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Effects of prolonged flooding on the cycling of dissolved inorganic carbon in Plinthosols

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RESUMO

O cultivo de arroz irrigado por inundação tem se desenvolvido em áreas úmidas do Cerrado em consequência da expansão da fronteira agrícola. Alterações no teor de umidade do solo devido a práticas agrícolas associadas a irrigação por inundação podem induzir transformações geoquímicas no solo. O presente estudo teve como objetivo investigar o efeito da irrigação por inundação sobre o ciclo do carbono inorgânico por meio da determinação de concentrações do carbono inorgânico dissolvido (CID) na solução do solo. Experimentos de incubação sob condições anóxicas e redutoras foram realizados em laboratório com amostras dos horizontes A, AB, Bf1 e Bf2 de perfis dos Plintossolos presentes em áreas sob irrigação por inundação há 18 e 28 anos e área natural preservada do Projeto de Irrigação Luiz Alves do Araguaia, GO. Amostras de solo sob inundação foram incubadas por 1, 7, 15, 30, 60 e 120 dias para simular o efeito da inundação prolongada e após a incubação a fração líquida foi analisada para CID. Os dados foram submetidos à análise estatística de variância e regressão linear e as médias comparadas pelo teste t de Student a 5% de probabilidade. Maiores concentrações do CID foram encontradas no horizonte A (até 37,2 mg/L) dos perfis do solo sob cultivo agrícola as quais podem estar associadas a calagem ou processos de dessorção das espécies do carbono. As análises estatísticas mostraram que o CID se correlacionou com a condutividade elétrica do solo e Eh. Conclui-se que a solubilização do carbono inorgânico é favorecida pela irrigação por inundação, em especial dos Plintossolos que recebem calagem, como também pelo estado redutor do solo e por maiores concentrações de íons em solução
Palavras-chave: *Geoquímica; Plintossolos; Irrigação por inundação; Carbono inorgânico dissolvido.*

ABSTRACT

Cultivation of flooded rice has developed in wetlands of the Cerrado Biome as a result of the expansion of the Brazilian agricultural frontier. Changes in soil moisture content due to agricultural practices associated with flood irrigation may induce geochemical transformations in the soil. The present study aimed at investigating the effect of flood irrigation on inorganic carbon cycling through the determination of dissolved inorganic carbon (DIC) concentrations in soil solution. Incubation experiments under anoxic and reducing conditions were carried out in laboratory with samples of horizons A, AB, Bf1 and Bf2 of Plinthosols profiles from areas under 18 and 28-year of flood irrigation and natural area of the Irrigation Project Luiz Alves do Araguaia, GO, Brazil. Soil samples under flooding were incubated for 1, 7, 15, 30, 60 and 120 days to simulate the effect of prolonged flooding and after incubation the liquid fraction was analyzed for DIC. Statistical analyses of variance and linear regression as well as means compared by Student's t-test at 5% probability were carried out on the data. Higher concentrations of DIC were found in the A horizon (up to 37.2 mg/L) from soil profiles under agricultural cultivation, which may be associated with liming or desorption processes of carbon species. Statistical analyses showed that DIC concentration correlated with soil electrical conductivity and Eh. It is concluded that solubilization of inorganic carbon is favored by flood irrigation, especially in Plinthosols that have received liming, as well as by the reducing state of the soil and higher concentrations of ions in solution.
Keywords: *Geochemistry; Plinthosols; Flood irrigation; Dissolved inorganic carbon*

1. INTRODUCTION

In the environment, three forms of carbon are considered as most abundant, carbon in the elemental form, inorganic carbon (IC) and organic carbon (OC) (APHA 2012; Schumacher 2002). It is common in soils the presence of IC and OC species associated with organic and mineral fractions. Agricultural practices may cause changes in soil carbon compounds due to, among other factors, oxidation of organic matter, changes in biota, soil moisture and fertilization (Don et al. 2010). It has been reported that in both aquatic and flooded soils environments, the predominant IC species are bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}) ions, carbonic acid (H_2CO_3), methane (CH_4) and free carbon dioxide (CO_2) (Ponnamperuma 1972, Kirk 2004).

