractions shows an increase mainly in the organic matter rich horizons. Specially in profile S3 the amount of clay in the deepest layers indicate a sudden reduction.

Table 1 a-e. Chemical and grain size characteristics of the investigated profiles F (a). FS (b). S1(c). S2 (d). S3 (e).

Profile F (forest) (a)

Depth	Al	K	Mg	Na	Ca	CEC	SB	BS	pH	C	Sand	Silt	Clay
cm	%	%	%	%	%	mmolc/kg	mmolc/kg	%	H_2O	%	%	%	%
5	45	2.1	2.0	0.2	4.0	132.3	8.3	6	4.6	2.8	16.9	44.3	38.8
15	41	1.1	1.0	0.2	2.0	108.3	4.3	4	4.6	1.9	17.3	39.7	43.0
25	41	0.9	1.0	0.2	1.0	83.1	3.1	4	4.8	1.2	17.3	38.7	43.9
35	35	0.7	1.0	0.2	1.0	72.9	2.9	4	5.0	0.8	15.5	39.1	45.4
45	n.d.	n.d.	n.d.	n.d.	1.0	n.d.	n.d.	n.d.	n.d.	0.7	n.d.	n.d.	n.d.
95	65	1.2	1.0	0.2	1.0	83.4	3.4	4	5.0	0.3	11.8	31.1	57.1
125	70	3.1	1.0	0.2	1.0	97.3	5.3	5	5.3	0.2	14.9	28.7	56.4
155	76	1.8	1.0	0.2	1.0	92.0	4.0	4	5.1	0.1	15.1	30.7	54.2
205	64	2.6	1.0	0.2	1.0	88.8	4.8	5	5.2	0.06	31.2	25.6	43.2
275	68	1.8	1.0	0.2	1.0	83.0	4.0	5	5.0	0.05	29.5	27.5	43.0

Profile FS (forest/savanna transition) (b)

Depth	Al	K	Mg	Na	Ca	CEC	SB	BS	pH	C	Sand	Silt	Clay
cm	%	%	%	%	%	mmolc/kg	mmolc/kg	%	H_2O	%	%	%	%
5	30	1.7	1.0	0.2	1.0	104.9	4.9	5	4.9	3.2	17.1	40.8	42.0
15	28	0.9	1.0	0.2	1.0	103.1	3.1	3	5.1	2.1	16.0	38.1	45.9
25	45	2.1	2.0	0.2	4.0	82.9	8.3	6	4.6	2	n.d.	n.d.	n.d.
35	27	0.6	1.0	0.2	1.0	76.8	2.8	4	5	1	n.d.	n.d.	n.d.
55	21	0.9	1.0	0.2	1	67.1	3.1	5	4.1	0.6	16.0	39.9	44.1
75	28	0.7	1.0	0.2	1.0	56.9	2.9	5	5.4	0.4	15.1	40.3	44.6
90	46	1.5	1.0	0.2	1.0	83.7	3.7	4	5.2	0.3	13.5	34.4	52.2
125	68	2.6	1.0	0.2	1.0	100.8	4.8	5	5.2	0.2	15.5	33.6	50.8
165	100	1.4	1.0	0.2	1.0	153.6	3.6	2	5.0	0.1	13.5	27.2	59.3
215	67	1.5	1.0	0.2	1.0	75.7	3.7	5	5.2	0.1	32.4	26.4	41.2

Profile S1 (savanna) (c)

