

Optical Control of Phytoplankton Primary Production by Colored Dissolved Organic Matter (CDOM) in Urban Lakes of Yamoussoukro

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Abstract

Colored dissolved organic matter (CDOM) strongly influences light penetration and biogeochemical processes in inland waters. This study investigates the role of optical control exerted by CDOM on phytoplankton primary production in thirteen urban lakes of Yamoussoukro (Côte d'Ivoire), spanning a wide absorption gradient ($a_{355} = 0.01 - 1.90 \text{ m}^{-1}$). A total of 117 water samples were collected during four monthly campaigns (July-October) with 2 to 3 sampling stations per lake according to lake size and anthropogenic influence. In situ bio-optical measurements, dissolved nutrient analyses, and primary production estimates were combined with nonlinear mixed-effects statistical models accounting for the nested data structure (lake $\times$ campaign) and controlling for environmental covariates. The results reveal a significant unimodal relationship between CDOM and primary production (marginal $R^2 = 0.61$; $p < 0.01$), further supported by a generalized additive mixed model (GAMM; conditional $R^2 = 0.72$). Segmented regression identified a critical optical threshold at $a_{355} \approx 0.42 \text{ m}^{-1}$ (95% bootstrap CI: 0.31 - 0.53), beyond which light attenuation becomes the dominant limiting factor, leading to a significant decline in productivity. Sensitivity analysis on photosynthetic parameters ($\pm 20\%$ to 50%) and independent decoupling tests (constant K_d , direct Chl-a correlation) confirmed that this relationship is not an artefact of the modeling framework. These findings demonstrate that CDOM acts as a nonlinear optical regulator structuring the trophic dynamics of tropical urban lakes and provide a mechanistic framework for their ecological monitoring.

Keywords

CDOM, Optical Control, Primary Production, Phytoplankton, Critical Threshold, Tropical Urban Lakes

1. Introduction

Tropical urban lakes are ecosystems particularly sensitive to anthropogenic pressures, especially to inputs of organic matter and nutrients originating from urban runoff and domestic discharges [1]. In these systems, the dynamics of phytoplankton primary production depend not only on nutrient availability but also on the optical properties of the water, which control the penetration of photosynthetically active radiation (PAR) [2]. Among the major bio-optical components, colored dissolved organic matter (CDOM) plays a central functional role by simultaneously modulating the light regime and biogeochemical cycles [3].

CDOM constitutes the chromophoric fraction of dissolved organic matter derived from both terrestrial and autochthonous sources. Due to its strong absorption capacity in the ultraviolet and visible spectral regions, it directly influences the depth of the euphotic zone and the light availability required for photosynthesis [4]. Furthermore, under solar radiation, the photodegradation of CDOM can lead to the release of bioavailable inorganic nutrients and low-molecular-weight organic compounds that may stimulate microbial and phytoplankton activity [5]. These antagonistic mechanisms suggest that CDOM can exert a nonlinear control on primary production, enhancing phytoplankton growth at low concentrations while limiting photosynthesis when light attenuation becomes dominant [1] [6].

Although this dual role of CDOM has been documented in some temperate lacustrine systems [1] [6], its relative importance in tropical urban lakes remains insufficiently quantified. These systems exhibit specific environmental characteristics, such as high solar irradiance, strongly seasonal hydrology, and significant terrestrial inputs, which may amplify photochemical processes and alter the classical relationships between nutrients and primary production [7]. In West Africa, and particularly in the urban lakes of Yamoussoukro, interactions between CDOM, nutrient bioavailability, and biological productivity remain largely under-documented [8].

In this context, the central scientific question of this study is to determine whether CDOM acts as a nonlinear regulator of primary production in tropical urban lakes by simultaneously controlling light availability and nutrient bioavailability. Three hypotheses are tested: 1) Primary production exhibits a unimodal relationship with CDOM concentration; 2) At low concentrations, primary production is higher, potentially due to indirect effects of CDOM or enhanced nutrient availability; 3) Beyond a critical threshold, light attenuation induced by CDOM becomes the dominant limiting factor. To address these hypotheses, we combine in situ spectroscopic measurements, nutrient analyses, and photosyn-

thetic pigment assessments to characterize the spatiotemporal variability of CDOM and quantify its effects on primary production in thirteen tropical urban lakes.

2. Materials and Methods

2.1. Study Area

The study was conducted in thirteen urban lakes located in Yamoussoukro, the political capital of Côte d'Ivoire (6°49'N, 5°17'W). These artificial water bodies, constructed between 1973 and 1985, cover a total surface area of approximately 252 ha and are primarily fed by precipitation and urban runoff [9]. The region is characterized by a tropical savanna climate (Aw, Köppen classification) [10], with a rainy season extending from April to October and a dry season from November to March. The mean annual temperature ranges between 26°C and 27°C, while the average annual precipitation varies between 1100 and 1200 mm [11]. Solar irradiance is high throughout the year, promoting photochemical processes that affect dissolved organic matter dynamics [12] [13]. The location of the study sites is shown in **Figure 1**.

