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Effect of Ecosystem Degradation on the Source of Particulate Organic Matter in a Karst Lake: A Case Study of the Caohai Lake, China

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Abstract: The cycle of biogenic elements in lakes is intimately linked with particulate organic matter (POM), which plays a critical role in ecosystem restoration and the control of eutrophication. However, little is known regarding the functionality of ecosystem degradation on the source of POM in the water of a karst lake. To fill this knowledge gap, herein we compared the temporal and spatial distribution characteristics of POM prior to and after ecosystem degradation in the karst lake Caohai Lake, located in the southwest of China, and analyzed the source of POM using a combination of carbon and nitrogen stable isotopes ($\delta^{13}C$–$\delta^{15}N$). Our results showed that the dissolved oxygen (DO) concentration and pH values decreased, and the concentrations of POM in water increased by 11% and 31% in the wet and dry seasons, respectively. The decrease in the $\delta^{13}C$ value of POM was accompanied by the increase in the $\delta^{15}N$ value of POM in the water of Caohai lake. Prior to the ecosystem's degradation, sediment resuspension (28%) and submerged macrophytes (33%) were the dominant sources of POM in lake water. In contrast, sediment resuspension (51%) was the major source of POM after the ecosystem's degradation. Environmental factors, including DO, turbidity, water depth, and water temperature, that are related to photosynthesis and sediment resuspension are the main factors controlling the spatiotemporal distribution of POM. The resuspension of sediment reduced the transparency of the water, limiting effective photosynthesis, impeding the survival of submerged macrophytes, and, consequently, deteriorating the ecosystem. We propose that the control of sediment resuspension is important for improving the water transparency that creates an appropriate habitat for the restoration of the submerged macrophyte community.

Keywords: particulate organic matter (POM); carbon and nitrogen stable isotopes; source tracing; ecosystem degradation; Caohai Lake

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1. Introduction

The transformation of clear water to turbid water in a lake is defined as degradation of a shallow lake ecosystem. In the steady state of clear water, the water body is clear, and the coverage of submerged macrophytes is high. In the steady state of turbid water, abundant phytoplankton is present, and the water quality is turbid [1]. Ecosystem degradation is the result of a comprehensive effect that comprises the influence of external driving forces (including input of exogenous nutrient loads, increase in the lake water level or destruction of lakeside belts, and biological regulation) [2]. The rapid dying-out of the submerged macrophytes causes increasing amounts of phytoplankton and, as a result, a rapid drop in the water's transparency. Additionally, the disappearance of submerged macrophytes enhances sediment resuspension, and moreover, due to the disruption of the food web, omnivorous fish must forage in the substrate, further exacerbating sediment resuspension. The combined impact of phytoplankton and sediment resuspension causes further reduction in transparency, and the lake ecosystem becomes completely transformed from a clear water steady state to a turbid water steady state [2,3].

Particulate organic matter (POM) is an important component of the cycle of biogenic elements in lakes and reservoirs and has a significant regulatory effect on lake organic carbon and inorganic carbon pools [4]. Moreover, it controls nutrients, including nitrogen (N), phosphorus (P), and heavy metals, to a large extent [5,6]. As well as the transport of organic pollutants, the identification of POM sources is the key to understanding the carbon cycle in lakes [7]. POM plays an important role in the circulation of carbon and energy within lake systems and largely controls the transport of macronutrients. Therefore, the study of the source and cycle of POM will provide a reliable basis for the prevention and, if necessary, reversal of lake ecosystem degradation [8,9].

The plateau karst lake ecosystem is very fragile and highly sensitive to environmental changes and human food disturbance [10–12]. With the urbanization of the Caohai Basin, a large amount of particulate matter and nutrients has entered Caohai Lake through surface runoff in recent years. Caohai Lake (Guizhou Province, China), a typical plateau karst lake, is facing serious environmental problems, including enhanced sedimentation, pollution of recharge water sources, and deterioration of water quality [9,13]. Since 2020, a large area of submerged macrophytes in Caohai Lake has died out and, with obvious turbid water bodies and serious water eutrophication, the aquatic ecosystem has been degraded. Currently, the ecosystem is in a critical transition stage from a steady state of clear water to a steady state of turbid water. However, few studies have focused on the source of organic matter in such types of lake particles and its impact on ecosystem degradation [14,15].

The carbon and nitrogen stable isotopes ($\delta^{13}C$–$\delta^{15}N$) of the endmembers of different POM sources show a significant difference. Therefore, the isotopes can trace the source and transformation process of POM, which is a reliable indicator for tracking the source of organic matter in lakes, allowing us to understand nutrient utilization and the fate of organic matter in lakes [5,11,16]. In this study, we combine the $\delta^{13}C$–$\delta^{15}N$ isotopes and SIAR (Stable Isotope Analysis in R) isotope mixture models to (1) analyze the effect of ecosystem degradation on the POM concentrations and $\delta^{13}C$–$\delta^{15}N$ distribution characteristics in Caohai Lake, (2) quantitatively evaluate the differences in the sources of POM in Caohai Lake prior to and after ecosystem degradation, and (3) reveal the driving factors of the source and distribution of POM in Caohai Lake.

2. Materials and Methods

2.1. Study Area

Caohai Lake (N 26°47′32″~26°52′52″, E 104°10′16″~104°20′40″) is located in the southwest of Weining County (China) at an altitude of 2170 m. The average water body temperature is 10.5 °C, the average water depth is 1.5 m, and the maximum depth is 5 m [17]. The wet season lasts annually from May to September, and the dry season lasts from October to April. The average annual precipitation in the Caohai Basin is about 951 mm, with 88% of the precipitation occurring during the wet period [18]. The lake is rich in aquatic plants, primarily *Potamogeton lucens L.*, *Myriophyllum verticillatum L.*, *Potamogeton wrightii Morong*, *Potamogeton maackianus A. Bennett*, and Najas graminea Del. Four major rivers enter the lake: the Zhong River, the Sha River, the Dongshan River, and the Maojiahaizi River, which are part of the typical plateau-karst-grass-type shallow water lake system (Figure 1).