Depth	Al	K	Mg	Na	Ca	CEC	SB	BS	pH	C	Sand	Silt	Clay
cm	%	%	%	%	%	mmolc/kg	mmolc/kg	%	H_2O	%	%	%	%
5	28	1.9	1.0	0.2	1.0	110.1	4.1	4	5.1	3.13	17.7	39.9	42.4
15	30	0.9	1.0	0.2	4.0	94.1	6.1	6	5.1	1.92	12.8	42.1	45.1
25	28	0.8	1.0	0.2	3.0	81.0	5.0	6	5.2	1.38	13.1	39.4	47.5
55	27	0.5	1.0	0.2	1.0	62.7	2.7	4	5.4	0.58	16.2	40.7	43.1
75	36	0.6	1.0	0.2	1.0	60.8	2.8	5	5.1	0.28	18.2	42.7	39.1
95	43	0.9	1.0	0.2	1.0	72.1	3.1	4	5.0	0.18	16.1	44.5	39.4
135	68	1.2	1.0	0.2	1.0	91.4	3.4	4	5.2	0.13	13.0	33.9	53.1
175	84	1.7	1.0	0.2	1.0	137.9	3.9	3	5.0	0.08	n.d.	n.d.	n.d.
215	90	3.0	2.0	0.2	1.0	126.2	6.2	5	5.1	0.06	8.7	33.2	58.1
5	28	1.9	1.0	0.2	1.0	110.1	4.1	4	5.1	3.13	17.7	39.9	42.4

Profile S2 (savanna/depression border) (d)

Depth	Al	K	Mg	Na	Ca	CEC	SB	BS	pH	C	Sand	Silt	Clay
cm	%	%	%	%	%	mmolc/kg	mmolc/kg	%	H_2O	%	%	%	%
5	16	1.0	1.0	0.2	1.0	169.9	3.9	2	5.0	14.9	7.4	42.3	50.3
15	11	1.7	1.0	0.2	1.0	143.0	3.0	2	5.4	9	5.0	42.8	52.1
35	28	0.8	1.0	0.2	1.0	103.0	3.0	3	5.4	2.3	1.5	29.6	68.9
55	28	0.8	2.0	0.2	4.0	125.5	7.5	6	4.8	1.7	1.5	31.9	66.6
85	40	1.3	1.0	0.2	1.0	98.8	2.8	3	5.3	0.4	1.6	56.6	41.8
115	33	0.6	1.0	0.2	1.0	53.6	2.6	5	5.2	0.1	15.7	55.8	28.5
155	40	0.9	1.0	0.2	1.0	61.1	3.1	5	5.4	0.1	15.0	45.5	39.5
215	74	2.5	7.0	0.2	1.0	108.7	10.7	10	5.4	0.1	5.7	40.1	54.1

Profile S3 (savanna/depression) (e)

Depth	Al	K	Mg	Na	Ca	CEC	SB	BS	pH	C	Sand	Silt	Clay
cm	%	%	%	%	%	mmolc/kg	mmolc/kg	%	H_2O	%	%	%	%
5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	10	n.d.	n.d.	n.d.
15	12	1.3	1.0	0.2	5.0	235.5	7.5	3	5.4	6.5	2.4	34.7	62.9
25	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	5.1	n.d.	n.d.	n.d.
35	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3	n.d.	n.d.	n.d.
55	30	1.5	1.0	0.2	2.0	146.7	4.7	3	5.3	1.8	1.8	27.9	70.3
85	72	0.9	1.0	0.2	2.0	154.1	4.1	3	4.9	0.8	5.6	28.3	66.1
115	62	0.6	1.0	0.2	2.0	133.8	3.8	3	5.2	0.4	13.2	42.7	44.1
145	32	0.5	1.0	0.2	1.0	70.7	2.7	4	5.2	0.1	22.6	50.9	26.5
195	29	0.8	1.0	0.2	2.0	70.0	4.0	6	5.4	0.04	26.7	50.3	23.1

n.d. = not determined; CEC = Cation Exchange Capacity; SB = Sum of Bases; BS = Base Saturation

The presence and distribution of clay minerals in the set of horizons reflect two alteration stages. In the bottom (60 – 250 cm depth), encompassing the mottled and white horizons submitted to the temporary presence of water table, was determined the association of illite and kaolinite reflecting lesser weathering of soil matrix when compared with upper set of horizons. In the superficial and subsuperficial horizons (0 – 60 cm depht) the increase of the weathering results in an assemblage composed by kaolinite and Al-vermiculite replacing illite.

