



Sedimentation rate and accumulation of nutrients in the Upper Paraná river floodplain

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Abstract

The objective was to rebuild the history of sedimentation and accumulation of nutrients rate in the Upper Paraná River floodplain. Two corers were collected and sliced at intervals of 2 cm. In the sub-samples geochronological analysis was performed by means of the isotope ^{210}Pb , and also the quantification of organic carbon, nitrogen and phosphorus. Garças Pond presented sedimentation rate of 7.7 mm yr^{-1} and Patos Pond 6.8 mm yr^{-1} . The flood pulse is the main regulating factor of the sedimentation rate on the Upper Paraná River floodplain. The total organic carbon derives from allochthonous origin and the limiting productivity nutrient in the system is nitrogen.

Keywords Eutrophication · Phosphorus · Isotope ^{210}Pb · Organic matter · Nitrogen

Introduction

The most significant change in aquatic ecosystems throughout the world is the anthropogenic eutrophication [1], the process is triggered by the ecosystems artificial enrichment with phosphorus and nitrogen. This process is mainly caused by the dump of domestic sewage, animal manure and mineral fertilizers used in agricultural practices, into the aquatic environments [1]. A paradigm suggests that the primary production of sweet aquatic ecosystems is limited only by the phosphorus availability [2]. However, there is evidence of eutrophication caused by nitrogen [3]. In addition to cases that prove that both phosphorus and nitrogen are responsible for the eutrophication [4]. Part of the nutrients are adsorbed by organic and inorganic particles

that eventually consolidate in environments of low energy, forming historical records of the environment geochemical conditions. Therefore, the sediments may act as a record of human impact in the areas where the formation of consecutive layers is processed in an undisturbed way [5].

The sedimentary historical records when accessed enable us to identify significant environmental changes [6]. The sedimentation rate, associated with the nutrients concentration in the sediment, shows us the changes occurring in the aquatic environment (such as changes in the hydrologic regime, increase or decrease of primary production, construction of dams and entry of contaminants) and terrestrial environment as changes in land use and the drainage basin occupation of the water body under study [7]. Countless forms were developed to quantify the sedimentation rate. Among them, the geochronology by means of the isotope ^{210}Pb is the most widely used to study paleoenvironments with formation between 10 and 100 years [8]. This sediment geochronology method is used to interpret the effects of anthropogenic alterations in environments such as marine environments [9, 10], estuaries [11], mangroves [12], rivers [13, 14], lakes [15, 16] and floodplains [17, 18]. The floodplains are important environments for biodiversity, in addition to controlling the retention and transformation of nutrients in river systems [19].

The Upper Paraná River floodplain has been described as the last stretch of the Paraná River, in the Brazilian territory,

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with river-floodplain interaction ecosystem [20, 21]. The Upper Paraná River floodplain has considerable variability of habitats, maintaining great diversity of terrestrial and aquatic species, being the flood pulse, considered as the main regulator of the communities structure and the functioning of this ecosystem. Due to its unique characteristics the Upper Paraná River floodplain has been the target of intense studies since 1980, mainly of taxonomic and ecological nature of the various communities [18]: phytoplankton [22], zooplankton, [23], periphyton [24] aquatic macrophytes [25], benthic macroinvertebrates [26] and ichthyofauna [27].

Stevaux and Souza [28] by means of the isotope ^{14}C estimated sedimentation rates averages for various environments of the Upper Paraná River floodplain, as channel (8.5 mm yr^{-1}), splay (1.3 mm yr^{-1}), lake (1.0 mm yr^{-1}) and natural levee (2.3 mm yr^{-1}) achieving general average of 5.01 mm yr^{-1} . However, studies focused on the evolution of the sedimentation and nutrient concentration rate in sediments are non-existent in the region.

In this context, the present study aims to reconstruct the history of rate and sedimentation and accumulation of nutrients in the Upper Paraná River floodplain, identifying the factors and/or phenomena that influenced these variables, with the aim of assisting the ecological-related research that are widely carried out in the area.

Material and methods

Study area

The Upper Paraná River floodplain is located between parallels $22^\circ 32'$ and $22^\circ 59'$ south latitude the meridians $53^\circ 08'$ to $53^\circ 40'$ west longitude (Fig. 1). The sediment corers were extracted in Garças Pond (GP) and Patos Pond (PP). GP ($22^\circ 43' 30.7'' \text{ S}$ and $53^\circ 18' 15.5'' \text{ W}$) is located on the right side of Paraná River, which is permanently connected by a channel. The pond has approximately 150 m wide and 2.0 km in length, 0.3 km^2 of area and average depth of 2.5 m. PP ($22^\circ 49' 30.64'' \text{ S}$ and $53^\circ 33' 12'' \text{ W}$) is located on the left bank of Ivinhema River, both permanently connected by a channel. The pond has area of 1.14 km^2 (0.65 m wide and 1.75 m in length) and depth of between 2.8 and 4.8 m.