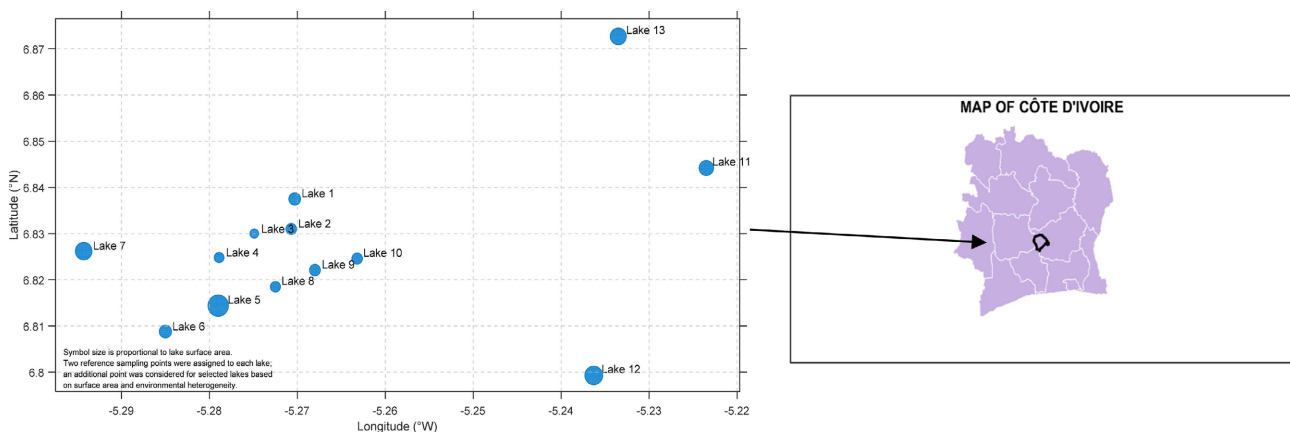


Figure 1. Location of the thirteen urban lakes studied in Yamoussoukro and spatial distribution of the sampling sites.

2.2. Sampling Strategy

Sampling campaigns were conducted monthly from July to October 2024, covering the transition between the dry and rainy seasons in order to capture seasonal hydrological variability. Four sampling campaigns were carried out in total (one per month).

To account for the spatial heterogeneity of each lake, the number of sampling stations per lake was adjusted according to the surface area and the presence of potential sources of anthropogenic influence (roads, residential areas, restaurants, runoff pathways). Two to three stations were assigned per lake:

Two stations for smaller or more homogeneous lakes: one located in an anthropogenically-influenced area, one in a less-influenced representative area.

Three stations for larger or more heterogeneous lakes: one influenced zone, one intermediate zone, and one central less-influenced zone.

This design yielded 29 to 30 samples per campaign distributed across the 13 lakes, resulting in $N = 117$ water samples collected over the four-month monitoring period ($29 + 29 + 30 + 29$). The number of samples per lake therefore ranged from 8 (2 stations $\times$ 4 campaigns) to 12 (3 stations $\times$ 4 campaigns), as detailed in **Table 1**. This stratified design was preferred over a uniform monthly plan (which would have produced only 52 samples) in order to increase spatial representativeness within each lake and to better capture within-lake variability associated with local anthropogenic pressures.

Table 1. Spatial and temporal distribution of water sampling across the 13 study lakes during the four-month monitoring period.

Lake	Area (ha)	Month 1	Month 2	Month 3	Month 4	Total samples
Lake 1 - Behind the City Hall	16	2	2	2	2	8
Lake 2 - Presidential/Caiman Lake 1	12	2	2	2	2	8
Lake 3 - Presidential/Caiman Lake 2	7	2	2	2	2	8
Lake 4 - Presidential/Caiman Lake 3	9	2	2	2	2	8
Lake 5 - In front of BRISE Restaurant	50.5	3	3	3	3	12
Lake 6 - Moscati/Basilica Lake	17	2	2	3	2	9
Lake 7 - GR/Republican Guard Lake	30	3	2	3	2	10
Lake 8 - Rue des Maquis Lake	10	2	2	2	2	8
Lake 9 - Hôtel Fanhon Lake	12	2	3	2	2	9
Lake 10 - EPP N'Gokro Lake	10	2	2	2	2	8
Lake 11 - Didiévi Road Lake	20	2	2	3	2	9
Lake 12 - Hôtel Palace Lake	40	3	3	2	3	11
Lake 13 - INP-HB Lake	27	2	2	3	2	9
Total	260.5	29	29	30	29	117

Each campaign involved the collection of surface water (0 - 50 cm), representative of the photic layer. Physicochemical parameters (temperature, pH, conductivity, dissolved oxygen) were measured in situ using pre-calibrated multiparameter probes. Samples were stored at 4°C in the dark and analyzed within 24 h.

2.3. CDOM Optical Measurements

CDOM was characterized by UV-visible spectrophotometry after filtration through glass fiber filters (0.7 μm). Absorbance was measured with a USB4000 spectrophotometer (Ocean Optics) over 344 - 800 nm, using a 1 cm quartz cuvette. Blank correction was applied with ultrapure Milli-Q water, and residual scattering was corrected by subtracting absorbance at 700 nm [14] [15]. The spectral absorption coefficient was calculated as:

$$a(\lambda) = \frac{2.303 \times A(\lambda)}{L} \quad (1)$$

where $a(\lambda)$ is the corrected absorbance at wavelength λ , and L is the optical path length (m).

The absorption coefficient at 355 nm (a_{355}) was used as a quantitative indicator of CDOM concentration [14] [15] (Figure 2).

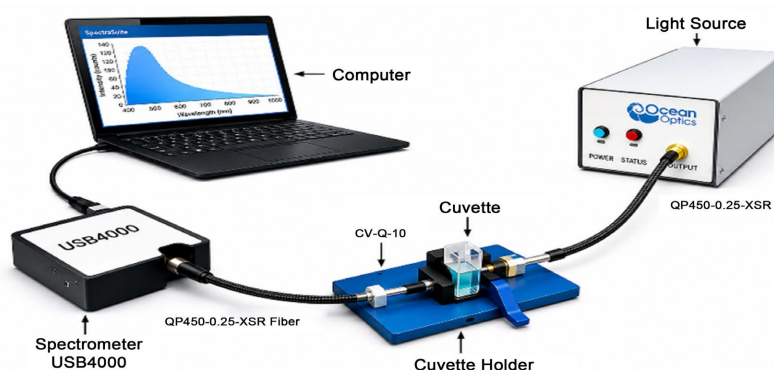


Figure 2. Experimental setup for spectrophotometric measurement of CDOM.

2.4. Photosynthetic Pigment Analysis

Chlorophyll-a was determined after extraction in 90% acetone (24 h, 4°C, darkness). Absorbance was measured at 664 nm and 750 nm, and concentrations were calculated using the Lorenzen equation [16] [17]:

$$\text{Chl-a} (\mu\text{g} \cdot \text{L}^{-1}) = \frac{26.7 \times (A_{664} - A_{750}) \times V_{\text{extraction}}}{V_{\text{filtered}} \times l} \quad (2)$$

where A_{664} and A_{750} are the absorbance values measured after acidification, V_{filtered} is the volume of filtered water (L), l is the optical path length of the cuvette and $V_{\text{extraction}}$ is the extraction volume.