Total Organic Carbon (TOC)

As shown in Figure 1 and Table 1a-e the total organic carbon (TOC) contents decrease with the depth. On the plateau, the forest and the savannah areas (profiles F, FS and S1) showed about 3% C in the upper 10cm. At 25cm depth, C contents diminished to about 2%, with a decreasing tendency to 0.5% at 50cm and 0.2% at 100cm. The TOC contents at the depression border zone of the savannah area (profile S2), were of about 4.4% in the upper 10cm. In the centre of the depression (profile S3), the values increased up to 10% which is attributable to a slow down of organic matter decomposition processes due to flooding conditions during the rainy season. The C content remains higher with depth (5% at 25cm, 0.5% at 100cm), as well as at the elevated parts of the plateau sites (profiles F, FS and S1). In all profiles, under around 125cm, the determined C contents are very similar and less than 0,2%.

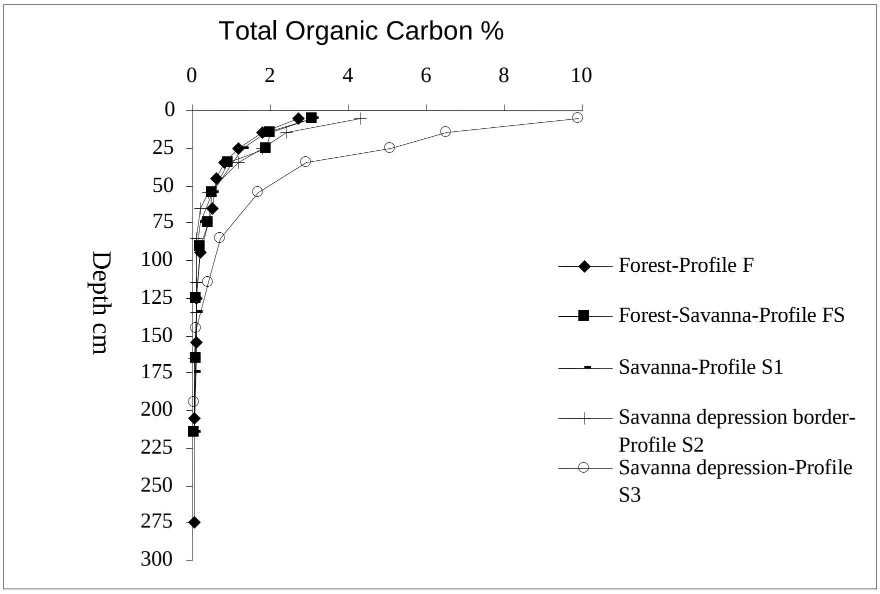

Figure 1. Total Organic Carbon (TOC) in five soil profiles of the toposequence studied: Forest (F), Forest-Savannah transition (FS), Savannah (S1), Savannnah depression border (S2) and Savannah depression (S3). The contents are diminishing downward to almost 0% at 200cm depth.

Stable Carbon Isotope signatures ($\delta^{13}C$)