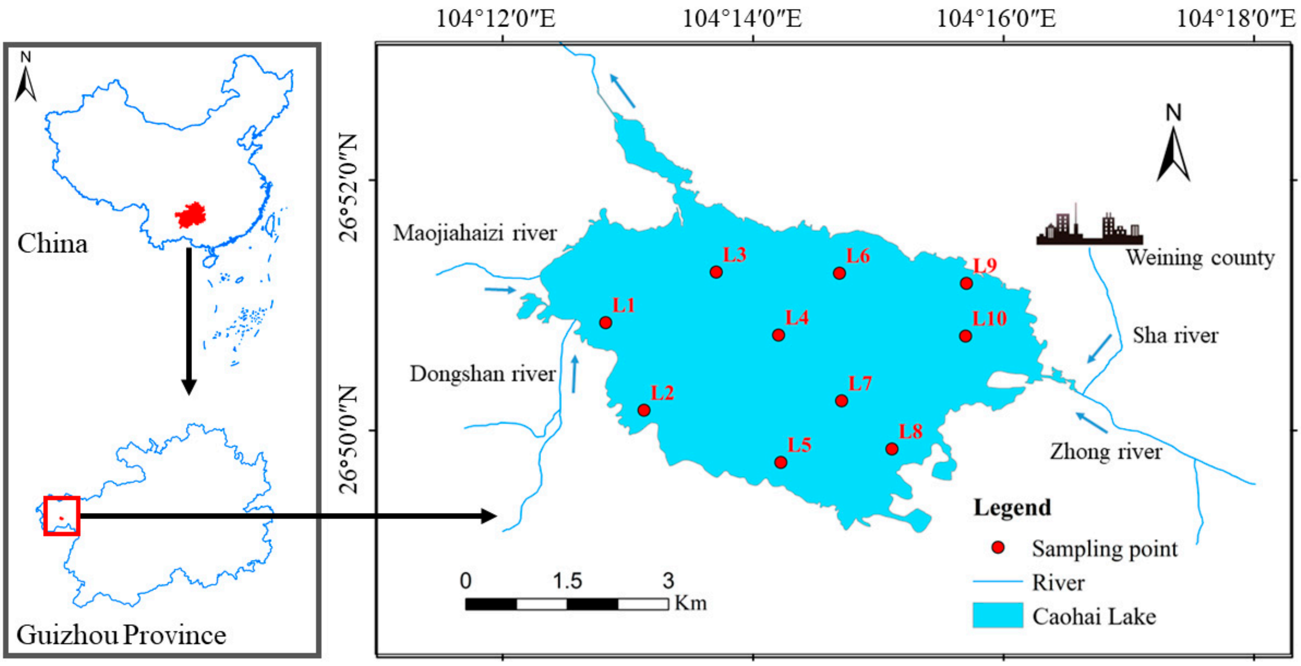

Figure 1. Distribution of sampling sites in Caohai Lake. Their positions were marked in red in the inserted maps of China and Guizhou Province.

2.2. Sample Collection and Analysis

The POM in the water of Caohai Lake was systematically sampled prior to (in 2019) and after (in 2021) ecosystem degradation. The sampling date are from April (dry season) and July (wet season), 2019 and August (wet season) and December (dry season), 2021. Ten representative sites were selected for taking the samples (L1–L10), which were collected at a depth of 0.5 m using a Niskin water collector. Water quality parameters—including temperature (T), electrical conductivity (EC), and dissolved oxygen (DO)—were measured on-site with a multi-parameter water quality monitor (YSI-6600V2). The water transparency (SD) of each sampling point in the lake area was measured with a Secchi disc. Source endmember samples of five main submerged macrophytes were collected in the center of the lake (L4) using a grab (Table S5). Surface sediment samples from the lake bottom were collected with a sediment grab sampler loaded in a crisper and dripped with saturated $HgCl_2$. The solution was poisoned and kept refrigerated.

The water samples were transferred through a silica gel tube to a stainless steel filter and percolated with a Whatman GF/F filter under positive pressure. After filtration of about 10 L of lake water per filter, we used clean tweezers to fold the filter and to place it in aluminum foil for storage at low temperature (<4 °C). After freezing, the filter membrane was freeze-dried using a freeze dryer, fumigated with 12 mol/L hydrochloric acid for 24 h to remove carbonate, subsequently dried at 60 °C, and finally stored in a desiccator. The collected fresh plant leaves were washed with ultrapure water to remove impurities, freeze-dried, grounded through a 100-mesh sieve, and packed in zip-lock bags. The surface sediment samples were centrifuged to separate the pore water of in the speed of 3800 rmp, and freeze-dried. The dried sediment samples were cleaned with an agate mortar after removing the gravel as well as animal and plant residues. After passing through a 120-mesh sieve, they were soaked in 1 mol/L hydrochloric acid for 24 h while heating to 100 °C to remove inorganic carbon. The samples were washed to neutrality, freeze-dried, ground into powder, and cooled in a desiccator. The particulate organic carbon (POC) and particulate organic nitrogen (PON) concentrations of all samples were determined with an organic element analyzer (Vario macro cube with a precision <0.5% rel); $\delta^{13}C$ and $\delta^{15}N$ values of samples were detected in all samples using a Thermo Fisher MAT-252/253 mass spectrometer with an accuracy $\leq$0.06‰.

2.3. Isotopic Mixing Model

We used the Bayesian SIAR mixture model to quantify the contribution of different endmembers to water POM. SIAR is available to download from the packages section of the Comprehensive R Archive Network site (CRAN)—http://cran.r-project.org/ [19] (accessed on 15 July 2012). The SIAR model is expressed in Equation (1):

$$X_{ij} = \sum_{k=1}^{k} P_k \left(S_{ij} + C_{ij} \right) + \varepsilon_{ij} \quad (1)$$

$$S_{jk} \sim N(\mu_{jk}, \omega_{jk}^2) \quad (2)$$

$$c_{jk} \sim N(\lambda_{jk}, \tau_{jk}^2) \quad (3)$$

$$\varepsilon_{jk} \sim N(\sigma_j^2) \quad (4)$$

where:

X_{ij} = observed isotope value j of the consumer i;

S_{jk} = source value k on isotope j; normally distributed with mean μ_{jk} and variance ω_{jk}.

c_{jk} =TEF (sources and trophic enrichment factors) for isotope j on source k; normally distributed with mean; λ_{jk} and variance τjk^2.

