Temporal variation of attenuation of the visible radiation in four lakes of Parque Estadual do Rio Doce (PERD), Minas Gerais, Brasil.

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ABSTRACT: Temporal variation of attenuation of the visible radiation in four lakes of Parque Estadual do Rio Doce (PERD), Minas Gerais. The present study aimed at characterizing seasonal variation of photosynthetic solar radiation (PAR) within the water column of four natural lakes of the middle Rio Doce basin (Carioca, Dom Helvécio, Gambazinho, and Jacaré lakes) during the period July 2004 to June 2005. Depths of PAR penetration within the water columns were measured in order to estimate the scalar light attenuation coefficient (K_o) for each lake. Chemical and biological water variables were also determined (total suspended solids - TSS, dissolved organic carbon -DOC, colored dissolved organic matter -CDOM, and chlorophyll a -Chl a) in order to determine their relative contribution to light attenuation. Measurements of K_o in the analyzed lakes showed marked variation with higher (0.92-1.74 m^{-1}) and lower K_o values (0.58-0.77 m^{-1}) recorded for lakes Carioca and Gambazinho, respectively. Among the lakes the variation of K_o can be explained mainly due to changes of Chl a and CDOM concentrations. When all lakes are considered together CDOM is the major component of K_o and explains 76% ($p < 0.001$) of its variation. Patterns of visible radiation penetration were analysed with potential contributions of allochthonous material and argued the possible causes in optical water quality differences among the studied lakes.
Key-words: colored dissolved organic matter; attenuation of visible radiation; temporal variation; Rio Doce State Park.

RESUMO: Variação temporal da atenuação da radiação visível em quatro lagos do Parque Estadual do Rio Doce (PERD), Minas Gerais. Este estudo teve como objetivo caracterizar a variação sazonal da penetração da radiação solar fotossinteticamente ativa (RFA) na coluna de água em quatro lagos naturais do Parque Estadual do Rio Doce (PERD), Minas Gerais (Lagoas Carioca, Dom Helvécio, Jacaré e Gambazinho), durante o período de julho de 2004 a junho de 2005. Foram determinadas as profundidades da penetração da radiação fotossinteticamente ativa na coluna de água e o coeficiente de atenuação escalar da luz (K_o) nos diferentes sistemas. Foram tomadas medidas de variáveis químicas e biológicas da água (sólidos totais em suspensão -STS, carbono orgânico dissolvido -COD, matéria orgânica dissolvida colorida -MODC e clorofila-a -clor-a) para se determinar a contribuição relativa destes componentes na atenuação da luz. As medidas de K_o nos lagos analisados apresentaram uma variação considerável, com os maiores (0,92-1,74 m^{-1}) e os menores valores de K_o (0,58-0,77 m^{-1}) registrados para as lagoas Carioca e Gambazinho, respectivamente. A variação de K_o entre os lagos pode ser explicada principalmente pelas mudanças nas concentrações de Clor-a e MODC. Quando os lagos são analisados em conjunto, MODC mostrou-se como o constituinte dominante de K_o, explicando 76% ($p < 0{,}001$) da sua variação. Foram analisados os padrões de penetração da radiação visível com as possíveis contribuições de material alóctone proveniente da bacia e discutidas as possíveis causas nas diferenças da qualidade óptica da água encontradas entre os lagos estudados.
Palavras-chave: Matéria orgânica dissolvida colorida; atenuação da radiação visível; variação temporal; Parque Estadual do Rio Doce.

Introduction

The behaviour of light within the water column particularly its attenuation with depth has important ecological implications on water quality. The optical properties of a waterbody can be an important factor regulating primary production and water appearance (Effler et al., 2002). Changes of underwater light climate can be a consequence of variations in sediment loadings or as a response to internal processes such as algae blooms or sediment resuspension (Kostoglidis et al., 2005).