$\delta^{13}C$ values obtained from different profiles are shown in Figure 2. In the first 10cm, under present forest and forest-savannah transition (profiles F and FS), measured $\delta^{13}C$ values changed from - 28.1‰ to -25‰, which are typical for forest, dominated by C_3 plants, and forest influenced surface soils (Volkoff & Cerri, 1987, Martin et al., 1990, Trumbore et al., 1995). In the savanna (profile S1) the $\delta^{13}C$ value of - 15.6‰ is mainly related to the presence of C_4 savannah grass (*Andropogun sp*.), which is also documented for other savannas of the Amazon region (McClaran & Mc Pherson, 1995, Desjardins et al., 1996; Gouveia et al., 1997; Pessenda et al., 1998a). The $\delta^{13}C$ value of this species is of about - 13.6‰ (Sanaiotti et al., 2002). At the depression border (profile S2) and in the centre of the depression (profile S3) the measured values were of - 19.4‰ and - 22.5‰, respectively. These values are suggestive of a mixture of C_3 and C_4 plants, with isolated occurrence of C_3 trees. Beside C_4 grass, both savannah areas are dominantly covered by C_3 grass *Panicum parvifolium* LAM with a $\delta^{13}C$ value of - 27‰. Hence, more depleted values found in profiles S2 and S3 can be attributed to both, C_3 and C_4 derived organic matter influence due to *Panicum parvifolium* LAM and *Andropogun sp.*, as well as C_4 derived organic matter transported from the nearby savannah in higher topographical positions (profile S1) during rainy seasons. This transport is influencing mostly the adjacent area (S2) with more enriched $\delta^{13}C$ value (- 19.4‰) than the depressed area (S3), showing more depleted $\delta^{13}C$ value (- 22.5‰). These results suggest that influ ence of C_3 derived organic matter, from upslope forest vegetation, is much less significant.

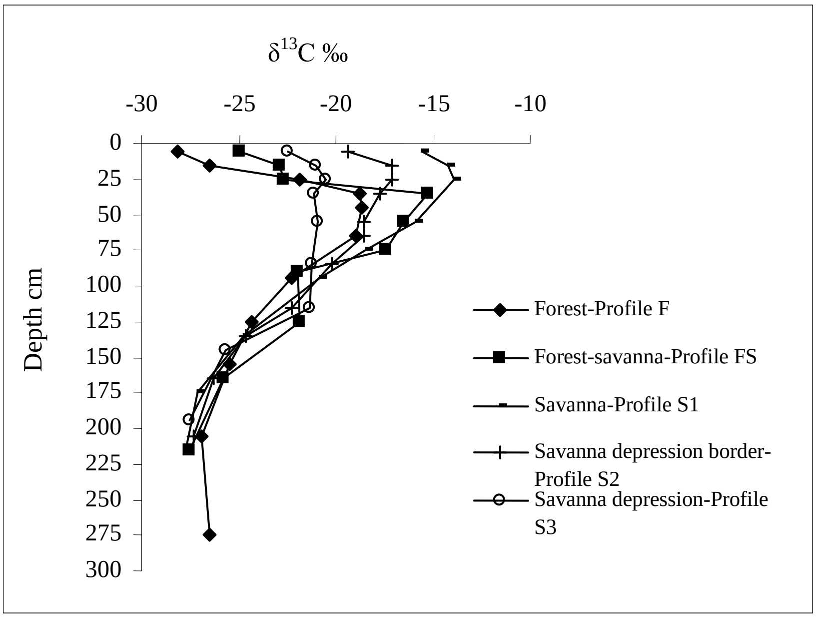

Figure 2. Stable Carbon Isotope ($\delta^{13}C$) in SOM of five soil profiles of the toposequence studied: Forest (F), Forest-Savannah transition (FS), Savannah (S1), Savannah depression border (S2) and Savannah depression (S3). The contents are diminishing downward to around -27‰.

In an underlying layer, situated between ~30 cm and 75 cm, the $\delta^{13}C$ values changed from - 19‰ to - 15.3‰ and showed more enriched values in the profiles F, FS, S1, S2, mainly due to the presence of organic matter derived by C_4 type savannah vegetation (Figure 2). However, in the profile S2 the above mentioned factors, probably due to the influence of C_3 and C_4 grasses have to be taken into account.

In the profile S3 (centre of the depression) the $\delta^{13}C$ values changing slightly from - 21.1‰ to - 21.3‰, between ~30 cm to 125 cm, indicate a homogeneous mixture of C_3 and C_4 grass vegetation. In all profiles deeper than 125 cm, $\delta^{13}C$ values were of around - 24.6‰ to - 27.7‰ suggesting uniform dominance of C_3 forest vegetation (Figure 2).