P_k = dietary proportion (external sources of variation not connected to isotopic uncertainty) of source k; estimated by the model.

q_{jk} = concentration of isotope j in source k.

ε_{ij} = residual error, describing additional interobservation variance not described by the model, ${\sigma_j}^2$ estimated by the model.

The Bayesian paradigm enables the calculations of the uncertainty of all parameters. P and σ^2 are the most important parameters—controls for the proportional contribution and residual variance, respectively. Model fitting is hierarchical, enabling flexibility in adding further complexity [19].

2.4. Data Analysis

We used the inverse-distance-weighted method in ArcGIS 10.6 to analyze and map the concentrations of POC, PON, and $\delta^{13}C_{POC}$ and $\delta^{15}N_{PON}$ data in water prior to and after the degradation of the Caohai Lake ecosystem. We used the R 4.0.3 software to calculate the contribution of POM quantitatively and analyzed the results with Origin 2018. Significant variability between variables prior to and after ecosystem degradation was verified using the Mann–Whitney test of IBM SPSS Statistics 21.

3. Results and Discussion

3.1. Water Quality Parameters

Prior to the degradation of Caohai Lake, the average pH values of all locations in the wet season and dry season were 8.50 $\pm$ 0.18 and 9.04 $\pm$ 0.31, respectively; after the degradation, they were 8.42 $\pm$ 0.28 and 8.28 $\pm$ 0.08, respectively. The pH of the water body decreased significantly with the ecosystem's degradation ($p < 0.01$; Figure 2a). The DO (dissolved oxygen) concentrations in the wet and dry seasons prior to degradation were 8.55 $\pm$ 2.78 mg/L and 12.53 $\pm$ 1.71 mg/L, respectively; after degradation, they were 7.74 $\pm$ 0.57 mg/L and 7.23 $\pm$ 1.16 mg/L, respectively, thus indicating a significant decrease in the water DO in Caohai Lake with ecosystem degradation ($p < 0.01$; Figure 2b).

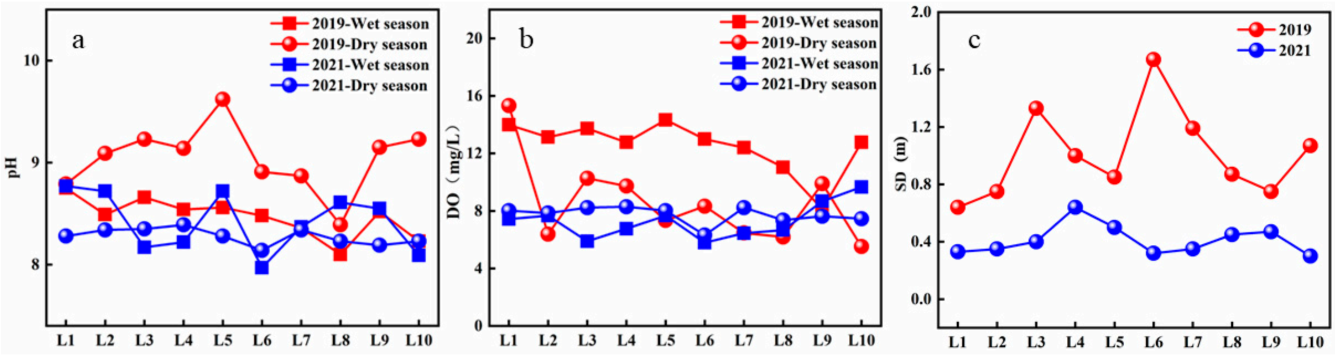

Figure 2. Distribution characteristics of environmental parameters: pH (**a**), DO (**b**), SD (**c**) in Caohai Lake (locations from L1 to L10).

After the degradation, Caohai Lake's water became turbid, with a transparency of only 0.41 m, which is a reduction of 59% compared to its pre-degradation status (Figure 2c). Weining County is located northeast of Caohai Lake. Until 2017, the sewage from Weining County was directly discharged into Caohai Lake (about 8000 tons per day), which occurred continuously [20]. The input of exogenous nutrient load caused a gradual increase in the concentration of nutrients in the water and an increase in phytoplankton production. Since March 2019, a total fishing ban has been implemented for Caohai Lake. As a consequence, the quantity of herbivorous fish in the lake has increased rapidly, which damages the submerged macrophytes community, but has also strongly disturbed the sediment, causing sediment resuspension. Due to the combined impact of increased phytoplankton production and sediment resuspension, the transparency of Caohai Lake's water became significantly reduced [2]. By 2021, submerged macrophytes had died out on a large scale, losing their fixation, and sediment resuspension has increased. In addition, due to the destruction of the food chain, omnivorous fish were forced to forage in the sediment, which further exacerbated sediment resuspension (Figure S1) [2].

High turbidity influences aquatic photosynthesis and respiration, which in turn affects the pH and DO concentrations of the lake, resulting in fluctuations in the concentrations of nutrients and other water components [21]. Prior to the degradation of the ecosystem, the water had high transparency, and the photosynthesis of aquatic plants was prosperous, causing high DO concentrations in the water. Photosynthesis was weakened after the degradation, so the consumption of free CO_2 in the water was reduced, and the free CO_2 combined with hydrogen ions in the water, thus changing the carbonate equilibrium and causing a decrease in the pH of the water (Figure 2a).

3.2. Spatiotemporal Distribution Characteristics of POM Concentrations in Water Prior to and after Ecosystem Degradation

After ecosystem degradation, the POC concentrations in the water of Caohai Lake increased by 11% and 31% in the wet and dry seasons, respectively, the concentrations of POC increased to 1.67 ± 0.67 mg/L and 1.28 ± 0.15 mg/L after degeneration. The concentrations of PON remained almost unchanged. Prior to the degradation, the PON concentrations were 0.30 ± 0.14 mg/L and 0.22 ± 0.10 mg/L in the wet and dry seasons, respectively, and after degradation, the PON concentrations were 0.26 ± 0.09 mg/L and 0.25 ± 0.04 mg/L, respectively (Figures 3 and 4). The overall POM concentrations decrease from the east towards the west and are higher during the wet season than during the dry season (Figures 3 and 4). The seasonal difference is significant ($p < 0.01$; Figures 3 and 4).