Transmission of solar radiation through the water column is attenuated by the sum of processes such as absorption and dispersion. Among the substances that absorb and/or disperse light are: (1) the water itself, (2) biotic and abiotic particulated material (e.g., phytoplankton, detritus, and suspended sediment), and (3) the dissolved organic matter (DOM). Absorption depends on the wavelength while dispersion is mostly independent. Inorganic particles predominantly cause dispersion while DOM only cause absorption. Phytoplankton contributes to both processes. The intensity of attenuation processes can be quantified from scalar light attenuation coefficients (K_o), based on measurements of scalar irradiance (E_o) with depth (Kirk, 1994).

The existing relationships between light attenuation and phytoplankton abundance have been well documented in lakes where cultural eutrophication presented as consequence wide range of trophic conditions. In regions where surface waters are nutrients poor, distinct factors can regulate light attenuation. Among these colored or chromophoric dissolved organic matter (CDOM) has been considered as the major factor in absorption and consequently in attenuation of underwater light (Bukaveckas & Robbins-Forbes, 2000). The absorption of CDOM is responsible for the major part of light attenuation within the ultraviolet range (280-400 nm) and also acting within the photosynthetic active radiation (400 – 700 nm) (Morris et al., 1995). The so-called humic substances (humic and fulvic acids) which constitute a variable fraction of dissolved organic matter within natural waters, are mainly originated from decomposition of aquatic and terrestrial plant biomass. The concentration of CDOM varies among the systems and also seasonally, and is affected by regional climate changes as well as other environmental variables due to the fact that climate influences hydrology and vegetation and consequently the exportation of carbon to water bodies (Schindler & Curtis, 1997).

The present study describes the results of measurements of K_o of the photosynthetic active radiation (PAR) in distinct lakes from Parque Estadual do Rio Doce, southeast Brazil and its surroundings. Its major objective was to determine the range of temporal variation of light attenuation and compare these changes based on chemical and biological variables of the lakes. Simultaneously to the measurements of irradiance it were also measured concentrations of dissolved organic carbon (DOC), total suspended solids (TSS), chlorophyll a (Chl a) and the absorbance of colored dissolved organic matter (CDOM) in order to quantify the relative contribution of these water variables in light attenuation. These relations were combined in models aiming at the forecast of K_o values from the particulated and dissolved components recorded from in situ measurements.

The study area

The Rio Doce State Park (PERD) is located in the middle streach of Rio Doce basin, southeast Brazil (19°29´S; 42°28´W) (Fig. 1). PERD constitutes the largest remaining fragment of the Atlantic Forest in the state of Minas Gerais (36,000 ha) surrounded mainly by Eucalyptus spp plantations (Barbosa, 1977; CETEC, 1981), comprising part of the middle Rio Doce lake system (ca. 50 lakes) occupying an area of 3,530 ha (9.8% of its total area). The dominant climate according to the Köpen classification is the humid tropical AW with a rainy season during summer and a dry period during the winter. Between 1998 and 2004 the monthly minima and maxima temperature values varied between 15.1 and 28.2 °C, respectively and precipitation varied from 0 to 323.68 mm (data from Ipatinga Meteorological Station).

Material and methods

Samplings were conducted every month from July 2004 to June 2005 in order to determine light attenuation and the concentration of DOC, CDOM, TSS, and Chl a in three lakes within the PERD: Carioca (19° 45'S; 42° 37'W), Dom Helvécio (19° 46'S; 42° 36'W), and Gambazinho (19° 47'S; 42° 34'W) and one lake of its surroundings, Jacaré Lake (19° 48'S; 42° 38'W). Moreover, these parameters were measured in September 2004 in other seven lakes around PERD (Amarela, Verde, Palmeirinha, Ariranha, Águas Claras, Aguapé, and Barra Lakes) surrounded by Eucalyptus spp plantations.