Generally, $\delta^{13}C$ values of SOM can be influenced by several factors. According to Krull and Skjemstad (2003) these values increase from 1 to 3‰ with depth due to one or more of the following factors: (a) $\delta^{13}C$ depletion in modern atmospheric carbon due to the industrialization (Suess effect); (b) $\delta^{13}C$ fractionation by microorganisms during SOM decomposition and addition of δ^{13}C enriched microbial biomass; (c) long-term changes in environmental stress factors which limit fractionation in the plant to conserve CO_2; (d) translocation of relatively undecomposed soluble carbon fractions down profile. Also other factors have been considered to cause isotopic changes with the soil depth, as soil chemical and mineralogical compositions or textures (Sanaiotti et al., 2002; Krull & Skjemstad, 2003). For example, Stout and Rafter (1978) reported a decrease of δ^{13}C values with soil depth in peats due to hydrolytic removal of labile and acid-soluble SOM fractions, resulting in the retention of ^{13}C depleted lignin. Balesdent et al. (1993) observed in forest stands that the clay fractions are less enriched in δ^{13}C compared to coarser fractions of surface soil layers. Martin et al. (1993) showed in native C_4 savannahs small enrichments of around 1-2‰ in finer compared to coarser fractions at the soil surface.

In the present study, no significant mineralogical, chemical or textural differences in the profiles were observed, except in deeper layers of profile S3 showing decrease of clay (Table 1a-e), that probably indicate no considerable influence on the isotopic composition of soil organic matter. Beside of these possible uncertainties causing minor δ^{13}C variations with soil depths, it is well documented that past vegetation changes represent the principal factor to explain isotopic changes with the depth (Schwartz et al., 1986; Mariotti & Peterschmidt, 1994; Desjardins et al., 1996; Martinelli et al., 1998; Victoria et al., 1995; Boutton et al.,1998; Roscoe et al., 2000; Freitas et al., 2001; Sanaiotti et al., 2002).

Our results have revealed isotopic enrichments and impoverishments of δ^{13}C larger than 2-3‰ which means that the main factor of the measured differences in δ^{13}C of SOM in the studied toposequence could be explained probably by vegetation changes. In order to correlate δ^{13}C changes with time, ^{14}C datings have been done.

Relationship between δ^{13}C data and ^{14}C dating

The Figure 3 shows a schematic overview of vegetation fluctuations and their chronologies through time. Only soil depths with radiocarbon ages are represented. Based on this information as well as on δ^{13}C data at all profiles (Figure 3), vegetation changes due to different paleoclimates, through time, can be proposed.

The δ^{13}C values from - 27‰ to - 27.7‰ obtained from the oldest SOM at a depth of ~200cm and an estimated age of ~10,000-12,000 yr B.P. suggest dominance of homogeneous forest vegetation in all profiles along the development of the studied toposequence. Hence, the culmination stage of humid and warm climate has been attained.