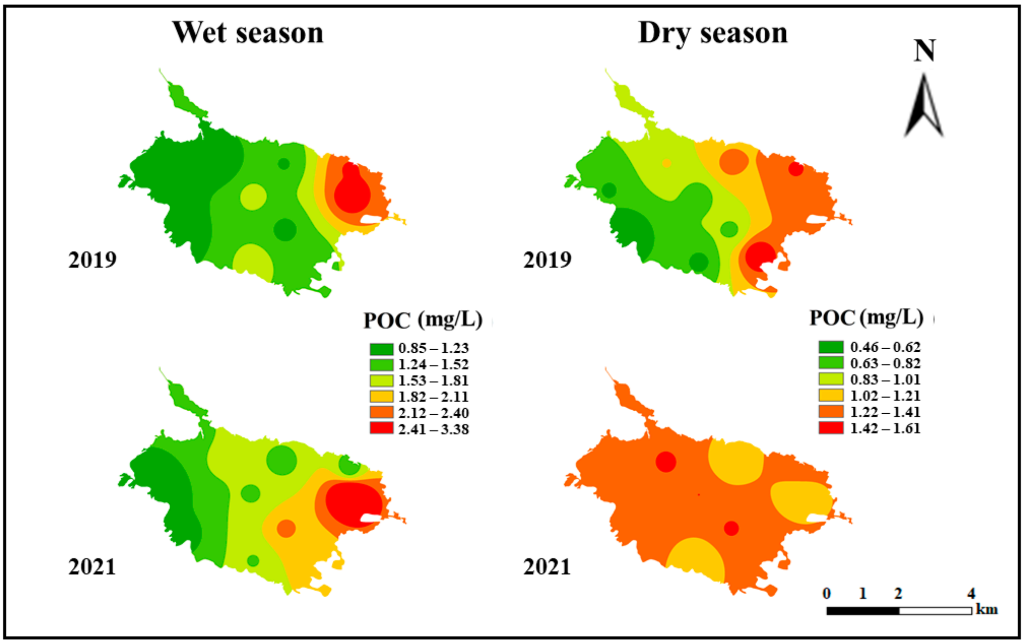

Figure 3. The temporal and spatial distribution of the concentrations of POC in wet season and dry season of Caohai Lake.

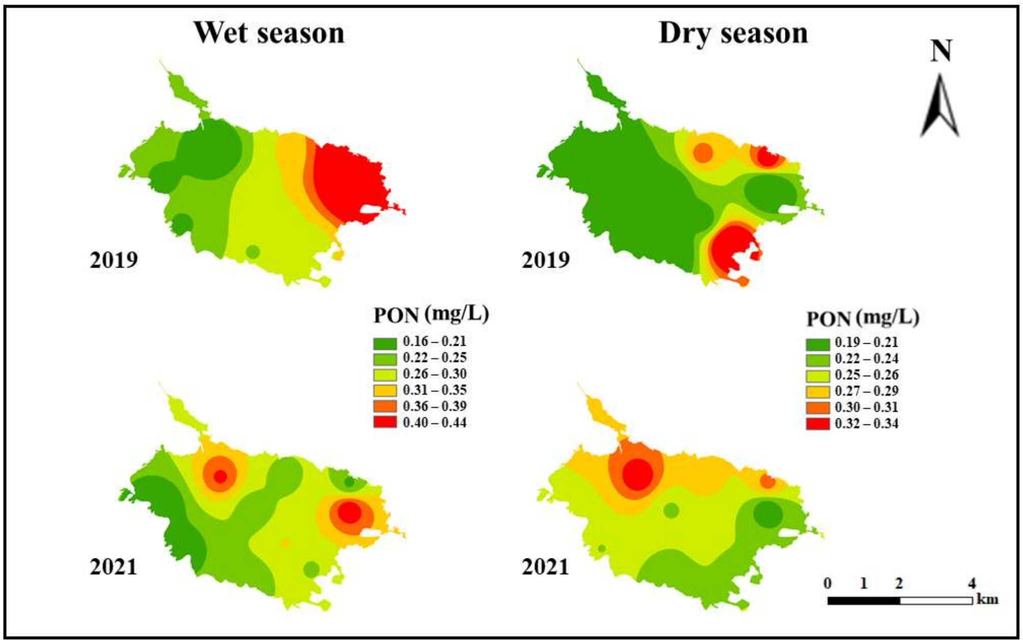

Figure 4. The temporal and spatial distribution of the concentrations of PON in wet season and dry seasons of Caohai Lake.

The strong sunlight in the wet season (from May to September) causes the growth of aquatic plants and algae that increase the endogenous contribution of the lake [22]. In addition, due the heavy rainfall in the wet season, the particles on both sides of the river entering the lake are drained into the river channel and enter the lake with the surface runoff, thus enhancing the external input in the wet season. Therefore, the concentrations of POM are significantly higher in the wet season than in the dry season ($p < 0.01$; Figures 3 and 4). Related to the discharge from Weining County, the POC concentrations of the sampling point L10 at the eastern tributary of the lake (with a flow rate of 225 L/s, which is the highest among the four main rivers) prior to and after ecosystem degradation during the wet season are very high—2.69 mg/L and 3.38 mg/L, respectively—which are 40% and

125% higher than in the center of the lake (Figure 3). These data show that terrigenous input has an important impact on the composition of the lake POM in this area.

The endogenous sources of POM in the Caohai Lake are mainly sediment resuspension and submerged macrophytes. After degradation of the ecosystem, the immobilization of submerged macrophytes gets lost, and sediment resuspension increases. The inferred release caused the increases of 11% and 31% in the POC concentrations in water of the Caohai Lake in the wet and dry periods, respectively (Figure 3). After the degradation, the concentrations of POC and PON increased in the dry season of the western outlet, which may be due to the deterioration of the water quality (decreased DO, increased pH, and water transparency less than 0.5 m), which promoted the growth of algae.

