Relationship between antropogenically caused turbidity and phytoplankton production in a clear Amazonian floodplain lake[*]

by

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Abstract

The present study was performed in Lake Batata, a clear water Amazonian floodplain ecosystem, located on the right bank of the Trombetas river (Pará State, Brazil). For a period of 10 years (1979-1989), the lake received a large quantity of bauxite tailings from a nearby mine. These tailings originally covered about 30 % of the lake sediments, but resuspension and redeposition have resulted in an even wider distribution of the tailings. Phytoplankton production was measured at different sites in natural an impacted areas at different hydrological phases. Incubations were exposed at 5 light depths using ^{14}C as tracer. All vertical profiles of primary production exhibited ca. 13 % light inhibition in the surface. The maximum primary production rates (Pmax) were always found near the surface at approximately 30 cm. Production rates ranged from 9 to 664 mgC m^{-3} d^{-1}, being the higher rates found during low water and lower rates during high water periods. Transparency measurements were good predictors of phytoplankton attributes. A strong predictive capacity of the turbidity effect was shown. An increase in turbidity of 3.6 times could reduce the carbon production in the lake by 51 %. In areal terms, it was estimated that Lake Batata produces ca. 122 g C m^{-2} per year. Our data reveal that although being poorer in nutrients, clear water systems are as productive as decanted white water systems. The results suggest that phytoplankton production is regulated by solar radiation and not nutrient. Despite the turbidity increase caused by resuspension of tailings, phytoplankton production remains relatively high and still plays a central role to the carbon flux in Lake Batata, especially during low water hydrological periods.
Keywords: **Primary production, phytoplankton, turbidity, Amazonian lake, tropical lake.**

Resumo

O presente estudo foi realizado no lago Batata, um ecossistema aquático Amazônico de águas claras, localizado na margem direita do rio Trombetas (Estado do Pará, Brasil). Ao longo de 10 anos (1979-1989), o lago recebeu uma grande quantidade de rejeito de bauxita oriundo de uma mina próxima. Este rejeito originalmente cobriu cerca de 30 % do sedimento do lago, mas processos de ressuspensão e redeposição

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têm resultado em uma distribuição ainda mais ampla do rejeito no lago. Produção fitoplanctônica foi medida em áreas afetadas e livres da ação do rejeito de acordo com a variação hidrológica. Amostras foram incubadas em 5 profundidades de acordo com a penetração de luz utilizando ^{14}C como traçador. Todos os perfis verticais de produção primária exibiram redução de cerca de 13 % na superfície devido à foto-inibição. Taxas de produção primária máxima (Pmax) foram sempre encontradas na sub-superfície, aproximadamente 30 cm. Taxas de produção variaram de 9 to 664 mgC m^{-3} d^{-1}, onde as mais elevadas taxas foram encontradas no período de águas baixas e as menores durante o período de água altas. Medidas de transparência foram sensíveis indicadores de atributos fitoplanctônicos. Os resultados mostraram uma forte capacidade preditiva da ação do rejeito. Um incremento de 3.6 vezes nos níveis de turbidez poderiam reduzir a produção fitoplanctônica em 51 %. Em termos de produção global, foi estimado que o Lago Batata produz cerca de 122 gC m^{-2} por ano. Nossos dados revelaram que, embora pobre em nutrientes, sistemas de águas claras são tão produtivos quanto aqueles com águas brancas-decantadas. Os resultados sugerem que a produção fitoplanctônica é regulada pela radiação solar e não por nutrientes. Mesmo com o incremento de turbidez causada pela ressuspensão de rejeito, a produção fitoplanctônica parece continuar desempenhando importante papel no fluxo de carbono no lago Batata, especialmente durante os períodos de águas baixas.

Introduction

The remarkable contrast between temperate and tropical regions in the annual variability of sunlight and temperature leads naturally to the hypothesis that the magnitude, efficiency and variability of energy flow in biological systems must also differ greatly between these regions (LEWIS 1974). Evidences suggest that tropical lakes are highly productive compared to temperate lakes (LEWIS 1974, 1987; TALLING 1966; SCHMIDT 1982; RAI & HILL 1984; MELACK 1996). According to LEWIS (1996), primary production at lower latitudes is about twice as high for a given nutrient base than at higher latitudes because of efficient nutrient cycling combined with higher mean temperatures and greater solar radiance stability. In contrast, SCHINDLER (1978) suggested that phytoplankton production in temperate and tropical lakes should not be very different. His statement is based on the correlation between latitude and nutrient input assuming that lake productivity and eutrophication are inseparable.