Sample collection and preparation

The sediment cores were collected in October 2011, from the deepest areas of the ponds (depths of 3.5 and 4.5 m in GP and PP, respectively). The samples were collected using polyvinyl chloride (PVC) hand corers that were 80 mm in diameter and 1.2 m long. The divers inserted the hand corers vertically into the sediment and then carefully extracted

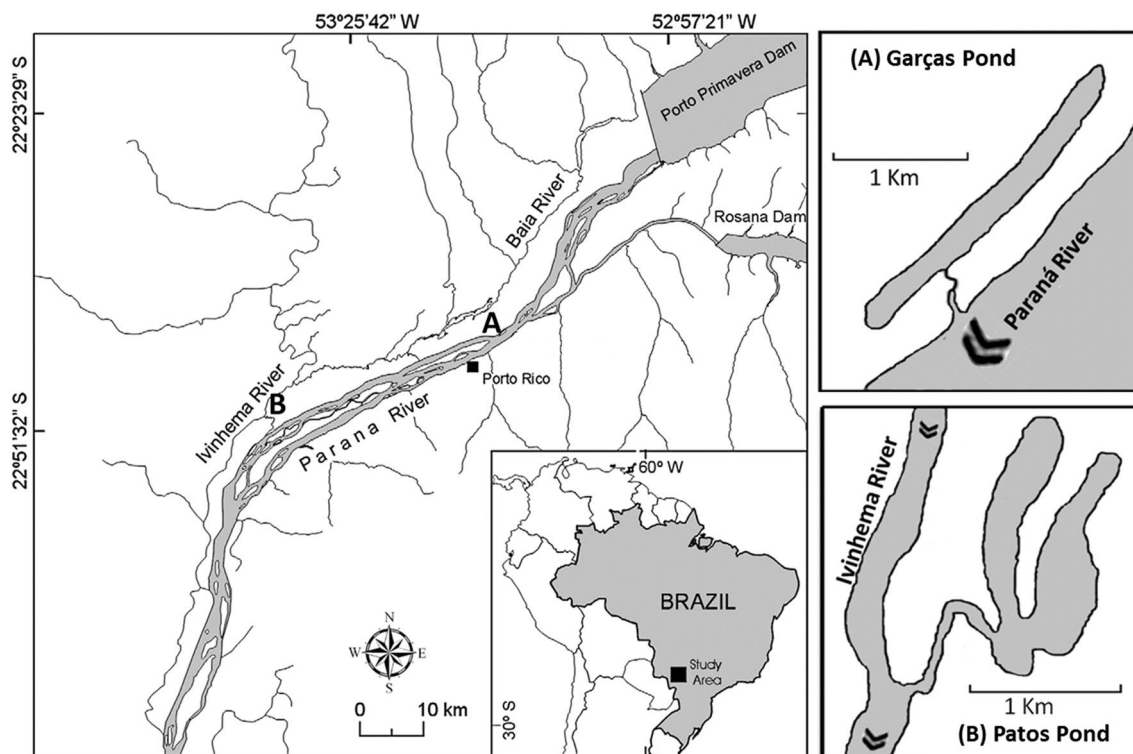


Fig. 1 Location of the study area. **A:** Garças Pond; **B:** Patos Pond

them. To minimize deformation of the cores, the bottom end was sealed with a stopper immediately after the hand corers were extracted [18].

The sediment cores taken at the GP and PP were sliced at uniform intervals of 2.0 and 2.2 cm, respectively, to obtain sub-samples. The sub-samples were placed in expanded polystyrene trays and dried at room temperature while protected from sunlight to avoid the loss of volatile chemical elements. After drying, the sub-samples were weighed [18].

Chronological analysis

The chronological analysis of the sediment cores using the ^{210}Pb method was performed at the Laboratory of Environmental Radiometry of the Institute of Nuclear Energy Research. Radionuclides ^{226}Ra and ^{210}Pb measurements were used to determine the dates of deposition of each slice of the sediment cores. The radionuclide activity concentration was measured every 4 cm from the first slice of each profile [18].