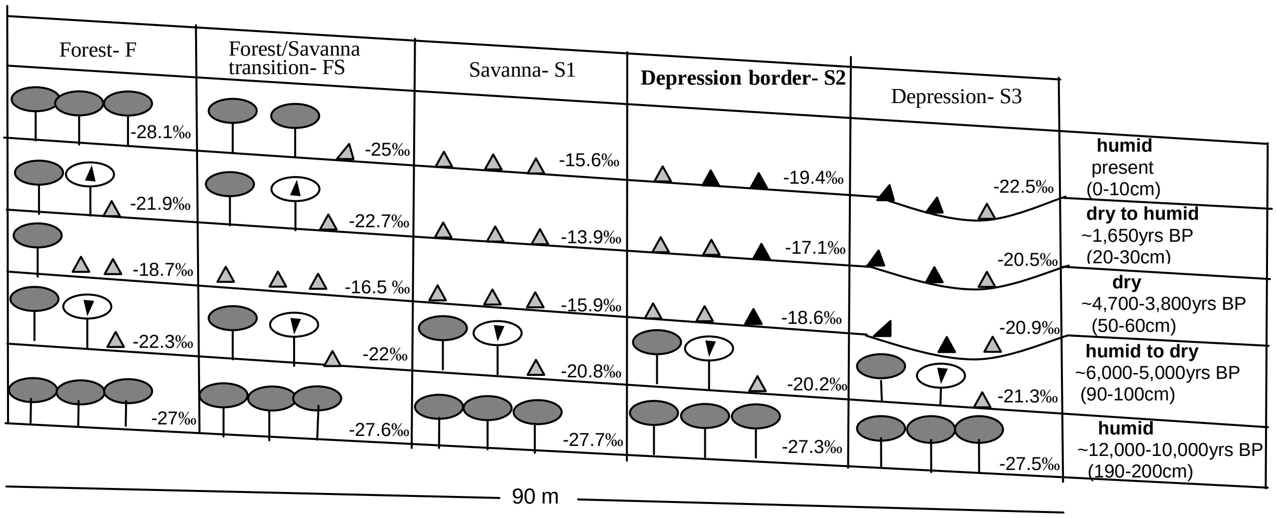

Figure 3. Summary of changes in vegetation dynamics through the time from ~12,000 yrs B.P. to present.

= Forest vegetation, = Regression of forest, Expansion of forest

= Savannah vegetation (C4), ▲= Savannah vegetation (C3)

The uniformly enriched $\delta^{13}C$ values between - 20.2‰ to - 22.3‰ at the upper layer in ~100cm with an age of ~ 5,000-6,000 yr B.P. in all profiles, correspond probably to a mixture of forest and savannah vegetations. This may be related to a forest regression and savannah expansion, probably due to drier paleoclimates. The more enriched $\delta^{13}C$ values, between - 15,9 ‰ to - 18.7‰ found in SOM from 50-60cm depth and with an age of ~ 3,800- 4,700 yr B.P., corresponding to a maximum of C_4 savannah grass expansion, are attributable to the driest paleoclimatic conditions (Suguio, 1999). The studied site is located in the border of the Brazilian amazon and is known that he impact of drier conditions of the early-mid-Holocene upon tropical forest varied across the Amazon basin and the greatest impact at sites at the ecotonal margins of the basin where the dry season is longest and more severe (Mayle & Power, 2008). However, the more depleted $\delta^{13}C$ value of - 20,9‰ of profile S3, situated within depression, was already interpreted as due to a plant community composed by a mixture of C_4 and C_3 savannah grasses (Chapter 3.3). Presumably, depression formation at this time propitiated C3 grass in response to small changing in environmental conditions (topography, microclimate and hydromorphological). According to Boutton (1996) different geomorphic surfaces, in close proximity and under same regional climatic conditions, may support very different vegetations. Probably, this depression was, at least temporarily, inundated at the beginning. According to Biedenbender et al. (2004), hydrological conditions can profoundly influence individual plants or their communities. In general, depressed areas have been formed by soluble material loss from the substrate (Filizola & Boulet, 1996). Depending on parent rock nature and climate condition losses in thicknesses by weathering are changeable from 0.5- 2.5m/100,000 yr (Nahon, 1991; Tardy, 1993), and cause a lowering of the relief surface. In the studied area the exact beginning time for depression formation has not been measured. However, based on $\delta^{13}C$ values (-20,9‰ for mixture of vegetation) and ^{14}C ages (3,800- 4,700 yr B.P.), as well as higher TOC (Total Organic Carbon), when compared to the other profiles (1.8% C in S3 and 0.55-0.7% C in all other profiles), at same depth (50-60cm) (Figure.1 and Figure 2), the beginning of local lowering could be associated with the end of the humid paleoclimate, as postulated above (Figure 3).