The net production in Amazonian floodplain lakes is primarily based on their linkage to terrestrial systems but also driven by a complex hydrological regime. The intense annual water level fluctuation in water level control nutrient dynamics (FORSBERG et al. 1988), light availability (FURCH & OTTO 1987) and organic matter balance (Mc-CLAIN & RICHEY 1996). These annual variations were defined as flood pulses by JUNK et al. (1989) and understood as pulses of energy and matter by NEIFF (1990). Three basic categories of water have been described for the Amazonian region: white waters (rich in suspended solids), black waters (rich in dissolved organic carbon) and clear waters (free of suspended solids); SIOLI (1964). Another category of water has been described as "decanted white" water by clear and rich in nutrients (SCHMIDT 1973).

Production by phytoplankton in Amazonian ecosystems has been studies since the sixties (MARLIER 1965, 1967; HAMMER 1965; SCHMIDT 1973, 1976, 1982; RIBEIRO 1978; FISHER 1978; RAI & HILL 1984; MELACK & FISCHER 1990; RODRIGUES 1994). However, most of the studies were performed in either white or black waters systems. Data about Lake Batata is important because this floodplain lake can be described as a clear water ecosystem (nutrient-poor and free of suspended solids). However, it also has some anthropogenically caused turbidity (see study area

section). Only a single study by SCHMIDT (1982) on the Tapajós river has examined the production of phytoplankton in a clear water system.

We asked the following questions about the production of phytoplankton in Lake Batata considering that suspended solids limit autotrophic production by reducing the depth of the euphotic zone (ROLAND & ESTEVES 1998) and that phytoplankton biomass is affected by water level variation (HUSZAR & REYNOLDS 1997): (1) Does primary production contribute substantially to planktonic particulate accumulation under the conditions of high-light scattering? (2) Are the phytoplanktonic dynamic controlled principally by the flood-pulse as proposed by JUNK et al. (1989) and not by other physical or ecological factors? In the present study we analyzed the effects of turbidity on the seasonal and spatial variation of phytoplankton production in the clear Amazonian lake.

Study area

Lake Batata, located adjacent to the Trombetas river (56°14'W and 1°28'S, Fig. 1), has an area that ranges between 29.5 km^2 at high water to 18 km^2 during the low water (ROLAND & ESTEVES 1993). Both the morphometry and depth of the lake change considerably during the year as a function of the river water level (PANOSSO et al. 1995). Lake depth varies between 0.5 and 9.0 meters during one year. The lake has three distinct features, i.e. a central basin, a bay and a canal. The central basin is the largest portion of the system. It has two distinct areas, i.e. a natural; area and an area impacted by tailings.

Over a period of 10 years (1979-1989), the lake received a large quantity of bauxite tailings at the rate of 50,000 m^3 day^{-1} (LAPA & CARDOSO 1988). Bauxite are processed by washing aluminum containing clay with water jets producing liquid tailings, composed of 7 to 9 % fine-grained solid particles (ca. 96 % are smaller than 50 μm, ROLAND & ESTEVES 1998). The tailings originally covered ca. 30 % of the lake bottom, however they have been widely redistributed due to intensive natural resuspension (ROLAND & ESTEVES 1993). The water is nutrient-poor with NO_3^- concentrations usually <50 μg L^{-1} and ratio between SRP and TP concentrations usually <20 μg L^{-1}. The water-column is generally quite well mixed and rarely anoxic (ESTEVES et al. 1994). The pH ranges between 6 and 7. Conductivity is usually <10 μS cm^{-2}.