All samples previously dried at 60°C were passed through a 63 μm sieve and digested in concentrated HNO_3 , 40% HF and 30% H_2O_2 . The procedure included the initial precipitation of ^{226}Ra and ^{210}Pb with 3 M H_2SO_4 , dissolution of the precipitate with nitrilotriacetic acid at an alkaline pH, precipitation of $\text{Ba}(^{226}\text{Ra})\text{SO}_4$ in a solution of ammonium sulphate and precipitation of $^{210}\text{PbCrO}_4$ in a solution of sodium chromate. The ^{226}Ra concentration was determined by gross alpha counting of the $\text{Ba}(^{226}\text{Ra})\text{SO}_4$ precipitate, and ^{210}Pb was analyzed based on its decay product ^{210}Bi by measuring the gross beta activity of the $^{210}\text{PbCrO}_4$ precipitate. The chemical yields of both radionuclides were determined by a gravimetric analysis of the precipitate, and the ages were calculated using the constant rate supply (CRS) model [29]. We assumed constant accumulation of ^{210}Pb because the results that we obtained for its concentration decreased exponentially, except for the results associated with flood events [18]. The same occurred in previous work performed for us in the Brazilian wetland of Pantanal [30].

The method detection limits were $2.2 \pm 0.2 \text{ mBq kg}^{-1}$ for ^{226}Ra and $4.9 \pm 0.4 \text{ mBq kg}^{-1}$ for ^{210}Pb . For validation of the procedures, the reference materials Pacific Ocean Sediment 367 and Irish Sea Sediment 385, both from IAEA, were analysed. The results were in agreement with the certified values; the relative standard deviation and relative error for ^{226}Ra were 16.1 and 10.3%, respectively, and the relative standard deviation and relative error for ^{210}Pb were 13.5 and 1.1%, respectively [18].

Physico-chemical analyses

The dried sediment samples were treated with H_2O_2 for removal of organic matter, dispersed with solution 10%

(NaPO_3)₆ and ultrasound, subsequently, granulometric analysis was performed by means of laser diffractometer CILAS 1180 liquid in the range from 0.04 to 2500 μm with 100 classes. The Total Organic Carbon (TOC) was determined by the Walkley–Black method [31]. The Total Nitrogen (TKN) was quantified by the Kjeldahl method [31]. The concentration of total phosphorus (P_T) was performed by colorimetry [31].

Data analysis

The existence of correlation between the sedimentation rate and the flood pulses was verified by means of the non-linear Spearman's correlation with 5% significance.

The sediment granulometry data were analyzed by means of the diagram of Shepard Diagram the Pejrup Diagram using the package *rysgran* [32] in the R software, for determination of the sediment texture and the environments hydrodynamics.

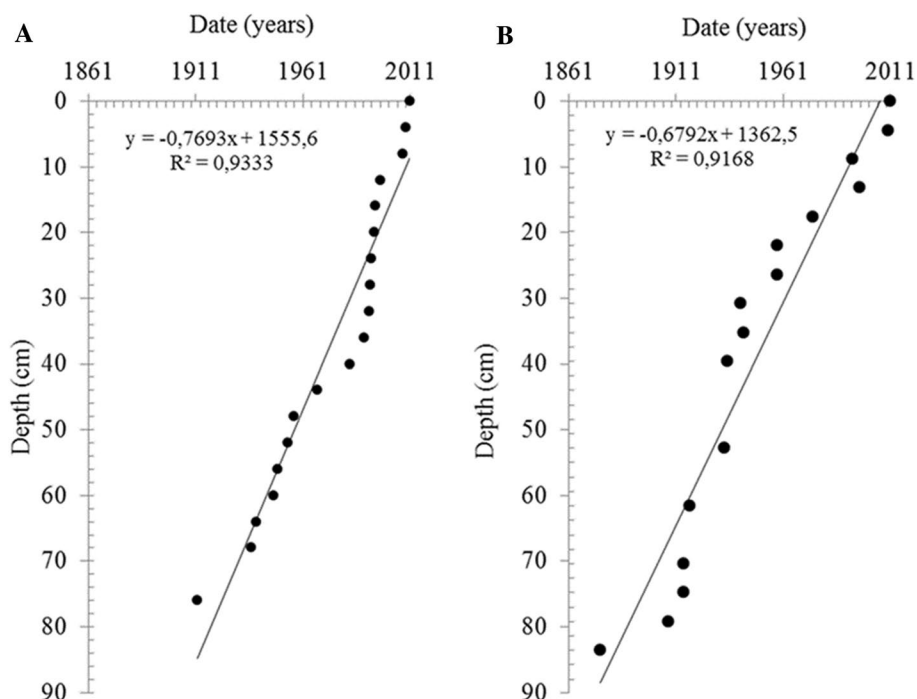
The existence of a correlation between the flood pulses and the concentration of nutrients in the bottom sediment of Garças Pond was verified by means of linear Pearson correlation and Spearman non-linear, with 5% of significance.