3.3. Spatiotemporal Distribution Characteristics of POM Carbon and Nitrogen Isotopes in Lake Water Prior to and after Ecosystem Degradation

The $\delta^{13}C_{POC}$ value in the water of Caohai Lake after the degradation is lower than prior to the degradation. The $\delta^{13}C_{POC}$ value in the water of Caohai Lake in wet season and dry season prior to the degradation is -21.6 ± 2.7‰ and -24.2 ± 1.7‰, respectively, and -23.9 ± 3.2‰ and -25.1 ± 0.6‰ after the degradation (Figure 5). The $\delta^{13}C_{POC}$ value in the water of Caohai Lake is generally higher than the average $\delta^{13}C_{POC}$ value of -29.7 ‰ for global lakes [16]. The karst basin has a strong weathering effect; the HCO_3^- enters the water, which leads to the DIC increases in the water. The $\delta^{13}C_{DIC}$ of the water, with a range from -15.7‰ to 3.7‰, eventually lead to the higher $\delta^{13}C_{POC}$ value in the water of Caohai Lake (Table S6). Prior to ecosystem degradation, the average values of $\delta^{15}N_{PON}$ in the water of Caohai Lake in the wet and dry seasons are 3.3 ± 1.5‰ and 3.4 ± 1.5‰, respectively, and 3.7 ± 2.3‰ and 0.1 ± 0.6‰ after degradation (Figure 6). The $\delta^{13}C_{POC}$ value in water of Caohai Lake is higher in the wet season than in the dry season and lower in the east than in the west. During the dry season, the $\delta^{15}N_{PON}$ value in the water of Caohai Lake became significantly lower after ecosystem degradation (Figure 6; $p < 0.01$).

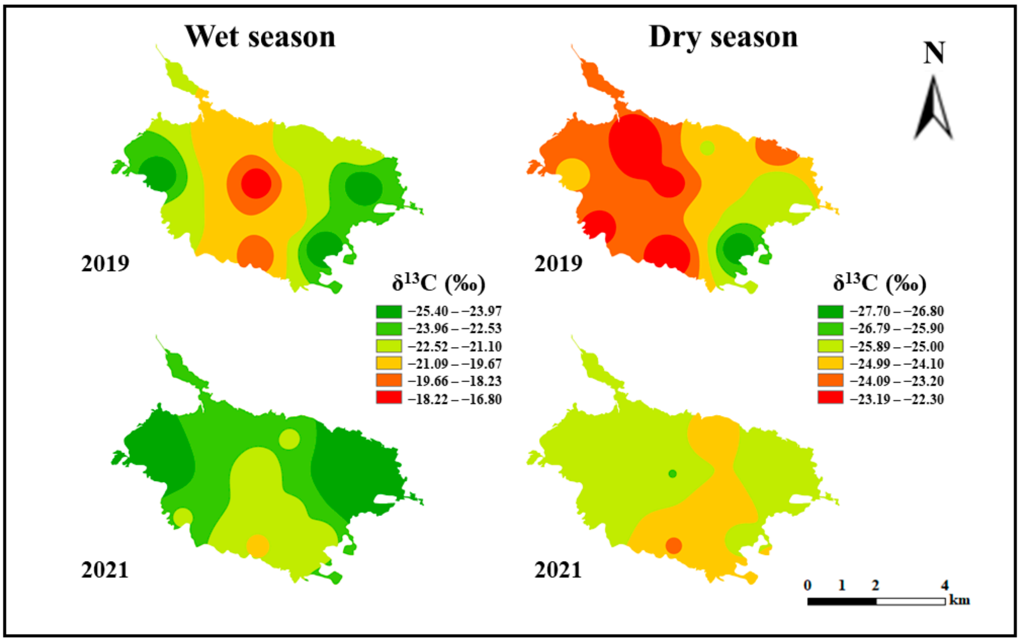

Figure 5. Temporal and spatial variation of carbon stable isotope in wet season and dry season of Caohai Lake.

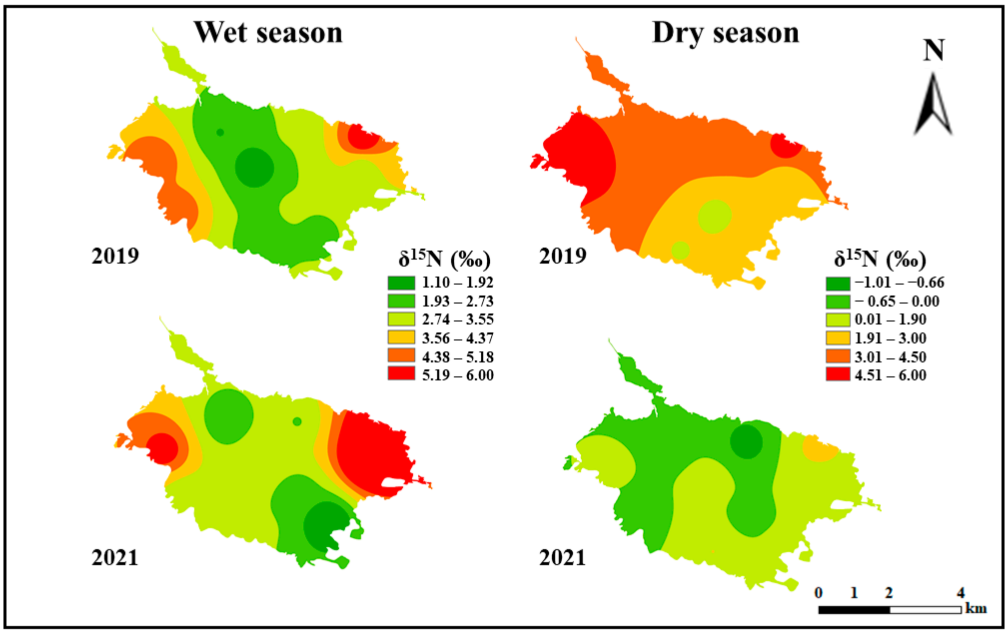

Figure 6. Temporal and spatial variation of nitrogen stable isotope in wet season and dry season of Caohai Lake.