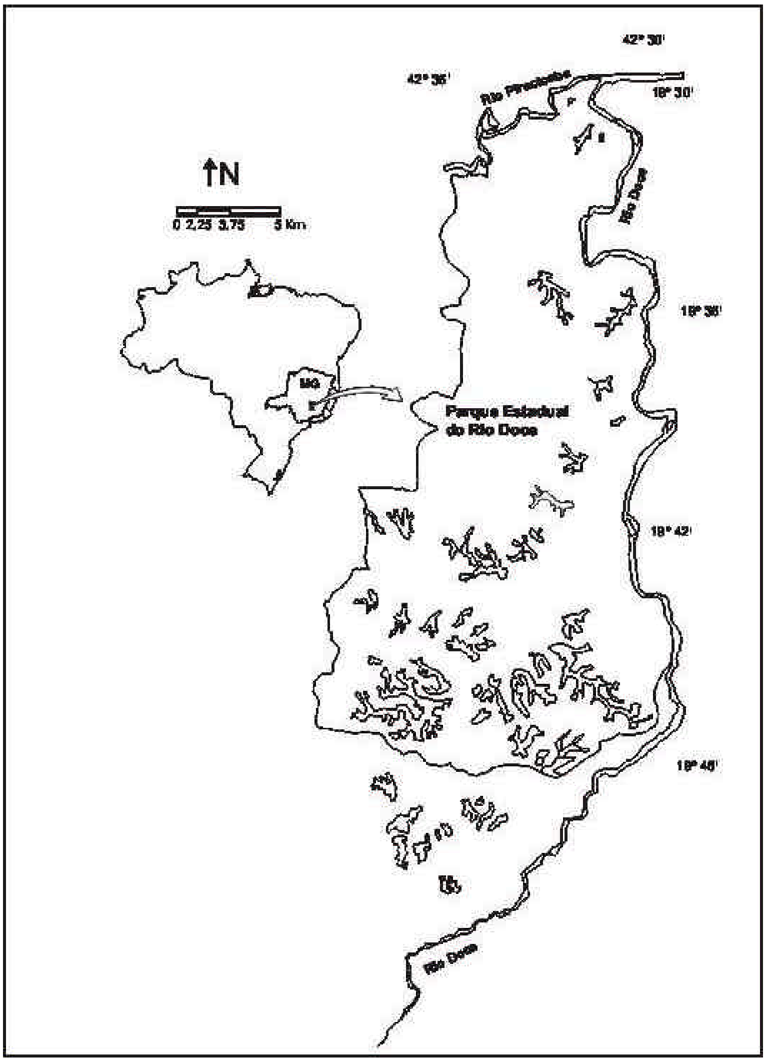

Figure 1: Map of location showing in the central part some of the lakes of the Rio Doce State Park, south-east Brazil.

PAR was measured using a Li-Cor radiometer with underwater Spherical Quantum Sensor (model LI 193; Li-Cor Inc). The scalar light attenuation coefficient K_o (PAR) (m^{-1}) was determined as the slope of the linear regression between depth and natural logarithm of scalar irradiance (E_o). All radiation measurements were recorded at noon (12:00 ± 2 hours).

Subsurface water samples (0.5 m) were obtained for analysis of TSS, Chl a, DOC and CDOM. Samples for Chl a measurements were immediately filtered through GF/C filters, frozen and kept in the dark for later analysis. Chl a concentration corrected for phaeopigments was estimated after extraction with 90% acetone according to Lorenzen (1967). Water samples for CDOM, TSS, and DOC determinations were kept refrigerated (4°C) in the dark until processing. For determination of total suspended solids concentrations (TSS), two replicates of known volume of sample were filtered through GF/C filters (Schleicher & Schuell) previously dried and weighted (105 °C, 1 h). These filters were dried again (105 °C, 1 h) and weighted resulting in total suspended solids values expressed in $mg.m^{-3}$ (APHA, 1998). CDOM samples were filtered (GF/F, Whatman) and stored in the dark at 4°C until analysis. The absorbance at 320 nm, used as an index of CDOM concentration (Williamson et al., 1999), was measured in 1 cm quartz cuvette in a Hitachi U-2000 spectrophotometer using Milli-Q water as reference. The absorbance values at 320 nm were then converted in absorption coefficient (a CDOM) using the equation (Kirk, 1994):

$$a\ CDOM\ (m^{-1}) = 2.303\ A_{»}/r$$

where $A_{»}$ = absorbance at 320 nm;
r = pathlength cuvette (mm).