Results and discussion

The date of the slices formation of sediment collected in the Upper Paraná River floodplain, estimated by the radioisotope ^{210}Pb method, is shown in Fig. 2. In Garças Pond (GP; Fig. 2A) a sediment core was collected with 76 cm, and the geochronology estimated the formation of deeper slice in 1912 (99 years), possessing thus, sedimentation rate of 7.7 mm yr^{-1} . In Patos Pond (PP; Fig. 2B) a sediment core was collected of 76 cm, and the geochronology estimated the formation of deeper slice in 1876 (135 years), possessing thus, sedimentation rate of 6.8 mm yr^{-1} . The sediment cores collected in the two ponds (Fig. 2) have formation date shorter than the maximum date (150 years) indicated for use of the isotope ^{210}Pb geochronology [8].

The sedimentation rate stipulated by the isotope of ^{210}Pb method in the two ponds is similar to the medium sedimentation rate (5.07 mm yr^{-1}) obtained in the study of Stevaux and Souza [28] at the alluvial plain of Upper Paraná River, using ^{14}C with isotopes for geochronology, and the study of Fávero [33] in Salina do Meio pond (6.1 mm yr^{-1}), which covers an area of 0.126 km^2 , in the Brazilian Pantanal. However, other studies in the Brazilian Pantanal showed lower rates of sedimentation. Godoy [34] reported sedimentation rates of 4.1 and 3.7 mm yr^{-1} in two ponds of Taquari river, and McGlue [35] calculated a sedimentation rate of 2.4 mm yr^{-1} in Gaíva lake (80 km^2 area). In general, the sedimentation rates may be

Fig. 2 Formation date of the slices of sediment estimated by radioisotope ^{210}Pb . **A:** Garças Pond; **B:** Patos Pond



smaller in lakes with greater surface area, because such lakes have less influence of the particles drag from the banks. However, this is only one of the factors that control the sedimentation rate not being possible to be considered as a rule. According to Bonachea [36], these results can be

better explained by the high natural variability that flood-plains systems have.

The sedimentation rate over time in the Upper Paraná River floodplain is demonstrated in Fig. 3. The medium sedimentation rate in GP is $5.94 \text{ kg m}^{-2} \text{ yr}^{-1}$, however

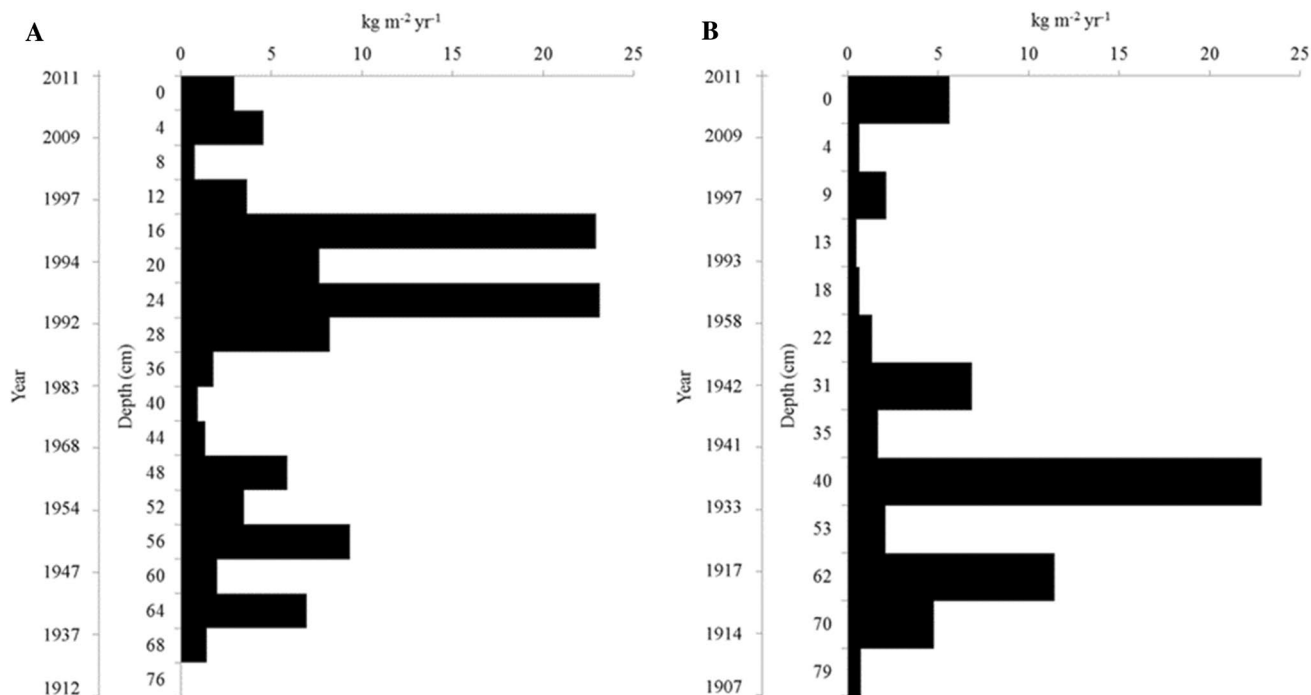


Fig. 3 Sedimentation rate of the Alluvial plain of Upper Paraná River. **A:** Garças Pond; **B:** Patos Pond