Methods

Field sampling and general measurements. Sampling was accomplished: (*i*) every three months during three hydrological cycles (1989-1991) at two sites, a non-impacted station and an impacted station in the central basin and (*ii*) every three months for a single hydrological cycle (1991) at two sites, bay and canal stations (Fig. 1). Samples for primary production, chlorophyll-*a*, and optical parameter measurements were taken at depth intervals of 100 %, 75 %, 50 %, 10 % and 1 % of incident photosynthetically active radiation (PAR), starting 5 cm below the surface.

The depth of PAR distribution was measured with a LiCor model LI-193SB 4π sensor (model LI-312 light meter). A Secchi disk was used to estimate water transparency. Turbidity was measured using a LaMotte turbidimeter, model 800. Chlorophyll-*a* contents were determined by spectrophotometry acetone extracts (GOLTERMAN et al. 1978).

Measurements of primary production. Water samples were collected at 5 PAR depths. The incubations were run in triplicate (both clear and dark bottles) for each sample, using 120 ml aliquots spiked with 0.5 μCi of $NaH^{14}CO_3$ (NEN; 80 mCi $mmol^{-1}$). An extra tube was fixed with 2 % formalin (v/v) to serve as an abiotic control. The bottles were incubated *in situ* at ambient light levels for 4 hours. Two daily

incubations were performed from 8:00 to 12:00 and from 13:00 to 17:00. Measurements were made on 4 dates and evaluated during each hydrological period. Upon termination of the incubations, samples were fixed with 2 % (v/v) formalin and immediately transported to the laboratory. Samples were filtered through 25-mm, 0.45 μm Millipore filters and the particulate material was dissolved in 10 ml Bray scintillation liquid. Total radioactivity was determined by scintillation counting using a Beckman LS 600. The hourly ^{14}C uptake data were converted to daily data assuming a period of 12 hours of day-light.

Although the ^{14}C uptake measurements provide values that are intermediate between gross and net production (PETERSON 1980), we assume that the $H^{14}CO_3$ uptake is phytoplankton production measurement as done by COLE et al. (1992) and BAINES et al. (1994).

Results and discussion

Phytoplankton production. Depression of photosynthetic rates was observed in all hydrological periods on phytoplanktonic production at the waters surface (Fig. 2). The maximum production rate (Pmax) was observed at 75 % of incident radiation, between 0.25 m (low water) and 0.50 m (high water). Phytoplankton production was inhibited by 13 % at radiation greater than 1500 μmol m^{-2} s^{-1} production by 13 % (ratio of the rates between surface and sub-surface; average across hydrological seasons). A phytoplankton production rate of 200 mgC m^{-3} d^{-1} was supported by solar radiation higher than 1000 μmol m^{-2} s^{-1} except in high water periods. The profiles in the impacted area were similar, but less pronounced due to light-scattering resulted from increased turbidity. The maximum production rate has also been observed in upper water levels in other systems. Pmax occurred near the surface in a white water lake (Lago do Castanho, SCHMIDT 1973) and in a clear water river (Tapajoz; SCHMIDT 1982). FISHER (1978) also found Pmax between 0.5 and 1 meters depth in a black water river (the Negro river), a white river (Solimões river) and in a decanted white water (Lake Janauacá).

Both effects of water level and turbidity on phytoplankton production rates (PP) were also pronounced (Fig. 3). The rates ranged from 14 to 664 mgC m^{-3} d^{-1} in the non-impacted area and from 9 to 412 mgC m^{-3} d^{-1} in the impacted area. Lower rates were observed during high water periods and higher rates during low water periods in both areas. In addition, the variance among and within the four hydrological periods was much higher in the non-impacted area than in the impacted area. The variance among hydrological cycles was relatively high in response to the magnitude of the previous flood as mentioned by several authors (FISHER 1978; SCHMIDT 1982; RAI & HILL 1984). All literature on phytoplankton production in Amazonian floodplain lakes indicates that the higher values of production occur during low water periods (see also SCHMIDT 1973, 1976; FORSBERG et al. 1993). The combination of high light availability per unit of water volume (ROLAND & ESTEVES 1998) and increased dissolved and inorganic material originating in previous flood (ROLAND & ESTEVES 1993; FERRÃO-FILHO & ESTEVES 1994) explain the higher production values during low water periods. Phytoplankton biomass is greater during low water periods because of less dilution of the water no dilution effect, because the lake continues to mix (HUSZAR & REYNOLDS 1997).

