Asian Journal of Chemistry; Vol. 24, No. 10 (2012), 4408-4414

ASIAN JOURNAL OF CHEMISTRY

www.asianjournalofchemistry.co.in

In Situ Microsensor Studies of Long-Term Environmental Effect of Sediment Dredging in the Shallow Lake

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(*Received*: 19 July 2011; *Accepted*: 4 May 2012) AJC-11398

A laboratory experiment was carried out through a fifteen-month incubation of undredged and dredged cores to study the long-term effect of sediment dredging on biogeochemistry. The pH, redox potential (Eh), O_2 profiles and the net rates of O_2 production and consumption at different light intensities were measured at high spatial resolution by microsensors. The results showed that dredging the uppermost 30 cm sediment layer can effectively control the phosphorus release in long-term effectiveness. However, the dredged cores were vulnerable to disturbance and the microbial community which on the sediment surface before lake dredging would not be recovered in a long time in the future. Consequently, dredging may be not a satisfied measure for rehabilitating the aquatic ecosystem to control water eutrophication.

Key Words: Sediment dredging, Microsensor, Light intensity, Biogeochemistry.

INTRODUCTION

Lake eutrophication is one of the major water pollution problem in industrialized countries as well as in the developing world[1]. The lake sediments, due to benthic release of some nutrients, have a profound effect on the quality of overlying water[2,3]. During the last decade, management measures to improve water quality have been focused on the lake restoration or rehabilitation technique. Dredging, considered as one of the most radical methods of the technique, much knowledge about it and its environmental effects have been proposed accumulated[4-8]. However, dredging is no panacea and success is still variable[4,5]. Because of high costs of dredging measures, it is necessary to study the long-term effect of sediment dredging on biogeochemistry of the sediment-water interface and other affect factors prior to dredging.

In order to research the pollutants migration and transformation law in the sediment-water interface of the shallow lake, the physical-chemical properties of the sediments should be mastered in the sediment-water interface. The upper few millimeters of shallow lake sediments are also characterized by a biologically mediated rapid turnover of several organic and inorganic compounds[9]. The very narrow zonation of the biological activities and the rapid turnover make analysis within this layer difficult. Oxygen microsensors have now made it possible to measure oxygen with a high spatial and temporal resolution and such measurement have been used to

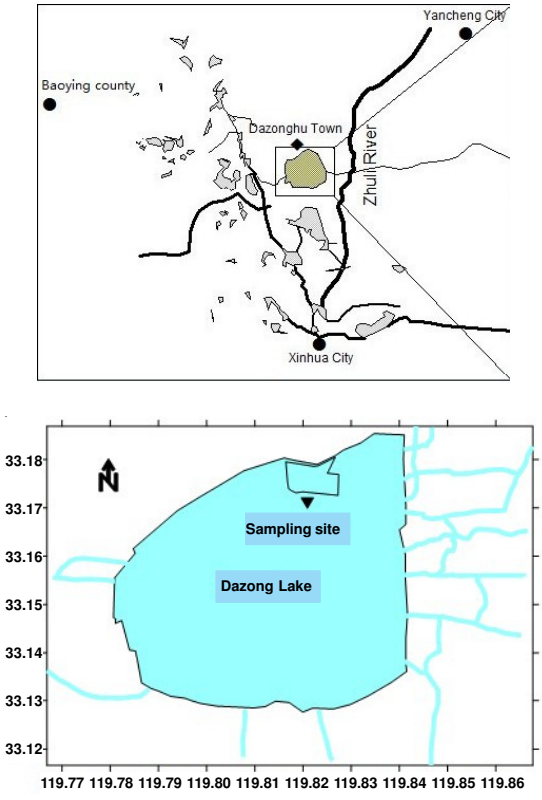

Fig. 1. Sketch map of the sampling site, Dazong Lake, Jiangsu Province of China

calculate rates of oxygen consumption and oxygen production within the surface layer of sediments[10-12]. Such applications make it possible to achieve a much more precise prediction of the location of zones of the oxygen production or consumption.

In situ microsensors have been applied to large number of benthic environments, but the technology has less been applied in the shallow lake, especially in the study of the environmental effect of lake dredging. In this study, pH, redox potential (Eh), O_2 profiles and the net rates of O_2 production and consumption at different light intensities were measured at high spatial resolution by microsensors, sediment-water microcosms for dredging simulation were conducted to understand the activity of the sediments after lake dredged, that could provide reference for evaluating the effects of the sediment dredging and discussing the mechanisms.

EXPERIMENTAL

Sampling site: The sampling site (33°10'18"N, 119°49'38"E) is located in the Dazong Lake of Jiangsu Province, China. The lake, part of the watercourse of the Lixiahe River Basin, has a total surface water area of 28 km^2 and is fairly shallow, with a mean depth of about 1.02 m. Due to the seriously enclosure culture in lakes, most of the lakes with the thick sediment in Lixiahe River Basin are at medium level of eutrophication and Dazong Lake is a typical case of them.