in Fig. 3A, it is possible to observe that the sedimentation rate is not constant. The variation in the sedimentation rate of GP over time is a consequence of the flood pulses intensity. This hypothesis is supported by the non-linear correlation (Spearman correlation coefficient = 0.71; p -value = < 0.05) among the sedimentation rates obtained in this study and the flow peaks presented by Stevaux [37]. The two highest sedimentation peaks in GP (23.1 and 22.9 $\text{kg m}^{-2} \text{yr}^{-1}$) occurred in 1993 and 1995, respectively. These peaks, in addition to possessing an association with the flood pulses, occurred during the construction of Porto Primavera Hydroelectric Dam, which is the upstream of the Upper Paraná River floodplain. The dams construction requires the removal and transport of large quantities of soil, part of the soil enters the system through surface runoff and/or wind erosion, increasing the sedimentation rate in downstream environments.

The medium sedimentation rate in PP is 4.71 $\text{kg m}^{-2} \text{yr}^{-1}$, however in Fig. 3B, it is observed that the sedimentation rate is not constant. The sedimentation rate variation over time in PP, probably, associated with the flood pulses of Ivinhema River flood. However, we do not have the river hydrological data to confirm this hypothesis. The highest sedimentation rate (22.9 $\text{kg m}^{-2} \text{yr}^{-1}$) occurred in 1935. From 1943 period of reduction in the sedimentation rate of PP begins. The gradual closure of cable connection between the ponds and the river were described originally by Drago [38]. This process, in addition to reducing the flow of water and suspended particulate material coming from the river channel, reduces speed and consequently the competence of the flow, by the increase of surface roughness due to implantation of vegetation.

The textural composition and hydrodynamic conditions of the Upper Paraná River floodplain are presented in Fig. 4.