Due to temperature and light intensity, photosynthesis of aquatic plants is intense in the wet season, leading to the fixation of atmospheric CO_2 into the water [21]. The $\delta^{13}C$ value of atmospheric CO_2 is higher than the $\delta^{13}C$ of the water and of bottom biodegradation. Organic matter preferentially releases lighter ^{12}C during the degradation process, making the $\delta^{13}C$ value of POM in the wet season higher than that in the dry season [23,24]. POM in dry seasons contains more detritus, which reduces water transparency and promotes the growth of microzooplankton. This results in higher $\delta^{15}N$ values in dry seasons compared to wet seasons [5]. The $\delta^{13}C$ value of terrigenous C3 plants is lower than that of sediments and submerged macrophytes, and the $\delta^{15}N$ value is higher (Table 1, Figure 7). Under the influence of exogenous input (such as plant debris and soil organic matter), the values of $\delta^{13}C_{POC}$ and $\delta^{15}N_{PON}$ were lower and higher, respectively, in nearshore area than those of in offshore area during the wet seasons prior to and after degradation (Figure 6; Tables S1 and S2).

Prior to the ecosystem's degradation, submerged macrophytes and sediment resuspension were the main source of POM in the water of Caohai Lake. However, sediment resuspension dominated as a source of POM after degeneration. The change in sources caused variation in the isotopic composition in water of Caohai Lake: lower $\delta^{13}C_{POC}$ value in the water regardless of wet season or dry season after degeneration (Figure 7). In addition, after the ecosystem's degradation, the $\delta^{15}N_{PON}$ value in water of Caohai Lake in the dry season became significantly lower than that in the wet season, which may be related to the absorption of nitrate by phytoplankton and isotopic fractionation under the condition of light limitation. Low temperature further aggravated the extinction of aquatic plants after degradation. At the same time, diatoms preferentially utilize ^{14}N in nitrate under low light intensity, resulting in a lower $\delta^{15}N_{PON}$ value of the water in the dry season [25,26].

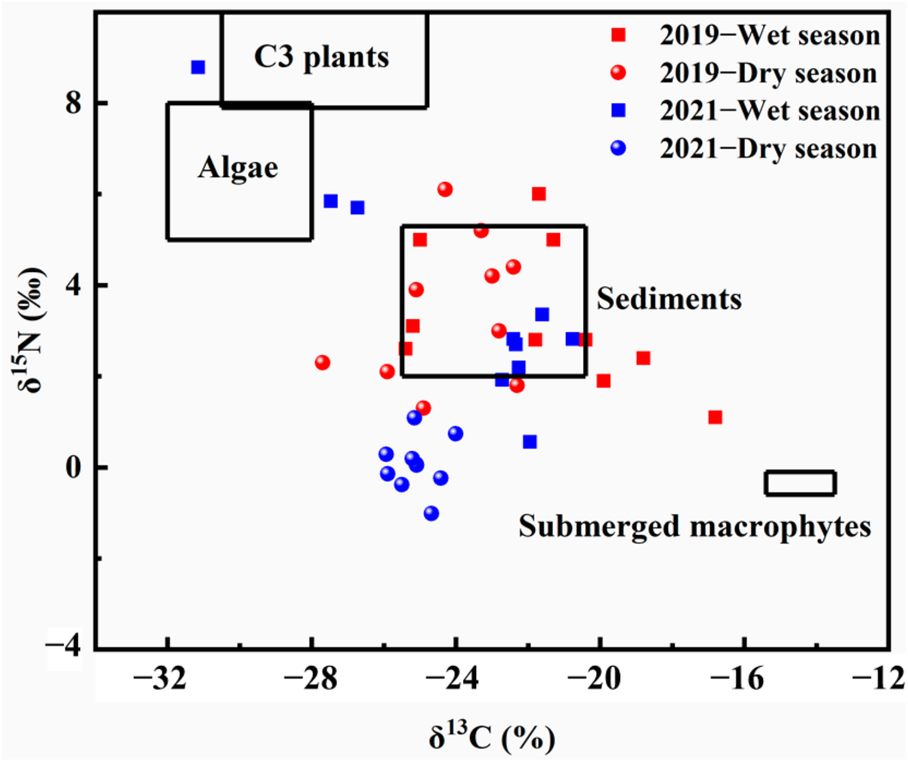

Figure 7. Mixing plots of the δ^{15}N and δ^{13}C values of the four different POM sources during the different periods (2019−wet season, 2019−dry season, 2021−wet season, 2021−dry season) of the Caohai Lake. The different POM sources were sediments, submerged macrophytes, algae, and C3 plants.

Table 1. The δ^{13}C and δ^{15}N (‰) of different sources to POM in water of Caohai Lake.

End Member	δ^{13}C		δ^{15}N		References
	Range of δ^{13}C	**Mean ± SD**	**Range of δ^{15}N**	**Mean ± SD**	
Sediment (n = 10)	−20.4 to −25.5	−23.3 ± 1.7	2.0 to 5.3	3.3 ± 1.1	this study
Submerged macrophytes (n = 5)	−13.5 to −15.4	−14.9 ± 0.7	−0.6 to −0.1	−0.1 ± 0.4	this study
Algae	−32.0 to −28.0	−30.0 ± 2.0	5.0 to 8.0	6.5 ± 1.5	[21,27]
C3 plants	−30.5 to −24.8	−27.6 ± 2.0	7.9 to 12.8	10.3 ± 2.0	[28,29]

3.4. POM Source Characteristics and Their Drivers

Exogenous input (C3 plants) and endogenous production (sediment resuspension, phytoplankton, and submerged plants) are the main sources of POM in Caohai Lake (Figure 7). We measured the δ^{13}C and δ^{15}N values of the endmembers of sediments and submerged macrophytes to determine the range of variation of the stable isotope values of sediments and submerged macrophytes. Citing data of previous studies on carbon and nitrogen stable isotopes of terrestrial plants and lake algae [21,27–29], our data document the following variation (Table 1, Figure 7): The range of δ^{13}C of terrigenous C3 plants is −30.5 to −24.8‰, with an average value of −27.6 ± 2.0‰. The range of δ^{15}N of C3 plants is 7.9 to 12.8‰, with an average value of 10.3 ± 2.0‰, and the range of δ^{13}C of lake algae is −32.0 to −28.0‰, with an average value of −30 ± 2‰. The range of δ^{15}N of lake algae is 5.0 to 8.0‰, and the average value is 6.5 ± 1.5‰.