Changes in soil moisture content associated with flooding can induce geochemical transformations of carbon compounds (Kirk 2004). It is known that flooding promotes anoxic and reducing conditions which in turn generate changes in the soil environment, which may interfere on the cycling of IC and OC species. Biological factors, such as organism activity, and abiotic factors, such as pH, Eh, electrical conductivity and temperature, can be strongly modified under anoxic conditions. They are reported as influential factors in the formation and transformation of IC and OC species in flooded soils (Kirk 2004; APHA 2012).

In Brazil, prolonged flood irrigation projects for agricultural purposes have been implemented in wetlands of the Cerrado Biome in which Plinthosols predominate. This is so because wetlands often show appropriate hydrological and topographic characteristics for irrigation by flooding. It is worth noting that flood irrigation rice cultivation is responsible for 75% of Brazilian rice production thus is an important income source for many farms. In many large wetlands of the Cerrado Biome used by flood irrigation projects, Plinthosols are the dominant soil class.

Plinthosols are characterized by the presence of plintic or petroplintic horizon, and their genesis is related to alternating annual cycles of humidity and drought (EMBRAPA 2006). The increase of the natural humidity of Plinthosols during the rainy season generates intense processes of chemical reduction of Fe and Mn-rich compounds leading to solubilization and mobilization of these elements in the soil profile. In conditions of low humidity found during the dry period, the solubilized chemical elements are oxidized and new mineral phases are formed. Thus, the soil profile can develop Fe, Mn, Al-rich horizons, called plinthic, when exposed to the annual cycles of moisture and drought (EMBRAPA 2006).

Plinthosols make up an important class of soil that does not occur only in the Cerrado Biome. According to the World Reference Base (2015), the global extent of Plinthosols is estimated at about 60 million hectares. They are found in eastern Amazon, in the African savannah region, in parts of South and Southeast Asia, and in northern Australia. In Brazil, Plinthosols have a distribution that covers about 7% of the national territory, which is equivalent to an area of 600.000 km^2. In general, these soils occupy lowlands with flat topography. In the Cerrado Biome, Plinthosols often occur in floodplains or terraces on recent sedimentary deposits, which gives them suitable conditions for irrigated rice cultivation.

In the present work the IC cycling in Plinthosols (*Plintossolo Argilúvico*, according to Brazilian soil classification system, EMBAPA 2006) used for agricultural purposes by the Luiz Alves do Araguaia Flood Irrigation Project (PILAA) was studied. The project was implanted in the Araguaia River floodplain areas and has a total agricultural area of 6.580 hectares (SED 2016). In this project, the natural hydrological regime was modified and Plinthosols horizons have remained flooded for a period of up to four months during irrigated rice cultivation. The use of agricultural fertilizers and soil liming are frequent in irrigated areas, which in combination with prolonged flooding can modify IC cycling.

Particularly in this research, we aimed at studying IC cycling in the laboratory by quantifying dissolved inorganic carbon (DIC) contents present in the soil liquid fraction. DIC quantification was performed for different Plinthosols profiles and horizons from both cultivated and natural areas thus simulating conditions of prolonged flooding for up to 120 days. This is a novel study that contributes to the understanding of inorganic carbon cycling in Plinthosols under the influence of prolonged flood irrigation.

2. MATERIALS AND METHODS

Study area

The study area is located in the municipality of São Miguel do Araguaia, State of Goiás, Brazil (Figure 1). In the PILAA two irrigation systems are intercalated, the flood irrigation system used in the wet season for rice cultivation, and the subsurface irrigation system managed by raising the water table used in the dry season for other crops. In the eastern part of the irrigation project there is a preserved area (buffer area) where the Plinthosols are under natural hydrological conditions.