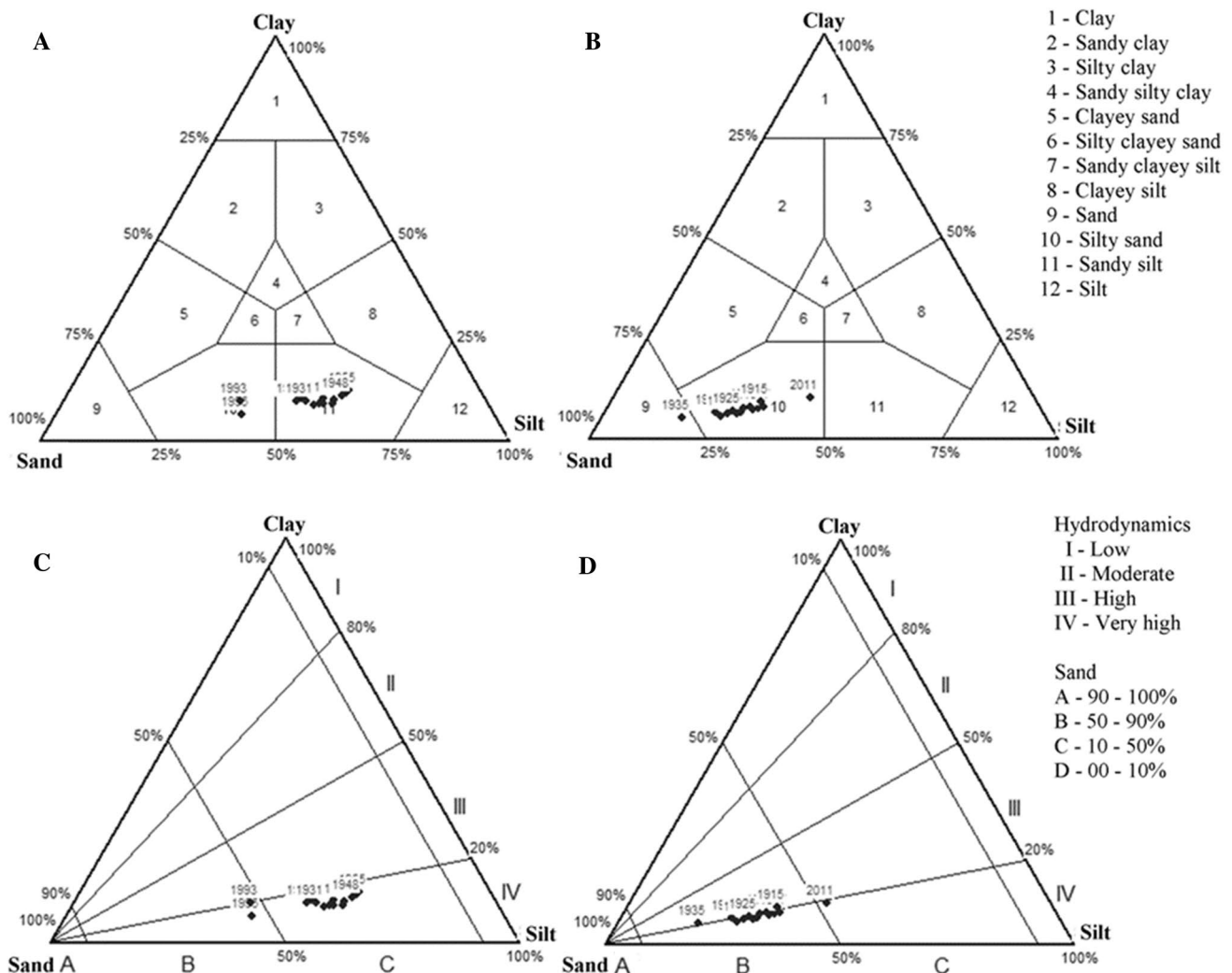


Fig. 4 Textural composition and hydrodynamic conditions of the bottom sediment of the Alluvial Plain of Upper Paraná River. **A:** Shepard diagram Garças pond; **B:** Shepard diagram Patos Pond; **C:** Pejrup diagram Garças pond; **D:** Pejrup diagram Patos pond

The sediment bottom from GP according to Shepard diagram (Fig. 4A) presents sandy silt texture in all the samples, except for the samples for the years 1993 and 1995 which showed silty sand texture. This fact confirms the hypothesis that the sedimentation rate in GP is influenced by flood pulses, because these samples differed from the others by presenting a higher content of the sand fraction. During the flood pulse there is an increase in surface runoff and the river flow, increasing the number and diameter of the material that enters the system. In addition, the resuspension of bottom sediments, mainly of upstream environments of the alluvial plains [20, 21], thus increasing the sedimentation rate and the particles granulometry in the system.

The sediment of PP according to the Shepard diagram (Fig. 4B) presents sandy silt texture in all the samples, except for the samples regarding the year 1935 which showed sand texture. In 1935 was the year that showed a higher sedimentation rate in PP (Fig. 3B). We can conclude that both the sedimentation rate and the change in the sediment texture are due to flood pulses, because the same phenomenon occurred in GP.

The Pejrup diagram of GP (Fig. 4C) and PP (Fig. 4D) demonstrate that the two ponds have very high hydrodynamics. However, both pond have little connection with the main beds of the respective rivers and presented the same hydrodynamic class over time. Thus, it is possible to conclude that the result of the Pejrup diagram corresponds to the soils natural characteristics of the drainage basin, which have medium texture with low clay portion.

The nutrients concentrations in the bottom sediment from GP are shown in Fig. 5. According to the linear correlation test of Pearson and non-linear Spearman, both with 5% of significance, the flood pulse does not exercise influence on

the nutrients concentration in the bottom sediment from GP, because there is no correlation between the flow peaks in the Paraná River and the nutrients concentration in the bottom sediment of GP. Thus, the flood pulse exerts influence only in the nutrients load, but not in the concentration of such sediments of the Upper Paraná River floodplain.

The TOC concentration in the GP sediment remained between 7.3 and 9.3%, without presenting significant peaks (Fig. 5). The TKN concentration (Fig. 5) can be divided into two periods, the first between 1912 and 1975, with greater variability, has concentration between 2497 and 4000 ppm with peak of 4200 ppm. The second period from 1983 to 2011, with less variability, with concentrations of between 4254 to 4692 ppm and peak of 4845 ppm. The increase in the TKN concentration in GP sediment is related to the increase of agricultural activity in the drainage basin. Ni and Wang [39] reported in their study an increase in the nitrogen concentration after 1970, due to the increase of agricultural activity in the drainage basin of Erhai lake in China. The reduction in the variability of TKN concentration in the sediment may be attributed to the dam construction upstream of the alluvial plain, because these help in regulating the flow of the main channel, in addition to sequestering the nutrients complexed to particulate upstream the floodplain [18].