The dissolved organic carbon (DOC) measured from filtered samples (GF/F, Whatman) was determined by catalytic oxidation at high temperature in a TOC-5000A (Shimadzu).

The relative importance of dissolved and particulated components in determination of K_o was evaluated through stepwise logistic regressions. The K_o was considered as dependent variables while DOC, Chl a, TSS, and CDOM were independent. In order to obtain a normal distribution both dependent and independent variables were log transformed (log X + 1).

Results

Table I shows the variation of K_o, the concentrations of chlorophyll a, total suspended solids, colored dissolved organic matter and dissolved organic carbon during the study period. The monthly average K_o values for lake Carioca were significantly higher (test p, pairwise) than recorded for lakes Dom Helvécio, Gambazinho, and Jacaré. Lake Jacaré showed K_o values significantly higher than the one recorded for Gambazinho Lake (test p, pairwise) although still lower than the one determined for Carioca Lake. There were no significant differences between K_o values found for Gambazinho and Dom Helvécio Lakes as well as for Jacaré and Dom Helvécio Lakes.

K_o values along the studied period ranged from 0.51 to 3.18 m^{-1}. Gambazinho and Carioca Lakes showed the lowest (0.66 m^{-1}) and the highest (1.12 m^{-1}) average K_o values, respectively (Tab. I).

Table I: Average values (and range) of K_o (PAR), CDOM, Chl a and TSS for the studied lakes isolately and their group during the period July 2004 to June 2005.

Lakes	K_o (PAR) (m^{-1})	Chl a ($mg.m^{-3}$)	TSS ($g.m^{-3}$)	CDOM (m^{-1})	DOC ($mg.l^{-1}$)
Carioca	1.12 (0.92–1.74)	14.05 (3.74–63.62)	2.22 (1.00–4.60)	7.83 (5.53–10.13)	8.19 (6.13–12.03)
D. Helvécio	0.80 (0.51–1.32)	8.49 (2.94–18.18)	1.67 (0.20–6.00)	4.09 (2.53–5.76)	6.35 (3.57–8.69)
Gambazinho	0.66 (0.58–0.77)	8.17 (2.41–23.52)	2.16 (1.20–2.90)	2.88 (2.07–3.92)	6.49 (3.35–11.54)
Jacaré	0.92 (0.74–1.20)	6.58 (1.87–22.99)	2.14 (0.15–10.40)	5.18 (3.68–8.75)	7.46 (4.95–14.09)
All lakes	0.92 (0.51–3.18)	9.09 (1.60–63.62)	1.93 (0.15–10.40)	6.12 (2.07–54.81)	7.28 (3.35–14.09)

Chlorophyll a values ranged from 1.60 to 63.62 $mg.m^{-3}$ during the sampling period; the highest average value was determined for Carioca Lake (14.05 $mg.m^{-3}$) (Tab. I). The lowest (0.15 $g.m^{-3}$) and highest values for TSS (10.40 $g.m^{-3}$) were registered for Jacaré Lake and the general average value was 1.93 $g.m^{-3}$ (Tab. I). DOC concentration varied between 3.35 and 14.09 $mg.l^{-1}$, with the highest average being recorded for Carioca Lake (8.19 $mg.l^{-1}$) while Gambazinho and Jacaré Lakes showed the lowest (3.35 $mg.l^{-1}$) and the highest values (14.09 $mg.l^{-1}$), respectively (Tab. I). Absorbance values of CDOM varied between 2.07 and 54.81 m^{-1}, with the highest average recorded in Carioca Lake (7.83 m^{-1}) and the lowest one in Gambazinho Lake (2.88 m^{-1}) (Tab. I).