After this dry phase vegetation dynamics show 3 main trends probably due to more humid paleoclimate:

(1) on profiles F and FS (Figure 2) the $\delta^{13}C$ values changing from - 21.9‰ to - 22.7‰ in 20-30cm of depth, with a radiocarbon age of ~1,650 yr B.P. This suggests a mixture of forest and savannah vegetations due to forest expansion and can be confirmed by $\delta^{13}C$ values of - 28.1‰ and –25.1‰ in 0-10cm of depth (present) that clearly indicate a recent forest expansion due to more humid conditions;

(2) on profile S1 the $\delta^{13}C$ values of - 13.9‰ in 20-30cm of depth during the same time interval suggest continuous existence of C_4 savannah vegetation until present (- 15.6‰, 0-10cm), however with a slight tendency to more depleted ^{13}C values and

(3) on profile S3 the $\delta^{13}C$ value of - 20.5‰ at ~1,650 yr B.P. and - 22.5‰ at present suggest also a vegetation mixture as observed in profiles F and FS. However, assuming a limited transport of forest derived organic matter from the upper to the lower parts of the plateau (S2 and S3), both $\delta^{13}C$ values of - 19.4‰ (S2) and - 22.5‰ (S3) at present reflect a continuation of the mentioned mixture of only C_3 and C_4 savannah grass community, which was assumed for the beginning of depression formation at the middle Holocene, due to the mentioned geomorphological changes in the transition from humid to the dry paleoclimate.

Different factors can influence forest-savannah border dynamics on large scale. It is well known that human interventions by burning and/or clearing reduce or prevent forest species settlements in savannah (Guillet et al., 2001; Favier et al., 2004). Termite activity can also influence vegetation dynamics. Field observations in a forest-savannah landscape of Rondônia state (SW Brazilian Amazon) showed abundant occurrence of termites within present savannah. As these organisms have preference for young tree seedlings as their foods, this can inhibit growth of trees and afforestation (Eschenbrenner et al., 2000). On the contrary, Youta Happi (1998) reported that termite mounds form fertile patches, where forest pioneer species emerge preferentially. Generally, the irregular advance of forest into savannah, as found in this study area, could be explained by above mentioned factors.

CONCLUSIONS

Based on $\delta^{13}C$ values and ^{14}C datings the studied toposequence developed within a forest-savannah transition landscape, showed different vegetation distributions through time. The obtained results were interpreted as consequences of regional climatic changes and/or small scale fluctuations of other ecological conditions (e.g. geomorphological changes). These abiotic factors had a major effect on forest-savannah changes. However, biotic factors, as human and animal interventions or inter-species competitions were also important.

Geomorphological alterations probably occurred in the middle Holocene, characterized by the relief surface lowering with depression formation. The deepening of the depression through the time results in the development of Gleysol in the former well drained soil. Vegetation community has been adapted to new environment and remained up to the present in the depressed area of the studied toposequence (mixture of C_3 and C_4 savannah grass). This gives reason to highlight, that different $\delta^{13}C$ values not only indicate forest/savannah vegetation changes or mixture, but can also refer to one vegetation type (e.g. C_3 and C_4 savannah grass community).

Generally, the question, if forest will again homogeneously cover or not the investigated area, as documented at ~ 12,000 yr B.P. apparently without geomorphological alteration, remains controversial.

The $\delta^{13}C$ values indicated a new forest expansion over savannah at present in the upper part of the studied toposequence. On large scale, remote sensing images show apparently completed savannah replacements by forest. On the other hand, still existing savannah areas revealed only forest invasion at the forest/savannah border. These findings confirm that forest progression does not always consist of a regular advance, possibly due to regional differences in interactions of ecological factors.

In order to get more insight on small scale ecological interactions or associated differences in vegetation fluctuations, studies of other transects in SW Brazilian Amazon are desirable.

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