The C/N ratio in GP sediment presents values between 17 and 29 with an average of 20.7 (Fig. 5). According to Kraushal and binford [40] the organic matter, in sediments, derived from phytoplankton has low C/N ratio (< 10), while the organic matter derived from terrestrial plants has C/N ratio > 20 . Therefore, it is possible to conclude that the TOC in GP sediment is derived mainly from allochthonous origin. This result is due because the GP has turbid water, limiting the phytoplankton development, due the low entry of light.

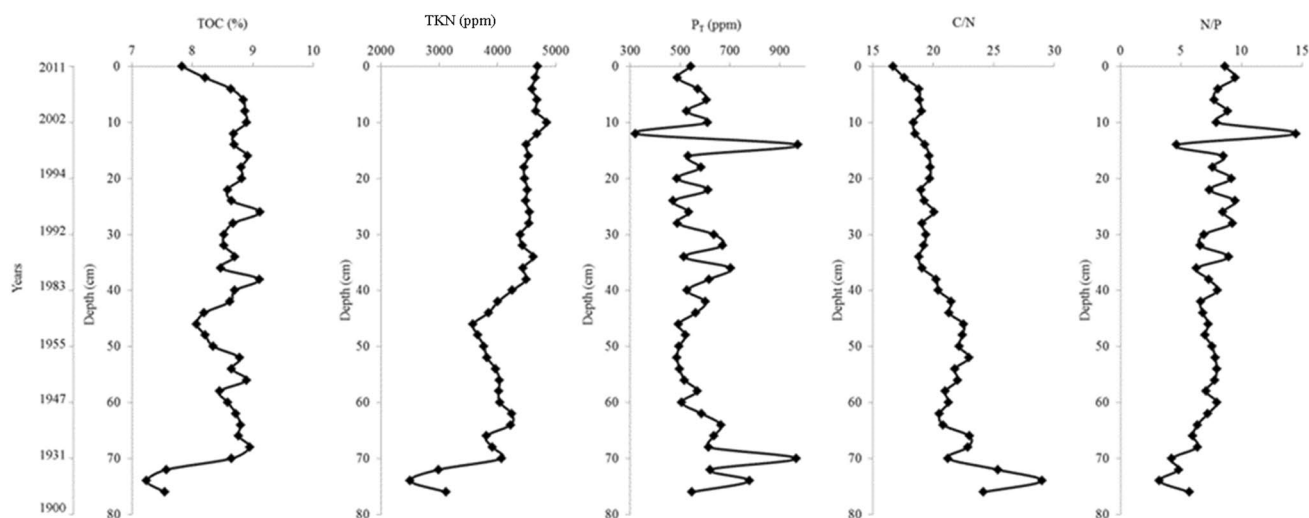


Fig. 5 Nutrients in the bottom sediment Garças pond. **TOC**: Total Organic Carbon; **NTK**: Total Kjeldahl Nitrogen; **P_T**: Total phosphorus; **C/N**: Carbon/nitrogen Ratio; **N/P**: Ratio Nitrogen/phosphorus

Wang et al. [41] and Yang [42] found similar result in lakes of the Taiwan floodplains.

The concentration of P_T in the bottom sediment of GP (Fig. 5) is between 320 and 970 ppm with average of 588 ppm not presenting a tendency of increase or reduction. Despite being widely used in agriculture [39], the concentration of P_T in GP sediment did not follow the trend of increase in TKN, because the phosphorus mobility in the soil is very small, reason why the losses by percolation in agricultural soils are deemed insignificant [43]. Thus, the possibility of a phosphorus sequestration upstream the floodplain.

The N/P ratio in GP sediment presents average of 7.47 and maximum value of 14.5 (Fig. 5). According to Carstensen [44] environments with low N/P ratio (<20) nitrogen is the limiting nutrient of productivity and environments with N/P ratio > 50 phosphorus is the limiting nutrient. Thus, it is possible to conclude that nitrogen is the limiting nutrient of productivity in GP. This hypothesis is supported by the Pearson linear correlation between TOC and TKN (coefficient of correlation 0.71; p -value < 0.05). P_T has no significant correlation with TOC (correlation coefficient -0.09 ; p -value > 0.05).

The nutrients concentrations in the bottom sediment from Patos Pond (PP) are shown in Fig. 6. The PP shows an increase in the concentration of TOC and TKN in the sediment over time. However, concentration P_T in PP sediment presents contrary trend, reducing the concentration over the sampled period.