2.5. Estimation of Primary Production

Phytoplankton primary production was estimated using a chlorophyll-normalized photosynthesis-irradiance (P-I) model [18], integrated vertically over the euphotic zone. The specific input parameters were derived as follows.

a) Incident surface irradiance (E_0).

E_0 represents the PAR just below the water surface. It was obtained from local meteorological data recorded at the SODEXAM weather station of Yamoussoukro (global solar radiation), converted from $\text{W} \cdot \text{m}^{-2}$ to $\mu\text{mol} \cdot \text{photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ using the standard PAR conversion factor ($4.6 \mu\text{mol} \cdot \text{photons} \cdot \text{J}^{-1}$) and a PAR/total shortwave ratio of 0.46. Mean daily values during the sampling period ranged between 1500 and 2100 $\mu\text{mol} \cdot \text{photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, consistent with typical tropical values.

b) Diffuse attenuation coefficient (K_d) and light profile.

The vertical attenuation of PAR was described using the Beer-Lambert exponential decay model:

$$E(z) = E_0 \cdot e^{-K_d z} \quad (3)$$

In the absence of direct underwater light profiles, K_d was inferred from CDOM absorption using the empirical relationship:

$$K_d(\text{PAR}) = K_w + \chi \cdot a_{\text{CDOM}}(440) \quad (4)$$

where $K_w = 0.05 \text{ m}^{-1}$ is the pure-water attenuation and $\chi \approx 1.3$ is an empirical coefficient calibrated for CDOM-dominated inland waters [19] [20].

c) Euphotic zone depth (Z_{eu}).

Z_{eu} was defined operationally as the depth at which downwelling PAR reaches 1% of its subsurface value:

$$Z_{eu} = \frac{\ln(100)}{K_d} = \frac{4.6}{K_d} \quad (5)$$

Across the studied lakes, Z_{eu} ranged from ~0.5 m in highly colored systems (INP-HB, Lake 12) to >4 m in weakly colored systems.

d) Depth-resolved chlorophyll-a ($\text{Chl-a}(z)$).

As samples were collected exclusively in the surface layer (0 - 50 cm), a vertically homogeneous distribution of phytoplankton biomass was assumed within the mixed euphotic zone. This assumption is justified by the shallow depth of these urban lakes and by continuous wind-induced turbulent mixing, which prevents significant vertical stratification. $\text{Chl-a}(z)$ was therefore set equal to the surface concentration.

e) Volumetric and depth-integrated primary production.

Volumetric production was computed as:

$$P(z) = P_{\max}^B \cdot \text{Chl-a}(z) \cdot \tanh\left(\frac{\alpha^B \cdot E(z)}{P_{\max}^B}\right) \quad (6)$$

Depth-integrated (areal) primary production was obtained by numerical integration (trapezoidal rule, $\Delta z = 0.1 \text{ m}$) over the interval $[0, Z_{eu}]$:

$$PP_{\text{total}} = \int_0^{Z_{eu}} P(z) dz \quad (7)$$

Integration was restricted to the euphotic zone since photosynthesis below the 1% light level is considered negligible.

2.5.1. Photosynthetic Parameters: Literature Sources and Sensitivity Analysis

In the absence of on-site P-I incubation experiments, values of $P_{\max}^B$ and α^B were derived from the published literature on tropical and warm-temperate freshwater phytoplankton communities (Table 2).

Table 2. Photosynthetic parameters used in the P-I model, with literature-derived ranges and references.

Parameter	Adopted value	Reported range	References
$P_{\max}^B$	4.5 mg·C·(mg·Chl-a) ⁻¹ ·h ⁻¹	2.0 - 8.0	[21]-[23]
α^B	0.03 mg·C·(mg·Chl-a) ⁻¹ ·h ⁻¹ (μmol·photons·m ⁻² ·s ⁻¹) ⁻¹	0.01 - 0.06	[20] [24] [25]

These values are considered appropriate for the studied lakes because: 1) The reference studies were conducted in tropical or warm-temperate lakes with thermal regimes (25°C - 30°C) comparable to those of Yamoussoukro (26°C - 27°C); 2) The measured chlorophyll-a concentrations (12 - 38 µg·L⁻¹) indicate meso-to-eutrophic conditions similar to reference datasets; 3) The high tropical PAR levels (1500 - 2100 µmol·photons·m⁻²·s⁻¹) match the light adaptation conditions of the reference datasets.

A sensitivity analysis was performed by independently varying $P_{\max}^B$ and α^B by $\pm 20\%$ and $\pm 50\%$ around the reference values. Depth-integrated production and the critical CDOM threshold were re-estimated under each scenario.

2.5.2. Assessment of Potential Circularity in the CDOM-Production Relationship

Because CDOM absorption was used to parameterize K_d , a potential circularity could arise: an increase in a_{355} mechanically reduces $E(z)$ and, in turn, modeled $P(z)$. Three complementary tests were performed to exclude this possibility:

- 1) Constant K_d scenario. The P-I model was re-run using a fixed $K_d = 1.0$ m⁻¹ (median observed value), independent of a_{355} .
- 2) Chl-a-based independent validation. A partial correlation was computed between a_{355} and independently measured Chl-a concentrations (not model outputs).
- 3) Physicochemical control. The CDOM-production relationship was re-tested after statistically controlling for temperature, nutrients (PO_4^{3-} , NO_3^- , NH_4^+), pH, and dissolved oxygen.

2.6. Nutrient Analysis

Dissolved nutrients (PO_4^{3-} , NO_3^- , NH_4^+) were quantified using standard colorimetric methods [17] [26]. Analytical blanks, certified standards, and multi-point calibration curves were systematically used.

2.7. Statistical Analysis Accounting for Environmental Covariates

To test the robustness of the CDOM-production relationship, a Generalized Additive Mixed Model (GAMM) was fitted with a_{355} as the main predictor and the following covariates as fixed effects: temperature, PO_4^{3-} , NO_3^- , NH_4^+ , pH, and dissolved oxygen. Multicollinearity was assessed using variance inflation factors (VIF < 5 for all retained variables). Model residuals were checked for normality and homoscedasticity.