Three Plinthosols profiles were studied in the perimeter of PILLA: AN, natural area; AC18, area under agricultural cultivation by 18-year flood irrigation and AC28, area under agricultural cultivation by 28-year flood irrigation (Figure 1). Pits were opened in the field and deformed soil samples from horizons A (0-20 cm) and AB (20-60 cm) and from plinthic horizons Bf1 (60-100 cm) and Bf2 (100-140 cm) were collected in the three soil profiles at the same depth, as the horizons in each soil profile were well correlated in the field (Figure 2). The soil samples were then air-dried, sieved (< 2 mm) and stored in plastic bags at room temperature for later use in laboratory experiments.

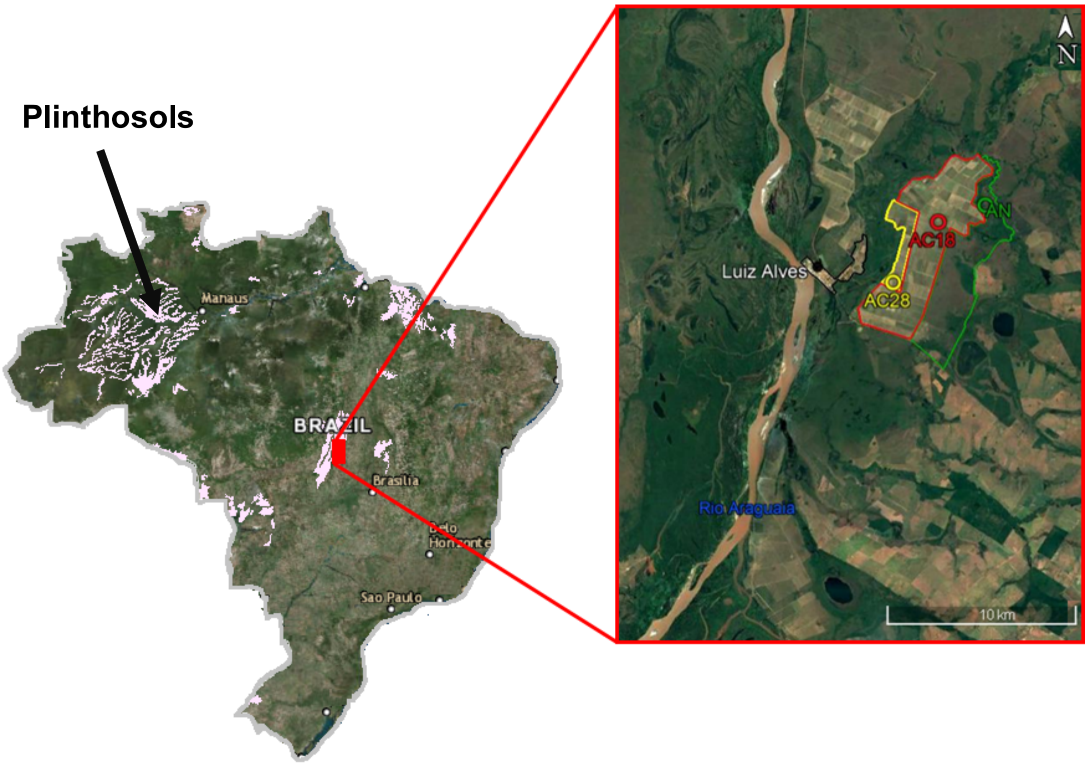

Figure 1

In the left side, distribution of Plinthosols in Brazil, with emphasis on the location of PILAA. In the right side, Lansat TM image (coordinates 549390.95 m E 8539441.91 m S zone 22 L) of the study area, highlighting the location of the sampled soil profiles (AN, AC18, AC28) and the Araguaia River to the west.