The temporal variation of K_o (PAR) was remarkable among the studied lakes (Fig. 2). Carioca and Dom Helvécio Lakes showed the highest K_o values during the dry and cold period (May to July) with average values of 1.45 m^{-1} (SD ± 0.27) and 1.07 m^{-1}(SD ± 0.26) for Carioca and Dom Helvécio Lakes, respectively. The warmer months of October to April coincided with the lowest K_o values (average of 0.92 m^{-1}) for Carioca Lake with small changes along the months (SD ± 0.05 m^{-1}). However, for Dom Helvécio Lake which also showed during this period the lowest K_o values (average of 0.63 m^{-1}), the variation among the months was higher (SD ± 0.10 m^{-1}) than registered for Carioca Lake (Fig. 2). Gambazinho Lake showed K_o values practically constant (average of 0.67 m^{-1} ± 0.06) (Fig. 2), differently of Jacaré Lake which showed a strong variation of K_o values (average 0.92 m^{-1} ± 0.16).

The stepwise multiple linear regression of K_o versus DOC, CDOM, Chl a and TSS for the studied lakes showed that 76% of K_o variation is explained by the concentration of CDOM (Fig. 3). The regression did not include any other independent variable at a $p < 0.05$. The values of the regression equation and the coefficients are all significant at $p < 0.001$ (n = 52). On the other hand the stepwise multiple regressions performed for each one of the lakes sampled monthly showed differences of explicative factors of the variation among the lakes (Tab. II). For lake Carioca, Chl a and CDOM were the variables included in the model with 55% of the variation of K_o being explained by Chl a and an additional 11% by CDOM ($p < 0.05$). For Lake Gambazinho only CDOM was included in the model with an r^2 of 0.33 and a $p < 0.05$ (Tab. II). For Dom Helvécio Lake, the Chl a was the only variable included in the model (r^2 = 0.76 $p < 0.05$) and for Jacaré Lake none of the four variables as included at a $p < 0.05$ (Tab. II).

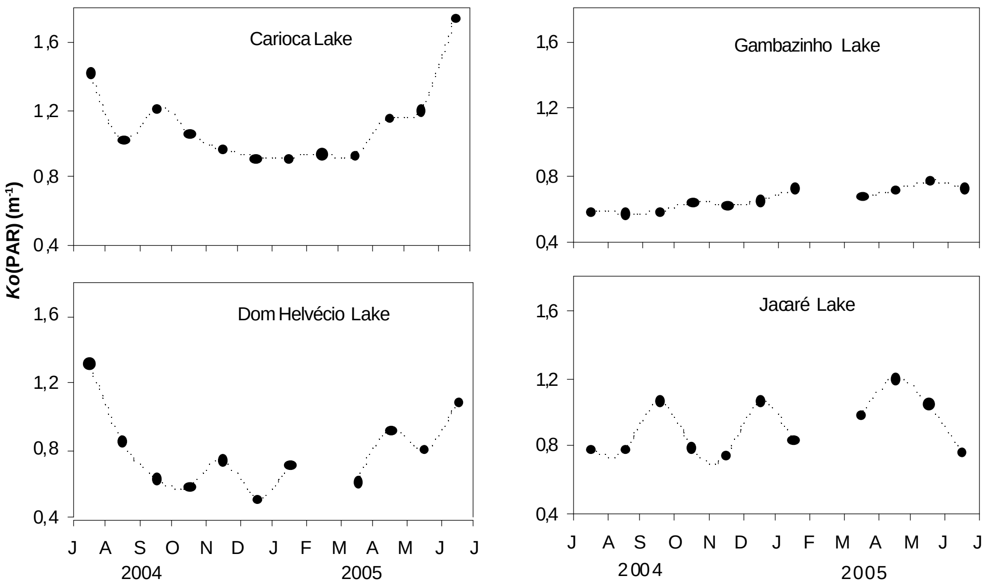

Figure 2: Seasonal variation of the scalar light attenuation coefficient (K_o - PAR) for the studied lakes during the period July 2004 to June 2005.