Correlations. Turbidity and water-transparency were inversely correlated (Fig. 4a). The highest turbidities were observed to occur in the impacted area were associated with tailing deposition. The particles were frequently resuspended by rising and falling water levels and remained in suspension as small particles (>50 % of frequency distribution), thereby increasing inorganic turbidity (>25 NTU) and PAR scattering (ROLAND &

ESTEVES 1998). A previous study (ESTEVES et al. 1990) showed that because bauxite tailings are no longer discharged into Lake Batata, a reduction of turbidity has occurred in impacted areas. But, the tailings have an impact beyond the dumping area because of the natural redistribution of tailings. The natural turbidity in the lake (in non-impacted areas) is generally lower than 10 NTU, and phytoplankton do not contribute to turbidity. Even during the low water period, when phytoplankton biomass is high (HUSZAR & REYNOLDS 1997), turbidity is low.

Transparency measurements and consequently mineral turbidity were correlated to Pmax and chlorophyll-*a* (Figs. 4b and 4c). The regressions have shown a strong predictive capacity for both production and biomass from transparency measurements. Furthermore, both Pmax and integrated chlorophyll-*a* were significantly correlated (Fig. 4d). Although we plotted all data (both area sets), the statistically significant correlations among these attributes provide multiple linear regression equations for both non-impacted and impacted sets separately. The equations for non-impacted area considering the different hydrological seasons (filling - 1a, high water - 1b, drawdown - 1c and low water - 1d) are:

Eq.1a - PP = 63.42+(1.095*Pmax)+(25.29*Transparency); r^2=0.90 and p<0.001;
Eq.1b - PP = -21.81+(1.50*Pmax)+(25.54*Transparency); r^2=0.84and p<0.001;
Eq.1c - PP = 546.75+(0.65*Pmax)-(87.48*Transparency); r^2=0.63 and p=0.012;
Eq.1d - PP = -646.01+(2.59*Pmax)+(78.19*Transparency); r^2=0.94 and p<0.001.

PP is expressed in mgC m^{-2} d^{-1}, Pmax in mgC m^{-3} d^{-1} and and Transparency in meters.

The high coefficient of determination (r^2) in both models showed (except for the drawdown period), that more than 80 % of the integrated phytoplankton production could be explained by its relation with Pmax and water transparency as measured by Secchi depth.

Effect of turbidity and annual production. Considering that water transparency could be distinguished as the major factor controlling phytoplankton production in the impacted area and in view of its relationship to turbidity, we can calculate variations in phytoplankton production if the lake was more turbid as consequence of tailing redistribution. Applying hypothetical turbidities in the non-impacted area, such as the observed on impacted area in the equations and figure 4b, the rates would be reduced to the impacted levels (Fig. 5). In this case, the reduction determined by simulated turbidity on non-impacted areas would be pronounced and not quite as variable across the hydrological period, reflecting the lower variance of PP observed under turbid conditions. Only during high water periods the reduction would be lower than 45 %, validating that in those hydrological seasons both areas had shown similar levels of PP (see Fig. 3).

Although SIOLI (1964, 1968) have emphasized the role of distinguishing chemical characteristics among the categories of water (white, black and clear) as drivers of primary production in Amazonian aquatic ecosystems, the principal factors that effect rates of primary production are water clarity and seasonal changes in water level. We are in agreement with FURCH & OTTO (1987), who have shown the importance of the scattering of PAR by suspend mineral solids. Scattering of light by suspended tailings plays the same role as naturally occurring suspended solids in white water systems, as noted by RAI & HILL (1984). The limnological characteristics of phytoplankton production in impacted areas are quite similar to those in white water systems. However, clear water systems are poorer than white water systems. Therefore rates are lower

in Lake Batata.