3. METHODOLOGY

In the laboratory, 216 soil samples from the three soil profiles and four horizons were flooded and incubated in triplicate under anoxic conditions for six different flood times (1, 7, 15, 30, 60 and 120 days) to simulate the present flood irrigation in the field. The reference to the period of 120 days is related to the maximum annual time of irrigated rice cultivation. For anoxic incubation 50 ml centrifuge tubes (reactors) containing 25 g of dry soil (2 mm mesh sieved) and 25 ml of deoxygenated ultrapure water (Milli-Q, 18 MΩ.cm) were used. During incubation, the anoxic environment was maintained by injecting nitrogen gas (98% purity) into the centrifuge tubes every 12 hours. Each reactor was covered with a black plastic to avoid contact with light and possible interference of the photocatalytic effect on soil compounds. All samples were incubated randomly and maintained at 28 ± 1°C in an automatic incubator.

After each incubation period, the reactors were opened in a globe bag saturated with nitrogen gas, where physical-chemical parameters data (potential redox (Eh), electrical conductivity (EC) and pH) were collected. Afterwards, samples were centrifuged and filtered (0.22μm) and aliquots of the soil liquid fraction (soil solution) were collected for dissolved inorganic carbon analysis. The DIC analyzes were performed on the equipment Analyzer Jena Multi N/C 2100 S, with

HT 1300 high temperature system. The analysis involves the oxidation of IC with acid, purging with inert gas and detection of CO_2 by FR NDIR (non-dispersive infrared sensor).

The data were statistically treated using the completely randomized design model in a triple factorial scheme. Analysis of variance (Two-way ANOVA) followed by Student's t-test (Least Significant Difference, LSD) were performed to compare means for the independent variables soil profile and horizon. Linear regression was performed for the independent variable incubation time through the model of second degree polynomial regression. The software Statistica, version 13.2, was used for performing the analysis of variance and t-test and the software SISVAR, version 5.6, was used for performing the linear regression.

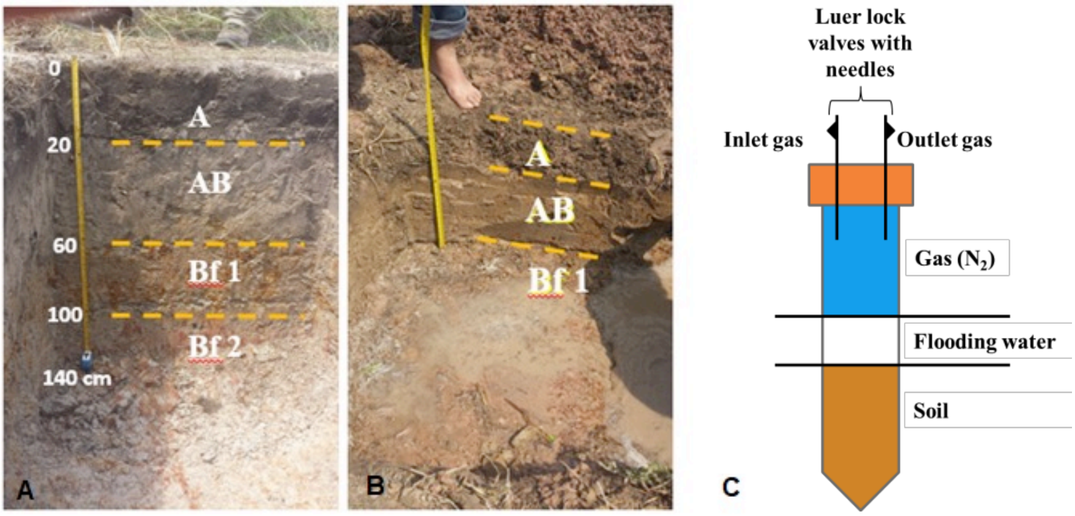

Figure 2
A) Complete Plinthosols profile from the natural area (AN); B) Partial Plinthosols profile from the area under 18 years' flood irrigation (AC18); C) Sketch of the reactors used in laboratory for incubation showing the nitrogen gas influx system used to maintain the anoxic environment.