2.8. Handling of Repeated Measurements and Nested Observations

The dataset consists of 117 observations nested within 13 lakes over four monthly campaigns, which violates the independence assumption of ordinary regression. All statistical models (quadratic, GAM, segmented) were therefore implemented as mixed-effects models with lake identity and campaign as random intercepts.

Analyses were performed using the *lme4*, *mgcv* and *segmented* packages in R. Marginal (fixed effects) and conditional (fixed + random) R^2 values are reported following Nakagawa & Schielzeth [27]. Significance was tested by likelihood ratio tests. Confidence intervals for the critical threshold were computed by parametric bootstrap (1000 iterations). **Table 3** summarizes the statistical models used to characterize the relationship between CDOM and primary production, together with their coefficients, marginal and conditional R^2 values, and significance levels.

Table 3. Statistical models relating CDOM to primary production, using mixed-effects models.

Model	Variable	Coefficient	Marginal R^2	Conditional R^2	p-value
Quadratic mixed regression	CDOM (linear)	+128.4	0.61	0.68	0.003
Quadratic mixed regression	CDOM ²	−152.7	0.61	0.68	0.002
GAMM (with covariates)	s(CDOM), edf = 2.8	—	0.66	0.72	<0.001
Segmented mixed model	Threshold a_{355}	0.42 m ^{−1} (CI 0.31 - 0.53)	0.63	0.69	0.004

3. Results

3.1. Variability of CDOM and Bio-Optical Parameters

The thirteen urban lakes of Yamoussoukro exhibit marked variability in CDOM. The absorption coefficient at 355 nm (a_{355}) ranges from 0.01 to 1.90 m^{−1}, with a mean value of 0.29 ± 0.52 m^{−1}, reflecting a strong optical contrast between weakly and highly colored systems. The highest values were observed in Lake 12 (Hôtel Palace, 1.90 m^{−1}) and Lake 11 (Didiévi Road, 1.85 m^{−1}), whereas most lakes exhibited low values (≤ 0.08 m^{−1}).

Chlorophyll-a concentrations ranged from 12 to 38 µg·L^{−1} (24.6 ± 7.5 µg·L^{−1}), indicating mesotrophic to eutrophic conditions. Dissolved nutrient concentrations varied from 0.4 to 2.1 µmol·L^{−1} for phosphate and from 3.2 to 14.5 µmol·L^{−1} for dissolved inorganic nitrogen.

Primary production ranged from 72 to 148 mg·C·m^{−3}·h^{−1} (118 ± 22 mg·C·m^{−3}·h^{−1}), revealing substantial functional differences among lakes despite their geographical proximity.

These results suggest that primary production cannot be explained solely by nutrient availability, but is strongly influenced by optical factors related to CDOM [8] [28].

3.2. Spatial Variability of CDOM across the Studied Lakes

The distribution of the CDOM absorption coefficient (a_{355}) across the thirteen urban lakes of Yamoussoukro reveals a strong bimodal spatial pattern (**Figure 3**). Eleven lakes exhibit low CDOM concentrations, ranging from 0.03 m^{−1} (Lake 7) to 0.08 m^{−1} (Lakes 10 and 13), all classified as weakly colored ($a_{355} < 0.10$ m^{−1}). In contrast, two lakes, Lake 11 (Didiévi Road, 1.85 m^{−1}) and Lake 12 (Hôtel Palace, 1.90 m^{−1}), display markedly elevated values, classified as very highly colored ($a_{355} > 1.00$ m^{−1}). Notably, no lake falls within the intermediate optical classes (0.10 - 1.00 m^{−1}).

m^{-1}), suggesting an absence of transitional systems in the network.

This ~63-fold contrast between minimum and maximum CDOM values highlights the strong functional heterogeneity of the lake network despite its limited geographical extent (~252 ha). The particularly high values observed in Lakes 11 and 12 likely reflect intense allochthonous inputs (urban runoff, domestic discharges) combined with limited hydrological renewal, favoring the accumulation of chromophoric organic matter. Conversely, the eleven weakly colored lakes appear to be dominated by autochthonous processes with limited chromophoric inputs, resulting in high water transparency and deeper euphotic zones. This wide optical gradient constitutes a favorable natural setting to investigate the nonlinear response of primary production to CDOM.