The increase in the concentration of TOC and TKN in PP (Fig. 6) sediment can be divided in three periods: the

first, between 1892 and 1935, can be considered the background; the second, between 1935 and 1970, when there was an enormous effort by the Brazilian government for the colonization of the country interior, by means of credit to purchase and preparation of areas intended for livestock and agriculture. The beginning of the second period matches the dates of foundation of major cities in the drainage basin of Ivinhema River, such as Dourados, Ivinhema and Rio Brilhante; and the third between 1970 and 2011, matches the agriculture intensification and the use of mineral fertilizers on a large scale in the region [45].

The C/N ratio in PP sediment presents values between 17 and 22 with an average of 19 (Fig. 6). Just as in GP the water of PP is turbid limiting the phytoplankton development, due to low entry of light. Therefore, it is possible to conclude that TOC in PP sediment is derived mainly from allochthonous origin. According to Brock [46] and MacDonald [47] the greatest values of C/N ratio are found in flooding periods, depending on the input of organic matter from allochthonous origin that has a higher C/N ratio than the autochthonous organic matter formed by phytoplankton [40].

The N/P ratio in PP sediment has an average of 3.93 and with maximum value of 9.50 (Fig. 6). Just as in GP, we can conclude that nitrogen is the limiting nutrient of productivity in PP [44]. This hypothesis is supported by the Pearson linear correlation between TOC and TKN (coefficient of correlation 0.93; p -value < 0.05). P_T has significant negative linear correlation with TOC (coefficient of correlation -0.70 ; p -value < 0.05), therefore, the increase in TOC is not influenced by P_T .

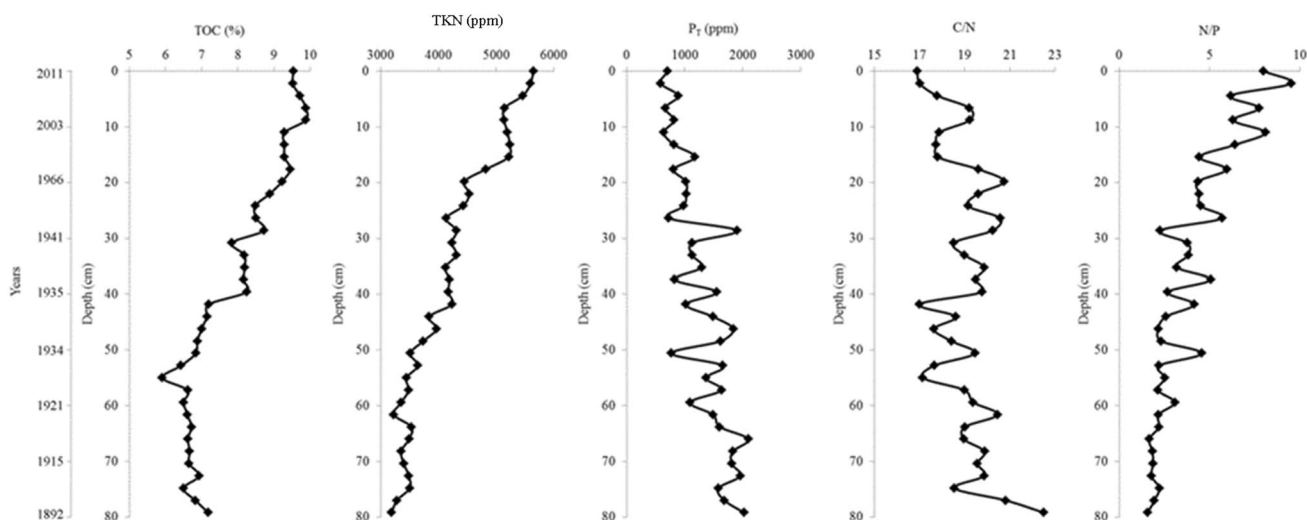


Fig. 6 Nutrients in the bottom sediment Patos pond. TOC: Total Organic Carbon; NTK: Total Kjeldahl Nitrogen; P_T : Total phosphorus; C/N: Carbon/nitrogen Ratio; N/P: Nitrogen/phosphorus Ratio

Conclusion

The flood pulse is the main regulating factor of the sedimentation rate at the Upper Paraná River floodplain, the higher the flood pulse the higher the sedimentation rate in the period. Concomitant with the extreme peaks of sedimentation rate, increase of the granulometry of bottom sediments was observed. However, the flood pulse does not exert an influence on the concentration of nutrients in the bottom sediment from the Upper Paraná River floodplain. The natural evolution of the water bodies of the floodplain affects somewhat the sedimentary input. As a rule, there is a trend of isolation (terrestrialization) of the body of water with a consequent reduction in the sedimentation rate.

The total organic carbon in the sediment of the Upper Paraná River floodplain derives mainly from allochthonous origin. However, the limiting nutrient of productivity in the system is nitrogen, having as main source, the agricultural practices in the drainage basin.

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