4. RESULTS AND DISCUSSION

In general, DIC concentrations were higher for samples from the A horizon for all soil profiles (Table 1). For the soil profiles under agricultural cultivation, DIC concentrations showed a peak on the 7th day of incubation for AC28 (36.02 mg/L) and on the 15th day for AC18 (6.82 mg/L), tending to decrease concentrations with increasing incubation time for these soil profiles (Table 2). For the soil profile from the natural area, the peak of DIC concentrations occurred at the 120th day of incubation, with a mean concentration of 2.91 mg/L (Table 2).

Statistical analysis indicated a significant triple interaction between the factors soil profile, soil horizon and incubation time in relation to DIC. In general, when analyzing the influence of the soil profile within each soil horizon-incubation time combination (Uppercase letter in Table 2), it was found that in the A horizon, in which the presence of DIC was greater, there was a significant difference between soil profiles, i.e., each soil profile behaved differently for the A horizon. In other horizons (AB, Bf1 and Bf2) the concentrations of DIC were detected only for some samples and the trend of DIC concentration was considered similar for all soil profiles. The results showed by lowercase letters in Table 2 refer to the influence of the soil horizon in relation to the soil profile-incubation time combination. These results confirm the distinct behavior of DIC concentrations in horizon A in comparison to other soil horizons.

In a more detailed analysis of DIC concentrations, it was observed that, except for the soil profile under natural conditions (AN), DIC concentrations were detected in the AB horizon of the soil profiles from areas under cultivation (AC18 and AC28), especially in the youngest area under cultivation (AC18) (Table 2)

The presence of higher concentrations of DIC in the soil profiles from the cultivated areas in relation to the soil profile from the natural area may be related to liming. Chemical analysis of the exchangeable calcium content in the original soil obtained by the resin method showed that calcium content in Plinthosols samples from the soil profiles AC18 and AC28 were initially high in relation to the soil profile from the natural area, indicating a possible fertilization of the A horizon with calcium carbonate (Table 3).

Table 1- Average mean of DIC concentrations (mg/L) in the soil solution for soil profiles, soil horizons and incubation times.

Horizon	Depth (cm)	Time (day)	DIC (mg/L)		
			AN	AC18	AC28
A	0 - 20	1	0.00	0.32	11.08
A	0 - 20	7	0.00	4.34	36.02
A	0 - 20	15	0.00	6.82	30.63
A	0 - 20	30	0.00	6.78	24.83
A	0 - 20	60	2.12	4.53	18.10
A	0 - 20	120	4.10	2.91	8.62
AB	20 - 60	1	0.00	0.00	0.00
AB	20 - 60	7	0.00	0.00	0.00
AB	20 - 60	15	0.00	0.72	0.00
AB	20 - 60	30	0.00	2.39	0.00
AB	20 - 60	60	0.00	0.88	0.00
AB	20 - 60	120	0.00	0.06	0.00
Bf1	60 - 100	1	0.00	0.00	0.00
Bf1	60 - 100	7	0.00	0.03	0.32
Bf1	60 - 100	15	0.00	0.00	0.00
Bf1	60 - 100	30	0.01	0.00	0.02
Bf1	60 - 100	60	0.00	0.00	0.00
Bf1	60 - 100	120	0.00	0.00	0.00
Bf2	100 - 140	1	0.00	0.00	0.00
Bf2	100 - 140	7	0.35	0.00	0.00
Bf2	100 - 140	15	0,00	0,00	0.00
Bf2	100 - 140	30	0,00	0,00	0,00
Bf2	100 - 140	60	0,00	0,00	0,00
Bf2	100 - 140	120	0.00	0.00	0.00

Table 2 - Mean values of DIC concentrations (mg/L) followed by Student's t-test analysis for soil profiles (uppercase) and horizons (lowercase).