Table II: Stepwise multiple regression of K_o (PAR) using as independent variables Chl a, TSS, CDOM and DOM.

Lake	Model	R^2	p
Carioca	Log K_o = 0.22 + 0.07 log Chl a + 0.16 log CDOM	0.66	< 0.05
Dom Helvécio	Log K_o = 0.05 + 0.22 Log Chl a	0.76	< 0.05
Gambazinho	Log K_o = 0.31 + 0.15 Log CDOM	0.33	<0.05
Jacaré	Regression not significant		

Discussion

There is little information on optical properties and the relative role of potential attenuators of visible radiation in the middle Rio Doce lake system. Among the existing ones deserves attention the study of Calijuri et al. (1997) considering light attenuation within 15 lakes during summer (1985) and winter (1987) periods. However, the relative role of several attenuators and the monthly variation were not considered.

Data registered in the present study suggest that Carioca and Dom Helvécio lakes exhibit considerable seasonal variation of light attenuation, differently of the observed for Gambazinho and Jacaré lakes. The seasonal variation was a decrease of 26% (Carioca) and 37% (Dom

Helvécio) of K_o values during summer (rainy period). The increase in depth for the euphotic zone in Carioca and Dom Helvécio lakes in this period had been previously reported by Calijuri et al. (1997). The authors argued that this process occurs due to strong and continuous stratification during summer within an epilimnion loaded with small concentrations of particulated organic matter and chlorophyll a. During the winter, the increases in particulated organic matter as a direct consequence of water circulation (turnover) cause an increase in light attenuation thus decreasing euphotic depth.

The present results corroborate these findings during summer for Carioca and Dom Helvécio lakes. Moreover, it was possible to demonstrate from the models generated by multiple regressions (Tab. II) that the majority of the variability in light attenuation can be explained by chlorophyll a concentration in Dom Helvécio lake and, at a lesser degree, for lake Carioca. Furthermore, for Gambazinho lake only CDOM was included in the regression model (Tab. II). Comparatively, this lake showed the lowest values of light attenuation and CDOM, there not existing a typical winter-summer pattern along the studied period. Gambazinho lake posses high water transparency, exhibiting during most of the year the mixture layer with a same depth than maximum depth (Zmix = Zmax) there resulting only episodic events of thermal stratification of the water column (non published data). These characteristics make this lake a very particular one among the lakes within Rio Doce Park which are predominantly warm-monomitic and atelomictic lakes (Barbosa & Padisák, 2002), a condition that could explain the absence of Chl a as an important factor for light attenuation in this environment. On the other hand, none of the three variables was significantly correlated with K_o at a $p < 0.05$ for lake Jacaré, a lake surrounded by an Eucalyptus sp plantation area and that holds a fishermen club thus subject to distinct land uses likely to affect its physical and chemical characteristics, particularly light attenuation.

Light absorption by the colored fraction of dissolved organic matter (CDOM) was the dominant PAR attenuation mechanism in a general global model when the lakes were analyzed as a group (Fig. 3).