Spatial heterogeneity among and within Amazonian flood-plain lakes is determined by their relationships with their respective rivers. During flooding, lakes are either remain isolated from the main river or flooded out by the rising water. Lake Mussurá, located on the opposite bank of the Trombetas River but near Lake Batata (Fig.1), is a good example of a lake which metabolism is not effected by the Trombetas River. Phytoplankton production in lakes such as Lake Batata, which floods out, is lower because the residence time the lake water is reduced (ESTEVES et al. 1994). In Lake Mussurá, a lake isolated from rising Trombetas River, production is not reduced during the flood as it is in central body of Lake Batata (ROLAND et al. 1997). However, the bay of Lake Batata (Fig.1) is hydrologically similar to Lake Mussurá because it is less effected by rising river waters. Annual integrated production of Lake Batata is highest in the bay area (Table 1). The integrated phytoplankton production in Lake Batata ranged from 70 mgC m^{-2} d^{-1} (impacted area, high water) to 1163 mgC m^{-2} d^{-1} (bay area, low water). The annual average productivity for the lake was 122 gC m^{-2} year^{-1}.

According to FORSBERG et al. (1993) phytoplankton is an important carbon source for many Amazonian commercial fish species. Algal production in floodplain lakes probally plays a critical role in sustaining the fish populations. In fact, other studies have shown that the net phytoplanktonic production could support a considerable portion of the aquatic food web in Amazonian aquatic ecosystems (FISHER 1978; SCHMIDT 1982). Even with some induced mineral turbidity, phytoplankton production is a key component in the carbon flux of Lake Batata, especially during the low water periods.

High phytoplankton production contributes greatly to the dissolved organic-C pool (SHARP 1977). It also contributes enormously to bacterial metabolism (MALINSKY-RUSHANSKY & LEGRAND 1996) as suggested in Lake Batata (THOMAZ et al. 1998). In addition, clay particles suspended in the water column provide a nucleus for concentrating DOC (ARRUDA et al. 1983). The combination of high productivity and DOC concentrated on clay particles could support bacterioplankton production as LIND et al. (1992, 1997) have shown for turbid aquatic ecosystems and as ANÉSIO et al. (1997) have previously suggested for Lake Batata. Even during the high water season (May to September), when the phytoplankton production is relatively low, the flooded rivers and forests carry allochthonous organic carbon into the lakes (FERRÃO-FILHO & ESTEVES 1994).

A comparison of the Amazonian aquatic ecosystems (Tab. 2) reveals that clear water systems such as at Lake Batata or Tapajoz River are as productive as decanted white water systems (Lake Janaucá) even though they are more nutrient poor. Light availability is most likely the major regulating factor of phytoplankton production in these ecosystems. In agreement with FISHER (1978) production does not seem to be limited by nutrients.

In summary, by applying the reduction factors derived from the simulated turbid conditions (Fig. 5) to each hydroperiod, we can estimate the reduction on daily integrated phytoplankton production for each area in Lake Batata (underlined numbers in the Table 1). We can also estimate the annual reduction in production for the whole lake. Increasing turbidity by 3.6 times (from 5 to 18 NTU, the average rates) resulted in a reduction of 51 % of phytoplankton production caused by the scattering of PAR by bauxite tailings. Tailings may also have the ability to complex inorganic nutrients (NO$_3$-N and PO$_4$-P), such as the suspended solids do in white-water systems (GROBBE-LAAR 1983). If this were the case and if Lake Batata had greater nutrient stocks, we could expected higher values in phytoplankton production even in impacted areas.

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Table 1: Areal daily and annual phytoplankton productivity across the hydrological seasons at different stations. The underlined numbers represent the modeled rates.(*) measured rate at impacted area.

Seasons / Sites	Filling	High water	Drawdown	Low water	Annual production Measured	modeled
		(mgC m^{-2} day^{-1})			(gC m^{-2} year^{-1})	
Canal	299	77	233	861	133.8	**64.5**
	145	**41**	**55**	**455**		
Bay	288	133	442	1163	184.4	**84.7**
	140	**72**	**105**	**614**		
Non impacted	366	111	388	537	127.6	**55.8**
	178	**60**	**92**	**284**		
Impacted	159	70	115	140	44.0	44.0(*)
Whole lake	1112	391	1178	2701	489.76	249.06
	623	**243**	**367**	**1493**		

Table 2: Comparison of estimated annual phytoplankton productivity among Amazonian aquatic ecosystems. The numbers between brackets represent the minimum and maximum rates.