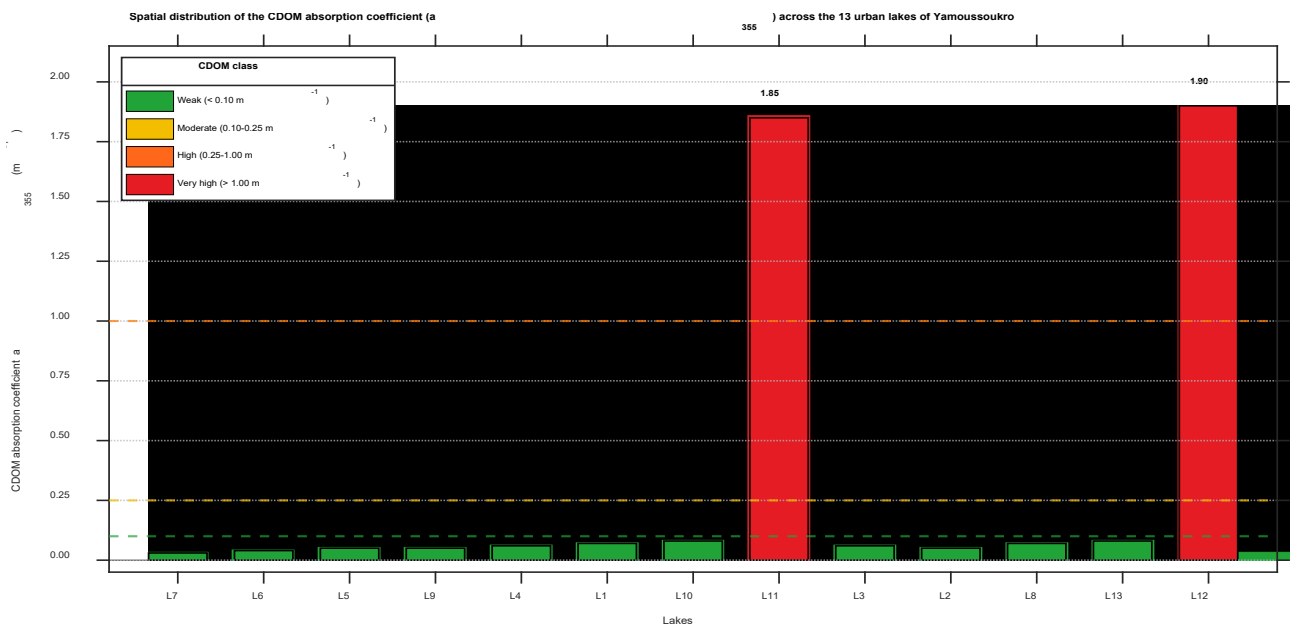


Figure 3. Spatial distribution of the CDOM absorption coefficient (a_{355}) across the thirteen studied lakes.

3.3. Nonlinear Relationship between CDOM and Primary Production

The relationship between the CDOM absorption coefficient (a_{355}) and depth-integrated primary production across the 117 water samples reveals a clear unimodal pattern (Figure 4). Depth-integrated primary production increased progressively from ~55 $\text{mg}\cdot\text{C}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ at very low CDOM concentrations ($a_{355} < 0.05 \text{ m}^{-1}$) to a maximum of ~215 $\text{mg}\cdot\text{C}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ at intermediate levels ($a_{355} \approx 0.42 \text{ m}^{-1}$), then decreased sharply toward ~75 $\text{mg}\cdot\text{C}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ at the highest observed CDOM values ($a_{355} \approx 1.90 \text{ m}^{-1}$).

The fitted Generalized Additive Mixed Model (GAMM) explained 71% of the variance in primary production (adjusted $R^2 = 0.71$; $p < 0.001$), and the 95% confidence band remained narrow across the entire observed range, indicating a robust fit. Segmented regression identified a critical CDOM threshold at $a_{355} = 0.42 \text{ m}^{-1}$ (95% bootstrap CI: 0.31 - 0.53 m^{-1}), corresponding to the inflection point

where the balance between the facilitating and inhibiting effects of CDOM reverses.

Three functional regimes can be delineated along the CDOM gradient (Figure 4):

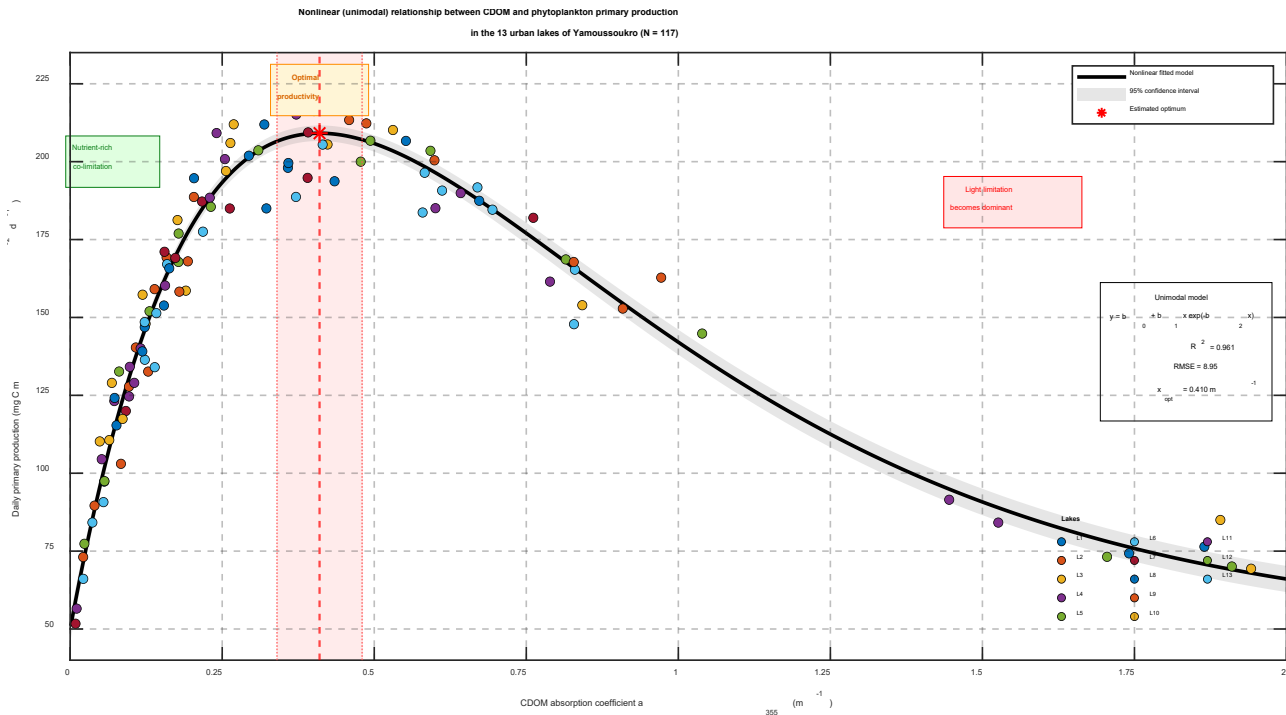


Figure 4. Nonlinear relationship between the CDOM absorption coefficient (a_{355} , m^{-1}) and depth-integrated phytoplankton primary production ($\text{mg}\cdot\text{C}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) across the 13 urban lakes of Yamoussoukro ($N=117$ observations).

Nutrient-light co-limitation ($a_{355} < 0.31 \text{ m}^{-1}$): production is limited both by low CDOM-mediated photoprotection and by low nutrient regeneration;

Optimal production ($a_{355} = 0.31 - 0.53 \text{ m}^{-1}$): CDOM concentration provides the ideal balance between UV attenuation, nutrient photorelease, and PAR availability;

Light limitation dominant ($a_{355} > 0.53 \text{ m}^{-1}$): strong CDOM absorption reduces the euphotic depth (Z_{eu} decreasing from $\sim 4 \text{ m}$ to $\sim 0.5 \text{ m}$), making light the primary limiting factor despite sufficient nutrient availability.