The SIAR model shows that from the wet season of 2019 to the dry season of 2021, the contribution percentages of sediment resuspension increased from 25% to 71% (Figure 8).

The contribution percentages of submerged macrophytes decreased from 41% to 12%. The changes in the contribution percentages of algae do not show any obvious systematic trend or variation, and the mean value was 22%. The contribution percentages of C3 plants were lower, with a mean value of 12% (Figure 8).

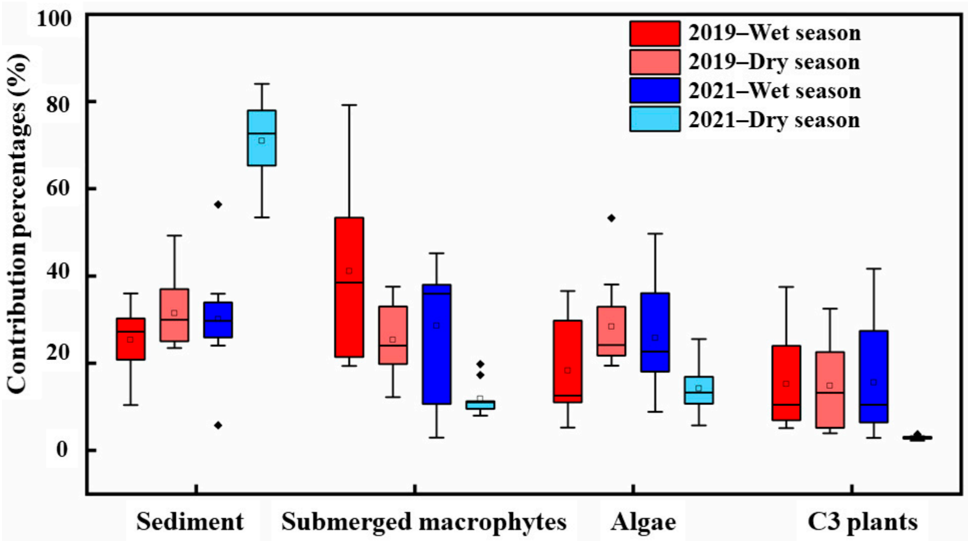

Figure 8. Relative contribution percentages of sediment, submerged macrophytes, algae, and C3 plants to POM in water of Caohai Lake. Red, light red, blue, and light blue represent the 2019−wet season, 2019−dry season, 2021−wet season, and 2021−dry season, respectively.

The dominant role of endogenous POM has been documented in several plateau karst lakes [5,11,16]. Our results show that the average contribution percentages of endogenous POM (including algae, submerged macrophytes, and sediment resuspension) in Caohai Lake can reach to 91% (Figure 8, Table S4). Compared with large deep-water lakes, such as Tai Lake, the material exchange between shallow-water lakes and sediments is stronger, and sediment resuspension contributes more to the POM, suggesting that shallow-water lakes are more susceptible to sediment resuspension than deep-water lakes [4]. However, the contribution percentages of algae in Caohai Lake are comparably small, and its contribution percentages are much lower than those of Tai Lake (the maximum contribution rates of algae is 57%), showing that the growth of algae in lakes with lush aquatic plants is significantly inhibited [30]. Compared with the floodplain lake Poyang Lake, the sediments in Caohai Lake are the result of multivariate mixing, whereas those of Poyang Lake are predominantly derived from soil erosion, indicating that large karst lakes have more complex carbon cycle patterns than other lakes [14].

Although the POM of Caohai Lake is generally dominated by endogenous sources, the influence of land sources is striking in some parts of the lake. Terrestrial organic carbon is mainly composed of terrigenous plant debris and organic matter. Physical erosion is generally the main controlling factor for POC concentrations in rivers. Soil erosion causes land degradation and migration of soil particles, related POC, and nutrients, thus affecting the global carbon cycle [31]. Four major rivers discharge into Caohai Lake at the eastern and western lakeshores. During the strong rainfall in the wet season, terrigenous soil debris enters the Caohai Lake through surface runoff, which affects the POM composition of Caohai Lake's water in the eastern and western parts of the lake. The contribution rates of submerged macrophytes are lower in the east and west than in the center of the lake (see Figure S1). On the contrary, the contribution of terrigenous sources in the nearshore lake area (L1, L2, L9) is significant, and the maximum value reaches 41% of the total POM.

As a typical karst lake system, Caohai Lake is highly vulnerable and sensitive to environmental changes and human disturbances [11]. Since 2013, the water level of the Caohai Lake has gradually increased, and since 2015, the water level has remained on a high value (more than 1 m higher than in 2012). In addition, the water level fluctuation amplitude has decreased, and the hydrological rhythm has changed significantly. The continuously high water level, reduced water level variation, and poor water mobility in Caohai Lake caused the extinction of emergent plants in the nearshore area, the inhibition of seed germination of submerged macrophytes, the degradation of aquatic vegetation, the weakening of wave-dissipating effects, and the reduction of water self-purification [32–34]. Moreover, in March 2019, a comprehensive fishing ban was implemented for Caohai Lake. As a consequence, the number of herbivorous and omnivorous fish (including carp, crucian carp, and wheat ear fish) in the lake area has increased rapidly. This further strongly disturbed the sediment, causing the resuspension of particulate matter, thus inducing water turbidity. As a consequence, photosynthesis of submerged macrophytes became limited and gradually vanished [35–37].