| Water features	Aquatic Ecosystems	Annual Phytoplankton Production (gC m^{-2} year^{-1})	Reference
Lakes			
White	Castanho	292 (237-657)	SCHMIDT (1973)
White	Camaleão	290 (36-547)	RODRIGUES (1994)
Decanted-white	Janauca	803 (299-1277)	FISHER (1978)
Black	Tupe	37	RAI & HILL (1984)
Clear	Batata	490 (243-1493)	This study
Rivers			
White	Amazon	23 (17-51)	FISHER (1978)
Black	Negro	69 (22-171)	FISHER (1978)
Black	Negro	400 (146-730)	RAI & HILL (1984)
Clear	Tapajos	474 (161-876)	SCHMIDT (1982)
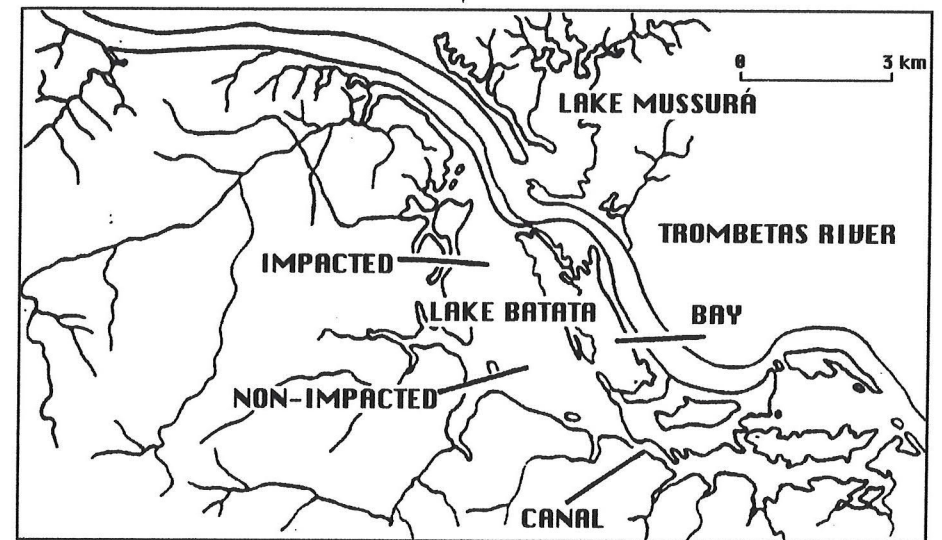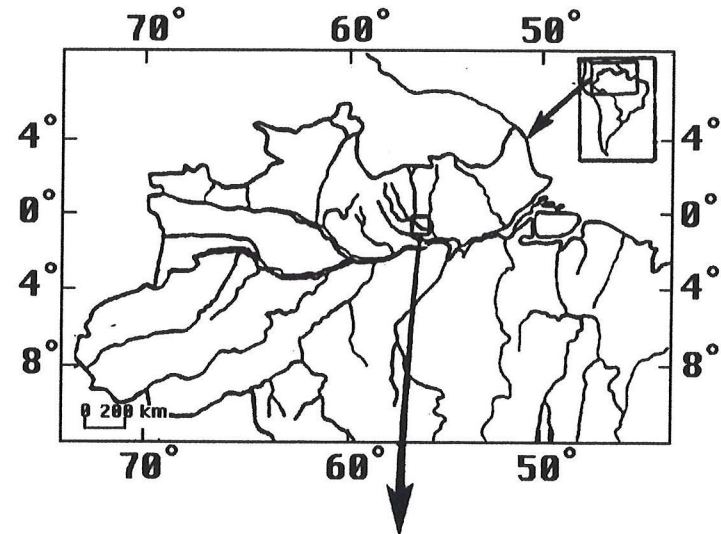
Fig. 1:
Location of Lake Batata in the Amazon River system, Brazil (above) and the sampling areas (below).