Profile	AN				AC18				AC28			
Horizon	A	AB	Bf1	Bf2	A	AB	Bf1	Bf2	A	AB	Bf1	Bf2
Time (day)												
1	0,00 A a	0,00 A a	0,00 A a	0,00 A a	0,33 A a	0,00 A a	0,00 A a	0,00 A a	11,10 B b	0,00 A a	0,00 A a	0,00 A a
7	0,00 A a	0,00 A a	0,00 A a	0,37 A a	4,33 B b	0,00 A a	0,03 A a	0,00 A a	36,00 C b	0,00 A a	0,33 A a	0,00 A a
15	0,00 A a	0,00 A a	0,00 A a	0,00 A a	6,83 B b	0,73 A a	0,00 A a	0,00 A a	30,63 C b	0,00 A a	0,00 A a	0,00 A a
30	0,00 A a	0,00 A a	0,00 A a	0,00 A a	6,77 B c	2,40 B b	0,00 A a	0,00 A a	24,80 C b	0,00 A a	0,00 A a	0,00 A a
60	2,10 A b	0,00 A a	0,00 A a	0,00 A a	4,50 B b	0,87 A a	0,00 A a	0,00 A a	18,13 C b	0,00 A a	0,00 A a	0,00 A a
120	4,13 A b	0,00 A a	0,00 A a	0,00 A a	2,90 A b	0,07 A a	0,00 A a	0,00 A a	8,63 B b	0,00 A a	0,00 A a	0,00 A a

* Averages in the same line followed by the same letter do not differ statistically at 5% probability by the two-way ANOVA with Student's t-test (LSD); Uppercase letters (A, B, C) evaluate the correlation between profiles within the horizons-incubation time combination and lowercase letters (a, b, c, d) assess the correlation between horizons within the profiles-incubation time combination.

The liming may have provided increases in the concentration of dissolved inorganic carbon species in the soil solution. Some hypotheses of abiotic and biotic nature may explain the relative increase in DIC concentration during the experiment for the Plinthosols under cultivation. It is known that $CaCO_3$ added to the soil by liming can react with water and produce HCO_3^- and CO_3^{2-} species (Brady & Weil 1999) thus partially explaining the higher levels of DIC found in horizons A and AB of the soil profiles under cultivation (Table 2). On the other hand, the consumption of dissolved carbon in water by the microbiota and flocculation or adsorption of the carbon in cations bridges formed by Ca content in the soil can contribute to increase the carbon losses from the solid fraction of the soil to the soil solution (Andersson 1999). Thus, in the Plinthosols under agricultural cultivation with higher Ca content, there may have been an increase in the desorption of DIC species from the solid fraction during incubation, thus contributing to the observed increase in DIC concentrations. In contrast, in soils without liming, i.e., with lower Ca contents, such as Plinthosols under natural conditions, the low concentrations of DIC may be associated with lower DIC species desorption from the solid fraction.

Table 3 - Chemical and physical characteristics of Plinthosols before incubation.

Profile	Horizon	Depth	Silt/Clay	OM	Ca^{2+}	pH	$H^{+} + Al^{3+}$	SB	CEC	V%
		(cm)	(%)	(g/dm^3)	($mmolc/dm^3$)		($mmolc/dm^3$)	($mmolc/dm^3$)	($mmolc/dm^3$)	(%)
AN	A	0-20	0.42	45	5	4.6	54	7.1	61.1	12
	AB	20-60	0.36	3	5	4.1	25	6.7	31.7	21
	Bf1	60-100	0.53	4	1	4.0	30	3.3	33.3	10
	Bf2	100-140	0.41	4	4	4.2	92	10.8	102.8	11
AC18	A	0-20	0.74	48	21	5.3	41	31.0	72.0	43
	AB	20-60	0.66	7	9	5.1	23	15.8	38.8	41
	Bf1	60-100	0.40	2	4	4.4	28	9.2	37.2	25
	Bf2	100-140	0.42	2	4	4.2	31	9.1	40.1	23
AC28	A	0-20	0.38	20	40	5.2	23	64.1	87.1	74
	AB	20-60	0.48	5	7	4.3	46	11.7	57.7	20
	Bf1	60-100	0.57	6	7	4.1	37	10.6	47.6	22
	Bf2	100-140	0.36	3	7	4.0	44	12.2	56.2	22

* OM = organic matter; $H^{+}+Al^{3+}$ = exchangeable hydrogen and aluminum; BS = sum of bases ($S = Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}$); CEC = cation exchange capacity at pH = 7; V (%) = base saturation (V = 100xS/T). Determination: OM through colorimetric method; Ca^{2+} through resin method; pH in $CaCl_2$ solution.