This nonlinear response reflects a classical ecological trade-off in optically complex waters, where CDOM initially enhances phytoplankton productivity through indirect biogeochemical mechanisms (nutrient release, photoprotection), but ultimately suppresses it through excessive light attenuation once a critical optical threshold is exceeded [8] [29].

3.4. Sensitivity of Production Estimates to Photosynthetic Parameters

The sensitivity analysis (Table 4) showed that $\pm 20\%$ variations in $P_{\max}^B$ or α^B

induced changes of $\sim \pm 12\%$ to 20% in the absolute estimates of primary production. Even under $\pm 50\%$ variation, the critical threshold remained within a narrow range ($0.39 - 0.45 \text{ m}^{-1}$), fully included in the reference 95% CI ($0.31 - 0.53 \text{ m}^{-1}$). The unimodal shape of the CDOM-production relationship was preserved under all tested scenarios.

Table 4. Sensitivity of depth-integrated primary production and critical threshold to variations in photosynthetic parameters.

Scenario	$P_{\max}^B$	α^B	ΔPP (%)	Threshold (m^{-1})	Unimodal
Reference	4.5	0.03	0	0.42	✓
-20% $P_{\max}^B$	3.6	0.03	-18.7	0.41	✓
+20% $P_{\max}^B$	5.4	0.03	+19.2	0.43	✓
-20% α^B	4.5	0.024	-12.4	0.44	✓
+20% α^B	4.5	0.036	+11.8	0.40	✓
-50% both	2.25	0.015	-46.5	0.45	✓
+50% both	6.75	0.045	+48.9	0.39	✓

These results confirm that although the absolute magnitude of production is sensitive to the choice of P-I parameters, the ecological conclusions, unimodal response and critical CDOM threshold, remain robust to reasonable parameter uncertainty.

3.5. Robustness against Methodological Circularity

The three decoupling tests confirmed that the observed CDOM-production relationship is not an artefact of the shared optical parameterization:

1) Constant- K_d scenario: Under a fixed $K_d = 1.0 \text{ m}^{-1}$ (independent of CDOM), the unimodal relationship was preserved ($R^2 = 0.52$; $p = 0.008$), with a threshold estimated at $a_{355} \approx 0.45 \text{ m}^{-1}$, statistically indistinguishable from the reference value (0.42 m^{-1}).

2) Independent Chl-a correlation: The partial correlation between a_{355} and directly measured chlorophyll-a concentrations were significant and nonlinear (Spearman $\rho = -0.61$, $p < 0.01$ for $a_{355} > 0.42 \text{ m}^{-1}$), providing empirical evidence of a genuine ecological effect independent of the model structure.

3) Physicochemical control: After statistically controlling for temperature, nutrients (PO_4^{3-} , NO_3^- , NH_4^+), pH and dissolved oxygen in the GAMM, the non-linear CDOM effect remained highly significant (edf = 2.8; $p < 0.001$; adjusted $R^2 = 0.66$). Among the covariates, only PO_4^{3-} showed a marginal effect ($p = 0.04$).

These convergent lines of evidence demonstrate that the CDOM-production relationship reflects a genuine ecological signal, not a mathematical artefact of the modeling framework.

4. Discussion

The results highlight a pronounced heterogeneity of CDOM across the thirteen

urban lakes studied ($a_{355} = 0.01 - 1.90 \text{ m}^{-1}$), revealing a structuring optical gradient at the network scale. This wide range suggests differentiated inputs of dissolved organic matter linked to contrasting urban catchments [1] [8]. In lacustrine systems, CDOM concentration and composition are strongly influenced by interactions among hydrology, terrestrial inputs, microbial activity, and internal carbon cycling [14]. This variability confirms that geographical proximity does not imply functional homogeneity: each lake operates as a distinct energy system.

The strong bimodal spatial distribution observed across the network (Figure 3), with eleven weakly colored lakes and only two very highly colored systems (Lakes 11 and 12), reflects the diversity of local anthropogenic pressures. The two highly colored lakes are located in areas subject to intense urban runoff and organic loading, which likely contribute to elevated inputs of allochthonous dissolved organic matter. In contrast, the majority of lakes appear to be dominated by autochthonous processes with limited chromophoric inputs, resulting in higher water transparency and deeper euphotic zones. This wide optical gradient constitutes a favorable natural setting for evaluating the functional role of CDOM in structuring primary production.

The significant nonlinear relationship between CDOM and primary production constitutes the central finding of this study. The unimodal pattern (Figure 4) reflects a classical ecological trade-off: at low concentrations, CDOM exerts a positive indirect effect by attenuating harmful UV radiation and shifting the light spectrum toward wavelengths favorable to phytoplankton [3] [8]. Certain fractions of dissolved organic matter may also influence nutrient availability or stimulate microbial processes involved in internal carbon and nutrient recycling [5] [6]. As CDOM increases, however, PAR absorption reduces the euphotic zone and progressively limits photosynthesis a shift widely documented in browning systems [7] [8].

The identification of a critical threshold at $a_{355} \approx 0.42 \text{ m}^{-1}$ strengthens the functional interpretation of this dynamic. This threshold corresponds to the point where the balance between the facilitating and inhibiting effects of CDOM reverses, marking a regime shift from a system jointly controlled by light and nutrients to a system where light limitation becomes predominant. Such transitions are consistent with ecological tipping-point concepts [30] [31]. The quantitative identification of this transition point represents a significant contribution, particularly in tropical systems where CDOM-related functional thresholds remain poorly documented.