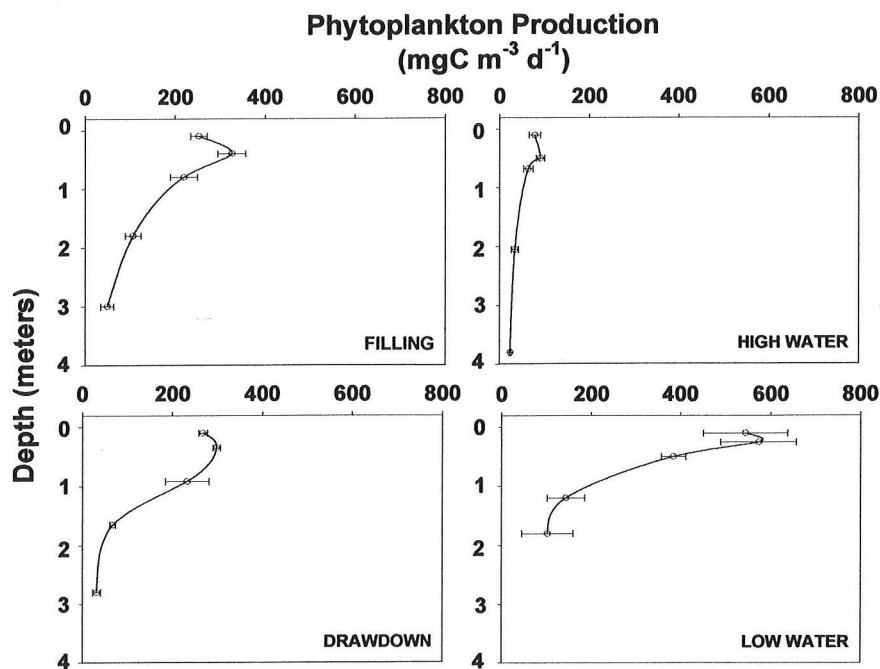**Phytoplankton Production**
(mgC m⁻³ d⁻¹)

Fig. 2:
Vertical profiles of phytoplankton productivity under natural light (photosynthetically active radiation - PAR) across the hydrological seasons measured at non-impacted area. Bars represent 95 % confidence interval.
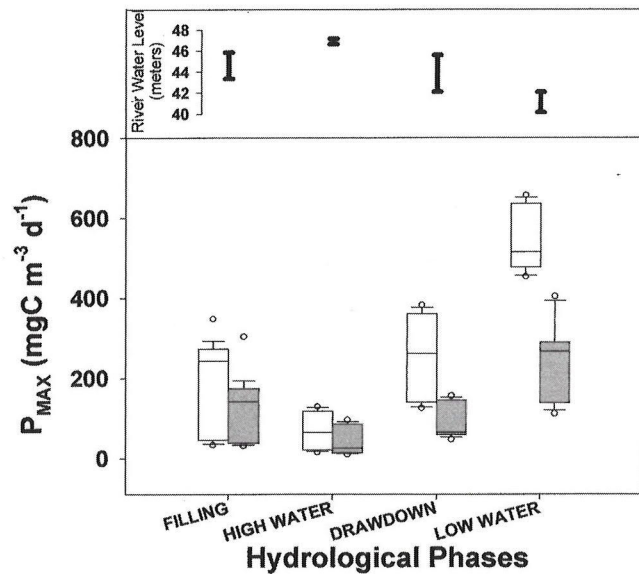