The effects of liming on DIC concentrations in the Plinthosols under cultivation via DIC reaction with water, apparently dominated the cycling of DIC in the first days of the experiment. The DIC levels in the A horizon of the soil profiles under cultivation remained relatively high up to 30 days of incubation and after that period decreased (Table 2). In contrast, the DIC levels for the A horizon of the soil profile under natural conditions, which did not receive liming, increased after 30 days of incubation (Table 2). This indicates that after 30 days of incubation desorption of DIC species may have predominated, becoming the main process responsible for the detectable DIC concentration observed for all soil profiles.

Another interesting result was the detection of DIC in the AB horizon of the soil profiles under cultivation, especially in the soil profile AC18 (Table 2). The presence of DIC in this horizon may also be associated with liming and mobility of DIC species. In general, the action of compounds used in liming is restricted to the near surface layers of the soil due to the fact that these compounds show low solubility and restricted mobility (Caires et al. 1998). However, limestone application effects have been observed in depth in soils over relatively short periods of time (Amaral et al. 2004). Such effects may reflect the vertical mobility of DIC species. According to Amaral et al. (2004), the vertical displacement of DIC species verified in Cambisols occurred by dissolving the inorganic carbon associated with liming in percolated solution. In agreement with Amaral et al. (2004), it is postulated here that DIC species related to liming migrated to the subsurface horizons of the Plinthosols under cultivation and were retained especially in the AB horizon. Interestingly, the AC18 soil profile that apparently have received lower dosages of limestone (Table 3) presented the highest concentrations of DIC in the AB horizon (Table 2). It is hypothesized that the silt/clay ratio may have influenced the distinct DIC behavior of the AC18 soil profile in comparison to the AC28 soil profile (Table 3). The AB horizon of the AC18 soil profile has a higher silt/clay ratio and this may have favored the formation of soil aggregates capable of retaining DIC species. However, this hypothesis is still speculative and more detailed studies should be developed to explain the distinct behavior of the DIC in the AB horizon.

In addition to the influence of the triple interaction between the independent factors soil profile, soil horizon and incubation time and the influence of liming, DIC was also influenced by soil physical-chemical parameters. The linear correlations between DIC concentrations and pH, Eh and EC values were respectively 0.51; -0.60; 0.79, all significant at $p < 0.05$. It is known that EC indirectly expresses the concentration of ions in solution (Drever, 1997), so the high correlation between DIC and EC may have been due to the presence of ionic species associated with DIC. Positive correlation between EC and DIC was also found by Amaral et al. (2000). The results from Amaral et al. (2000) and from this study suggest that EC is a parameter which can be indicative of the presence of DIC species in the soil solution. There was also a negative correlation between Eh and DIC. This is a unique result which indicates that the redox state of the soil can influence the cycling of DIC. Thus, the concentration of DIC species tends to increase under reducing conditions. In the present study it was not possible to elucidate this hypothesis and further studies are needed to test it.

5. CONCLUSIONS

It is concluded that agricultural management in Plinthosols with the use of prolonged flood irrigation generates changes in the dissolved inorganic carbon cycling. In Plinthosols, prolonged flooding triggers favorable conditions for solubilization of DIC species in horizons A and AB, especially for those soils which have received agricultural additives. Also, the increase in DIC concentrations is favored by high concentration of ions in solution and the reducing state of the soil.

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