Several methodological considerations reinforce the robustness of the observed CDOM-production relationship. First, the sensitivity analysis on photosynthetic parameters ($\pm 20\%$ to 50%) confirmed that the unimodal pattern and the position of the critical threshold are preserved across all realistic parameter ranges (Table 4), indicating that the conclusions do not depend on the specific choice of literature-derived P-I values. Second, the potential circularity introduced by parameterizing K_d from CDOM absorption was rigorously tested through two independ-

ent approaches: 1) a constant- K_d scenario, which preserved the unimodal relationship and yielded a threshold statistically indistinguishable from the reference value; and 2) an independent partial correlation with directly measured chlorophyll-a, providing empirical evidence of the ecological effect of CDOM independent of the modeling framework. Third, the CDOM effect remained highly significant after statistically controlling for nutrients, temperature, pH and dissolved oxygen in a mixed-effects framework accounting for the nested structure of the observations (13 lakes $\times$ 4 campaigns). Together, these convergent lines of evidence demonstrate that CDOM is a genuine, statistically robust driver of primary production, independent of modeling assumptions or environmental covariations.

In the context of increasing urbanization and climate change, both of which are expected to enhance organic matter inputs and water browning in tropical inland waters, our findings suggest that many lakes may cross the identified critical threshold and shift toward a persistently light-limited regime. CDOM thus emerges as a key driver of ecosystem energy balance, and its monitoring should be considered a priority indicator for the assessment of the ecological status of urban lacustrine networks.

Despite the advances provided by this study, several limitations should be acknowledged. First, sampling was limited to the July-October period, capturing only the seasonal transition between the dry and rainy seasons; year-round monitoring would be necessary to confirm the temporal robustness of the observed relationships. Second, although the role of CDOM was quantitatively assessed, the relative contributions of allochthonous versus autochthonous sources were not directly evaluated, which would require complementary optical (spectral slopes, fluorescence) or isotopic analyses. Finally, the photochemical mechanisms involved in the release of nutrients from CDOM were not directly measured and remain inferred from the observed statistical relationships.

5. Conclusion

This study demonstrates that CDOM is not merely a descriptive parameter of water color, but a major energy regulator governing the functioning of tropical urban lakes. The wide observed range ($a_{355} = 0.01 - 1.90 \text{ m}^{-1}$) reveals a pronounced functional heterogeneity within a single lake network, confirming that light availability can override nutrient availability in controlling primary production. The identified unimodal relationship, together with the detection of a critical threshold at $a_{355} \approx 0.42 \text{ m}^{-1}$, highlights a clear ecological transition between a photosynthesis-favorable regime and a light-limited regime. Rigorous methodological checks (sensitivity analysis, circularity tests, mixed-effects models controlling for nutrients and physicochemistry) confirm the robustness of this pattern. Beyond its theoretical significance, this threshold represents an operational indicator for the management of urban ecosystems subjected to anthropogenic pressures and increasing water browning.

Author Contributions

O.K. Bagui conceived and designed the study, performed data processing and statistical analyses, interpreted the results, and wrote the manuscript. C.T. Kalou contributed to water sampling, physicochemical and nutrient analyses, data processing, and interpretation of the results. J.M. Bosson contributed to the scientific interpretation of the results and participated in the review of the manuscript. A.S.D. Yamoah contributed to the acquisition and processing of bio-optical data, as well as to the analysis and interpretation of the results. K.K. Anicet contributed to the writing of the manuscript. J.T. Zoueu supervised the study and contributed to the revision and validation of the manuscript. All authors contributed to the revision of the manuscript and approved the final version.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Cole, J.J., Prairie, Y.T., Caraco, N.F., McDowell, W.H., Tranvik, L.J., Striegl, R.G., *et al.* (2007) Plumbing the Global Carbon Cycle: Integrating Inland Waters into the Terrestrial Carbon Budget. *Ecosystems*, **10**, 172-185. <https://doi.org/10.1007/s10021-006-9013-8>
- [2] Thrane, J., Hessen, D.O. and Andersen, T. (2014) The Absorption of Light in Lakes: Negative Impact of Dissolved Organic Carbon on Primary Productivity. *Ecosystems*, **17**, 1040-1052. <https://doi.org/10.1007/s10021-014-9776-2>
- [3] Williamson, C.E., Stemberger, R.S., Morris, D.P., Frost, T.M. and Paulsen, S.G. (1996) Ultraviolet Radiation in North American Lakes: Attenuation Estimates from DOC Measurements and Implications for Plankton Communities. *Limnology and Oceanography*, **41**, 1024-1034. <https://doi.org/10.4319/lo.1996.41.5.1024>
- [4] Vasconcelos, F.R., Diehl, S., Rodríguez, P., Hedström, P., Karlsson, J. and Byström, P. (2016) Asymmetrical Competition between Aquatic Primary Producers in a Warmer and Browner World. *Ecology*, **97**, 2580-2592. <https://doi.org/10.1002/ecy.1487>
- [5] Zhang, Y., van Dijk, M.A., Liu, M., Zhu, G. and Qin, B. (2009) The Contribution of Phytoplankton Degradation to Chromophoric Dissolved Organic Matter (CDOM) in Eutrophic Shallow Lakes: Field and Experimental Evidence. *Water Research*, **43**, 4685-4697. <https://doi.org/10.1016/j.watres.2009.07.024>
- [6] Bushaw, K.L., Zepp, R.G., Tarr, M.A., Schulz-Jander, D., Bourbonniere, R.A., Hodson, R.E., *et al.* (1996) Photochemical Release of Biologically Available Nitrogen from Aquatic Dissolved Organic Matter. *Nature*, **381**, 404-407. <https://doi.org/10.1038/381404a0>
- [7] Kosten, S., Huszar, V.L.M., Bécares, E., Costa, L.S., van Donk, E., Hansson, L., *et al.* (2012) Warmer Climates Boost Cyanobacterial Dominance in Shallow Lakes. *Global Change Biology*, **18**, 118-126. <https://doi.org/10.1111/j.1365-2486.2011.02488.x>