Fig. 3:
Box-and-whisker plots showing the range on maximum phytoplankton productivity (Pmax) across the hydrological seasons. Each set includes 24 data – two daily incubations, four days and three years. Empty boxes – Non-Impacted area and full boxes – Impacted area. The hydrological variation is shown in the top panel.
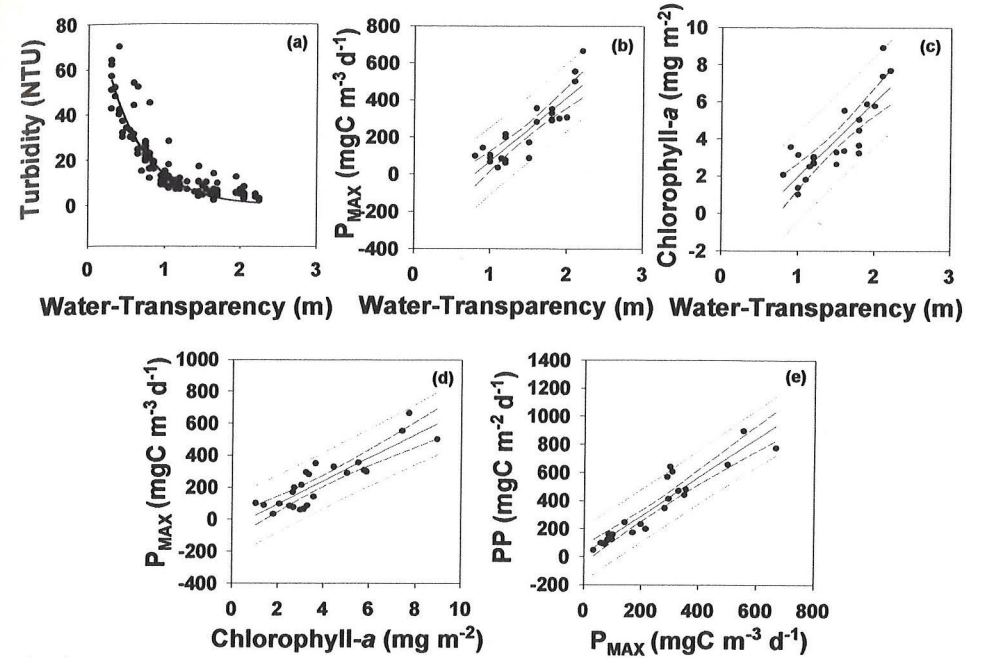

Fig. 4:
Relationships between general limnological attributes including both non-impacted and impacted set data. (a) Turbidity and transparency including 150 measurements (both three hydrological cycles and other subsequent measurements; unpubl. data). This relationship revealed r^2=0.84 and p<0.0001; (b) Maximum phytoplankton productivity (Pmax) and Secchi disk; (c) Chlorophyll-a and Secchi disk; (d) Maximum productivity (Pmax) and Chlorophyll-a and (e) Integrated phytoplankton productivity and Maximum productivity (Pmax). For those regressions were used the average for each season at the three hydrological cycles; they revealed r^2> 0.75 and p<0.001.
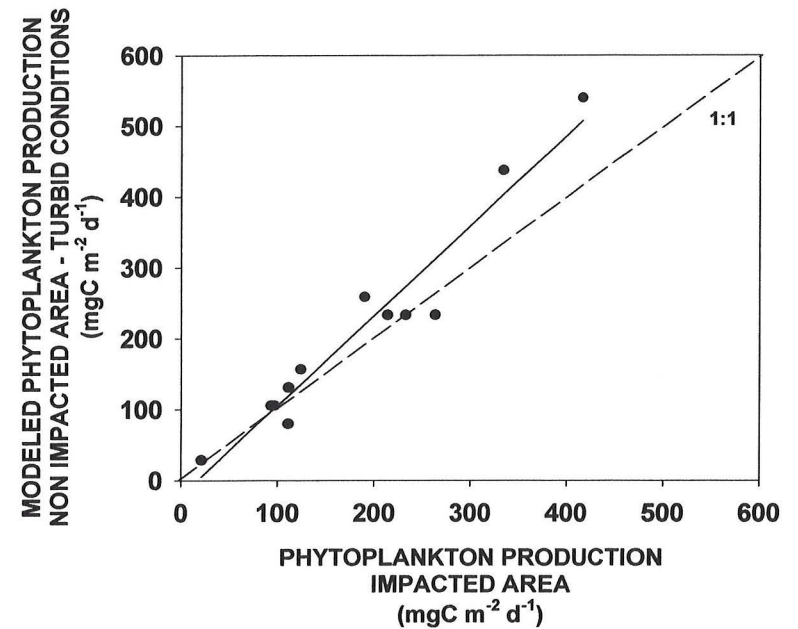

Fig. 5:
Comparison between integrated phytoplankton productivity applying a crescent gradient of turbidity on Non-Impacted models (Eq. 1; axes Y) against measured rates from Impacted area (axes X). The full line is the regression (slope = 1.27, r^2= 0.94 and p<0.001). The 1:1 line (dash) is shown for comparison.