Laboratory microcosm experiment: Six intact sediment cores (10 cm diameter and 50-60 cm long) were collected with a gravity sampler at the sampling site on Nov. 11, 2009. The bottom of the cores was sealed with an additional rubber bung. Sediment structure was preserved carefully during sampling and transported to lab in 6 h.

In the laboratory, the overlying water was siphoned from each core. Half of the intact sediment cores were dredged up the uppermost 30 cm sediment layer as the dredged treatment and the others were undredged as the control. Undisturbed cores (control) and dredged cores (20 cm sediment and 20 cm overlying water) were incubated in a water bath that was maintained at *in situ* water temperature and left open to the atmosphere in the dark-room.

In order to study the long-term environmental effect of sediment dredging, sediment cores were incubated in the laboratory for 15 months. During the incubation, the water overlying the undredged and dredged cores was replaced by *in situ* lake water monthly. Ending of the incubation, the sediment cores were got out to the experimental analysis platform. To avoid the influence of the illumination, the sediment cores were darkened using aluminum foil.

Microsensors *in situ* measurements were carried out with a commercially available profiler (Unisense, Arhus, Denmark). Redox potential (Eh), pH and oxygen (O_2) concentrations were measured in sediment-water interface with the miniaturized Clark-type microsensors (Redox microsensor, pH microsensor and O_2 microsensor) equipped with a reference electrode. The microsensors had a tip diameter of 25 μm, a stirring sensitivity of < 1 % and a 90 % response time of 2-3 s. They were connected to a high-sensitivity picoammeter (PA2000, Unisense) that simultaneously kept the cathode polarized against the internal reference. The O_2 and pH microsensor were prepared and calibrated as described by Revsbech *et al.*[13,14]. The Eh microsensor was calibrated immediately before profile measurements using standard buffers as described in the redox microelectrode manual. The sediment cores were standing for at least 0.5 h before measurements to ensure that steady-state profiles were obtained. The microsensors were mounted on a motor-driven micromanipulator for accurate positioning and the concentration profiles in the sediment were recorded at intervals of 100 μm into the sediment. Although the technique was invasive, the tiny tips had only a small influence on structures and processes. The sediment surface was identified from a slight shift of the slope of the profiles. If optical verification was possible we always found a good agreement between optical and indirect determination of the interface.

To further indicate the influence of the illumination on the O_2 concentrations profiles in the sediment-water interface, the sediment cores were illuminated at different level light intensity for measurement. The light intensity is selected according to the diurnal cycle of which *in situ* measure from the Dazong Lake. Light intensity was measured by a quantum meter (PAM, Heinz Walz GmbH, Germany).

After the microcosm experiment on the microprofilers, the physical and chemical parameters of the overlying water and the sediment cores were determined immediately. The overlying water about 5 cm above the sediment-water interface was collected, the sediment was extruded and sliced into 2 cm intervals for upper 10 cm sediment.

Total phosphorus (TP), ortho-phosphate (PO_4^{3-}), total nitrogen (TN), ammonium nitrogen (NH_4^+) and nitrate nitrogen (NO_3^-) in the water samples were determined using an antoanalyzer (Skalar-SAN^{2+}, Skalar, Netherlands). The water turbidity was determined by a turbidimeter (2100AN, HACH, USA). Water content of sediment samples was determined by drying sediment samples at 105 ºC to the point of reaching a constant mass. Porosity of the sediment was analyzed according to the methods of Graca[15]. Loss on ignition (LOI, %) was measured by calculating the weight loss after heating sediment samples to 550 ºC for 6 h. The grain size distribution of the sediment was determined by laser particle size analyzer (LS13320, Beckman Coulter, USA).

Calculations of net consumption and production rates: As the basis for the calculation of net consumption and production rates of O_2 from the measured microprofiles we used Fick, s second law of diffusion including a production and a consumption term[16]:

$$\frac{\delta C(z,t)}{\delta t} = D_s \times \frac{\partial^2 C(z,t)}{\partial z^2} - R(z) + P(z) \quad (1)$$

where D_s is the effective sediment diffusion coefficient for O_2 and C(z,t) is the concentration at time t and depth z, R is the respiration rate, P is the production rate. The D_s was calculated from the free solution molecular diffusion coefficient (D_0) for O_2 and the sediment porostity (Ø) according to Ullman and Aller[17]:

$$D_s = Ø^2 D_0 \quad (2)$$

The D_0 for O_2 (2.104×10^{-5} cm^2/s) in freshwater at 20 ºC was refereed to the Sensor Trace PRO 3.0.2, the data analysis software of Unisense.