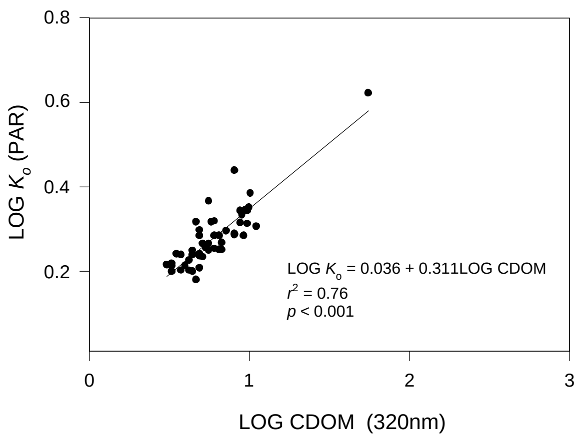

Figure 3: Relation between the values of K_o (PAR) and CDOM ones for the studied lakes.

The particulate material was a minor component in light attenuation suggesting that the input of mineral and organic particulates from the watershed together with the particulate matter from sediment resuspension are not important factors influencing optical properties of the studied lakes. Moreover, the majority of these lakes constitute relatively well protected watersheds where the effects of particulates are minimal. Differently from the results obtained from seasonal analysis, chlorophyll a was not included in the global model of light attenuation among the lakes within the Rio Doce State Park. An analysis of these results together with the recorded models for each lake separately (Tab. II) shows that chlorophyll a was an important factor in the seasonal variation of light attenuation within the lake (e. g. Carioca and Dom Helvécio). However, the colored dissolved organic carbon, which showed small variation within the lake, was important in determining the variation of light attenuation among the lakes thus indicating that at a regional scale the variations of CDOM are potentially determinants of K_o variation.

From this model two types of lakes could be identified for the Rio Doce State Park lakes: i) those exhibiting low transparencies values associated with high values of CDOM (e. g. Carioca and Amarela) and ii) lakes exhibiting high transparency values and low values of CDOM (e.g. Gambazinho and Verde). The linear model based on the absorbance of CDOM responded for 76% of K_o variation (Fig. 3). For the CDOM absorbance variation recorded in the present study (2 – 54 m^{-1}) the increase of one unit of CDOM absorbance corresponded to an increase ca. 0.31 m^{-1} of K_o which means that a small increase in the absorbance values resulted in a high increase in light attenuation.

Differently from other studies (e.g. Bukaveckas & Robbins-Forbes, 2000; Reche & Pace, 2002) the concentration of DOC was not significantly correlated with the absorbance values of analyzed samples. According to Morris et al. (1995) for some lakes not only the concentration of DOC must be considered in determining water transparency but also its optical properties. Moreover, these properties such as specific absorbance and the shape of the DOC absorption spectrum vary largely among lakes and depend on the origin and composition of DOC. The studied lakes showed a wide variation of specific DOC absorbance among themselves as well as within each lake (ratio between absorbance at 320 nm : mg L^{-1} DOC) indicating a wide variability of the colored fraction of the dissolved organic carbon.

The concentration and composition of DOC in a lake depend both on the inputs of allochthonous and autochthonous material together with the mineralization and loss processes (e. g. outflow) of these substances (Wetzel, 1992). Several studies show that the variability of DOC can be affected among others by factors related to morphometry (ratio between shore lake length and its volume, lake area) (Bukaveckas & Robbins-Forbes, 2000), the vegetational characteristics of the drainage basin (Schindler & Curtis, 1997; Sachse et al., 2001) and to pluviosity (Reche & Pace, 2002). On the other hand, the concentration of the colored fraction of DOC will depend on the concentration of refractory or photoreactive compounds that enter and/or are produced within the system opposing to light-degradation processes (Bertilsson & Tranvik, 2000). These processes can have their effects enhanced by the mixing events of the water column (Waiser & Robarts, 2004), by the biogeochemical characteristics of the studied water body (e. g. alkalinity) (Reche et al., 1999) and by the utilization of bacteria (Tranvik, 1992).

The present results suggest that the variability of the underwater light climate among the lakes is related with the variations of DOC inputs from watershed and more specifically to the biogeochemical processes that promote the increase or decrease of light attenuation by these substances, processes responsible for the variability of the colored fraction of DOC within the studied lakes and that ultimately influence the depth of euphotic zone.

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