The source to POM in the water of Caohai Lake changed significantly after ecosystem degradation (Figures 2, 8 and S1). The POM in the water of Caohai Lake was mainly controlled by sediment resuspension and submerged macrophytes prior to the degradation. In the wet season, the temperature was high and the photosynthesis of submerged macrophytes was intense. The average contribution percentages were higher than that of the sediments (41%)—as high as 79% in the center of the lake. The contribution (25%) in the dry season was slightly lower than that of sediment, further confirming that environmental factors related to photosynthesis and sediment resuspension are the main factors affecting the contribution of POM source in karst lakes (Figure 2). After the degradation, the POM of Caohai Lake's water gradually changed and became controlled by sediment resuspension. Due to the low temperature, inhibiting the photosynthesis of aquatic plants, and the minor rainfall, which reduced external input, the average contribution of sediment resuspension during the dry season reached 71%.

Significant seasonal differences in POM contribution percentages indicate the direct effects of water movement on air temperature and rainfall caused by seasonal changes (Figure 8; $p < 0.01$) [23]. Turbidity has an important indirect effect on phytoplankton photosynthesis through its impact on the availability of sunlight in the water. The DO is controlled by water−vapor exchange, water photosynthesis and respiration, mineral oxidation, and water mixing that occur in aquatic ecosystems, as well as by cycling and other important indicators of physicochemical processes [38]. Moreover, aquatic photosynthesis is an important source of DO [39]. The pH value of water is an important factor in the eutrophication of the lake. It is the result of the comprehensive effect of various factors, such as geological background, climate conditions, exogenous input, etc., and is closely related to algae growth [21]. After the degradation, change in the carbonate equilibrium caused a decrease in the pH in Caohai Lake. In addition, nutrient levels (i.e., N and P) are crucial for the primary production and growth of phytoplankton. We detected for Caohai Lake that algae have higher contribution percentages at the sites with higher PON concentrations (L9, L10) (Table S1). During the wet season, the contribution percentages of algae attained a maximum of 50% in the east after the system was degraded (Figure 8), further confirming the important contribution of primary production to POM [40]. Fish, wind, and wave disturbances can cause sediment resuspension, which has a major impact on POM. Our study shows that the contribution percentages of sediments continue to increase after ecosystem degradation, and the average value can reach 71% in the dry season after ecosystem degradation (Figure 8). The spatial distribution characteristics of POM and the differences among the influences of various driving factors further illustrate the complexity of the carbon cycle process in large karst lakes, such as Caohai Lake.

We have detected that the ecosystem degradation in Caohai Lake is related to the following main factors: sediment resuspension caused by wind and waves, sediment resuspension caused by fish foraging, reduced transparency impeding the survival of submerged macrophytes, increased nutrient concentration in the water, and the growth of large quantities of phytoplankton in submerged water. These factors lead to a reduction in the transparency of the water (Figure 2) and, as a consequence, the effective photosynthesis of the submerged macrophytes is largely inhibited (Figure 8). These processes improve the stability of the turbid water steady state. Therefore, we suggest controlling the sedimentation of the water particles and the resuspension of the sediment. This strategy will improve the transparency of the water and will create an appropriate habitat for the restoration of submerged macrophyte communities. Based on this strategy, the submerged macrophyte community will be reconstructed, and the food web will be optimized and regulated to restore the aquatic ecosystem of Caohai Lake [41].

4. Conclusions

We used carbon and nitrogen stable isotopes ($\delta^{13}C-\delta^{15}N$) and SIAR mixed model to quantitatively assess the source of POM in the water of karst Caohai Lake prior to and after ecosystem degradation and to explore the driving factors of POM. Our results document a trend of the spatial distribution of the POM concentrations in the water of Caohai Lake, with high values in the east moving towards low values in the west, which is related to the influence of terrigenous input and rainfall distribution. Moreover, our data show that the distribution characteristics of the POM concentrations in the wet season are larger than those in the dry season. The isotope characteristics show low $\delta^{13}C$ values near the shore and high values near the lake's center. In contrast, the $\delta^{15}N$ values are high near the shore and low in the lake's center. After the degradation of the ecosystem, the DO concentrations and pH value in the water of Caohai Lake decreased due to the extinction of a large quantity of submerged macrophytes. Moreover, POM concentrations increased by 11% and 31% in the wet season and the dry season, respectively. Prior to the ecosystem's degradation, sediment resuspension (28%) and submerged macrophytes (33%) were the major sources of POM, while sediment resuspension (51%) dominated the source of POM after the ecosystem's degradation. Environmental parameters (including DO, turbidity, water depth, and water temperature) that are related to photosynthesis and sediment resuspension are the main factors driving the spatiotemporal distribution of POM. Sediment resuspension reduces water transparency, thereby impeding the survival of submerged macrophytes. Growth of large quantities of phytoplankton is related to increased nutrient concentrations in water. Finally, the reduced water transparency induced by these factors caused the ecosystem's degradation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14121867/s1, Figure S1. Photos of Caohai Lake before and after the ecosystem degradation between 2019 and 2021. Figure S2. Contribution percentages (%) of sediment, submerged macrophytes, algae and C3 plants to POM in water of Caohai Lake. W and D represents the wet season and dry season, respectively. Table S1. Hydrochemical parameters of the lake water (T, DO, EC, and pH), concentrations of POC and PON, δ13CPOC and δ15NPON in Caohai Lake of wet season and dry season in 2019. Table S2. Hydrochemical parameters of the lake water (T, DO, EC, and pH), concentrations of POC and PON, δ13CPOC and δ15NPON in Caohai Lake of wet season and dry season in 2021. Table S3. Relative contribution percentages (%) of sediment, submerged macrophytes, algae and C3 plants to POM in water of Caohai Lake in 2019. Table S4. Relative contribution percentages (%) of sediment, submerged macrophytes, algae and C3 plants to POM in water of Caohai Lake in 2021. Table S5. The δ13C and δ15N (‰) of sediment (n = 10) and submerged macrophytes (n = 5) of Caohai Lake. Table S6. The δ13CDIC (%) in water of Caohai Lake of wet season and dry season in 2019.

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