- [8] Tranvik, L.J., Downing, J.A., Cotner, J.B., Loiselle, S.A., Striegl, R.G., Ballatore, T.J., *et al.* (2009) Lakes and Reservoirs as Regulators of Carbon Cycling and Climate. *Limnology and Oceanography*, **54**, 2298-2314.
https://doi.org/10.4319/lo.2009.54.6_part_2.2298
- [9] Sylla, I., Koffi, M., N'dri, K.M., Bony, K.Y., Asseman, N.E., Konan, K.F., *et al.* (2019) Évaluation de la diversité et de la charge parasitaire des lacs de la ville de Yamoussoukro en Côte d'Ivoire. *Journal of Applied Biosciences*, **134**, 13630-13642.
<https://doi.org/10.4314/jab.v134i1.2>
- [10] Peel, M.C., Finlayson, B.L. and McMahon, T.A. (2007) Updated World Map of the Köppen-Geiger Climate Classification. *Hydrology and Earth System Sciences*, **11**, 1633-1644. <https://doi.org/10.5194/hess-11-1633-2007>
- [11] Fick, S.E. and Hijmans, R.J. (2017) Worldclim 2: New 1-Km Spatial Resolution Climate Surfaces for Global Land Areas. *International Journal of Climatology*, **37**, 4302-4315. <https://doi.org/10.1002/joc.5086>
- [12] Mopper, K. and Kieber, D.J. (2002) Photochemistry and the Cycling of Carbon, Sulfur, Nitrogen and Phosphorus. In: Hansell, D.A. and Carlson, C.A., Eds., *Biogeochemistry of Marine Dissolved Organic Matter*, Elsevier, 455-507.
<https://doi.org/10.1016/b978-012323841-2/50011-7>
- [13] Cory, R.M., Ward, C.P., Crump, B.C. and Kling, G.W. (2014) Sunlight Controls Water Column Processing of Carbon in Arctic Fresh Waters. *Science*, **345**, 925-928.
<https://doi.org/10.1126/science.1253119>
- [14] Stedmon, C.A. and Markager, S. (2001) The Optics of Chromophoric Dissolved Organic Matter (CDOM) in the Greenland Sea: An Algorithm for Differentiation between Marine and Terrestrially Derived Organic Matter. *Limnology and Oceanography*, **46**, 2087-2093. <https://doi.org/10.4319/lo.2001.46.8.2087>
- [15] Helms, J.R., Stubbins, A., Ritchie, J.D., Minor, E.C., Kieber, D.J. and Mopper, K. (2008) Absorption Spectral Slopes and Slope Ratios as Indicators of Molecular Weight, Source, and Photobleaching of Chromophoric Dissolved Organic Matter. *Limnology and Oceanography*, **53**, 955-969.
<https://doi.org/10.4319/lo.2008.53.3.0955>
- [16] Lorenzen, C.J. (1967) Determination of Chlorophyll and Pheo-Pigments: Spectrophotometric Equations. *Limnology and Oceanography*, **12**, 343-346.
<https://doi.org/10.4319/lo.1967.12.2.0343>
- [17] Baird, R.B., Eaton, A.D. and Rice, E.W. (Eds.) (2017) Standard Methods for the Examination of Water and Wastewater. 23rd Edition, American Public Health Association, American Water Works Association, Water Environment Federation.
- [18] Jassby, A.D. and Platt, T. (1976) Mathematical Formulation of the Relationship between Photosynthesis and Light for Phytoplankton. *Limnology and Oceanography*, **21**, 540-547. <https://doi.org/10.4319/lo.1976.21.4.0540>
- [19] Morel, A. (1988) Optical Modeling of the Upper Ocean in Relation to Its Biogenous Matter Content (Case I Waters). *Journal of Geophysical Research: Oceans*, **93**, 10749-10768. <https://doi.org/10.1029/jc093ic09p10749>
- [20] Kirk, J.T.O. (2011) Light and Photosynthesis in Aquatic Ecosystems. 3rd Edition, Cambridge University Press. <https://doi.org/10.1017/cbo9781139168212>
- [21] Talling, J.F. (1971) The Underwater Light Climate as a Controlling Factor in the Production Ecology of Freshwater Phytoplankton. *Mitteilungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie*, **19**, 214-243.
<https://doi.org/10.1080/05384680.1971.11903932>

- [22] Lewis, W.M. (1974) Primary Production in the Plankton Community of a Tropical Lake. *Ecological Monographs*, **44**, 377-409. <https://doi.org/10.2307/1942447>
- [23] Reynolds, C.S. (2006) The Ecology of Phytoplankton. Cambridge University Press. <https://doi.org/10.1017/cbo9780511542145>
- [24] Platt, T., Gallegos, C.L. and Harrison, W.G. (1980) Photoinhibition of Photosynthesis in Natural Assemblages of Marine Phytoplankton. *Journal of Marine Research*, **38**, 687-701.
- [25] Behrenfeld, M.J. and Falkowski, P.G. (1997) A Consumer's Guide to Phytoplankton Primary Productivity Models. *Limnology and Oceanography*, **42**, 1479-1491. <https://doi.org/10.4319/lo.1997.42.7.1479>
- [26] Strickland, J.D.H. and Parsons, T.R. (1972) A Practical Handbook of Seawater Analysis. 2nd Edition, Fisheries Research Board of Canada.
- [27] Nakagawa, S. and Schielzeth, H. (2012) A General and Simple Method for Obtaining R^2 from Generalized Linear Mixed-Effects Models. *Methods in Ecology and Evolution*, **4**, 133-142. <https://doi.org/10.1111/j.2041-210x.2012.00261.x>
- [28] Wetzel, R.G. (2001) Limnology: Lake and River Ecosystems. 3rd Edition, Academic Press.
- [29] Seekell, D.A., Lapierre, J., Ask, J., Bergström, A., Deining, A., Rodríguez, P., *et al.* (2015) The Influence of Dissolved Organic Carbon on Primary Production in Northern Lakes. *Limnology and Oceanography*, **60**, 1276-1285. <https://doi.org/10.1002/lno.10096>
- [30] van Nes, E.H. and Scheffer, M. (2007) Slow Recovery from Perturbations as a Generic Indicator of a Nearby Catastrophic Shift. *The American Naturalist*, **169**, 738-747. <https://doi.org/10.1086/516845>
- [31] Scheffer, M. (2009) Critical Transitions in Nature and Society. Princeton University Press.