Assuming steady state we have:

$$\frac{\delta C(z,t)}{\delta t} = 0 \quad (3)$$

So eqn. 1 can be reduced to:

$$D_s \times \frac{\partial^2 C(z,t)}{\partial z^2} = R(z) - P(z) \quad (4)$$

Defining $A(z) = \frac{R(z) - P(z)}{D_s}$, using Euler's formula for numeric integration we find:

$$\frac{\partial C}{\partial Z_{n+1}} = \frac{\partial C}{\partial Z_n} + h \times A_n \quad (n = 1, 2, 3, ...) \quad (5)$$

where h determines the step size used for numerical integration. After further integration we have:

$$C_{n+1} = C_n + h \times \frac{\partial C}{\partial Z_n} \quad (6)$$

Substituting $\partial C/\partial Z_n$ with eqn. 5 we find:

$$C_{n+1} = C_n + h \times \left[\frac{\partial C}{\partial Z_{n-1}} + h \times A_{n-1} \right] \quad (7)$$

Using eqn. 7 we can calculate concentration profiles on the basis of net activities[18]. As a boundary condition we introduced a point below the deepest measuring point with concentration and activity equal to zero. Starting from this point we stepwise integrated upwards toward the sediment surface with h = 0.1 mm (the actually used step size during the measurement of the profile).

RESULTS AND DISCUSSION

Physical and chemical parameters of the supernatant water and the sediment cores: Physical and chemical parameters (average ± standard deviation, n = 3) of the overlying water in the sediment cores are shown in Table-1. The overlying water quality in the sediment cores was not very good, while the water quality in the original undredged sediment cores was better than that in the dredged sediment cores. Both phosphorus (P) and nitrogen (N) of the overlying water in undredged and dredged cores were exceeding local standard of surface water. Average values of total phosphorus and PO_4^{3-} in undredged cores were 0.83 and 0.15 mg/L, slight higher than that in dredged cores. However, the values of total nitrogen (TN), NH_4^+ and NO_3^- in dredged cores were much higher than that in undredged cores. It was suggested that dredging is a useful measure for controlling the phosphorus release, but not an effective way to reduce the nitrogen pollution in long-term effectiveness in study area, although a mass of total phosphorus, total nitrogen was cut down at the beginning of the dredging. The average turbidity in overlying water of the undredged sediment cores was 2.8 NTU and that in the dredged cores was 23.5 NTU, nearly 9 times higher than the undregded cores. It was estimated that the microorganism in the undredged cores was more easily to absorb the sunlight than that in dredged cores at the sediment-water surface and the surface sediment in dredged core was more easily suffered disturbance than that in undredged core.

The main physical characteristics of the original undredged and dredged sediment cores used in the laboratory incubation are shown in Fig. 2. In the upper 0-10 cm sediment layers of the undredged cores, the water content, porosity, organic matter content (calculated as LOI) and grain size generally decreased with depth. There was the same changing trend of the main physical characteristics of the dredged cores, but not obvious, especially the organic matter content and grain size. Above the 10 cm depth, all the parameters values of dredged cores were lower than that in undredged cores at the same depth. Average values of porosity in undredged and dredged cores were 87.9 and 81.7 % in the upper 2 cm, respectively. These values were used to calculate the D_s as the average values of the porosity in the sediment-water surfaces according to eqn. 2. The porosity of the undredged cores was higher than that in the dredged cores because of an increasing compaction and dehydration of sediment with depth. According to soil texture scheme from the Katschinski, for the undredged cores, the range in grain size (median volume) was from 40-14 μm, belonged to physical sand particle. For the dredged cores, the grain size ranged from 8.4-6.5 μm, belonged to physical clay particle. The different attribution of particle size would have effects on biogeochemistry in the sediment cores to some extent.

***In situ* measurements:** In May 2010, we measured a complete dataset in the original undredged and dredged sediment cores with a pH microsensor, redox potential (Eh) microsensor and O_2 microsensor under natural light condition, temperature 20 ± 3 ºC. Fig. 3 shows microprofiles of pH and Eh values in the sediment-water interface of the sediment cores. For the undredged cores, the highest pH was 8.2 and Eh was 356 mV in the overlying water. From the sediment-water interface to the 8 mm depth, pH decreased from 8.2-7.3 with depth and then kept a relatively constant value. Redox potential had a slight increase below the sediment surface firstly and then it decreased with depth from 339 mV (sediment surface) to -309 mv (13 mm depth). Compared to the undredged cores, pH and Eh had similar variation trend in the dredged cores. However, the range of depth changing from the parameters was wider than the undredged cores. In the depth of 13 mm, pH decreased to a constant value in the dredged cores, while in the depth of 8 mm, pH decreased to a constant value in the undredged cores. In the 10 mm of depth, redox state in undredged cores had a significant change that the oxidation state instantly turned to the reduction state. The depth in

TABLE-1
SUMMARY OF PHYSICAL AND CHEMICAL PARAMETERS OF THE SUPERNATANT WATER IN THE SEDIMENT CORES. VALUES INDICATE AVERAGE ± STANDARD DEVIATIONS

Sediment core	Turbidity (NTU)	TP (mg/L)	TN (mg/L)	PO_4^{3-} (mg/L)	NH_4^+ (mg/L)	NO_3^- (mg/L)
Undredged	2.8 ± 0.01	0.83 ± 0.01	1.47 ± 0.04	0.15 ± 0.03	0.13 ± 0.02	0.59 ± 0.05
Dredged	23.5 ± 0.05	0.52 ± 0.01	2.97 ± 0.07	0.05 ± 0.02	0.21 ± 0.01	0.83 ± 0.07

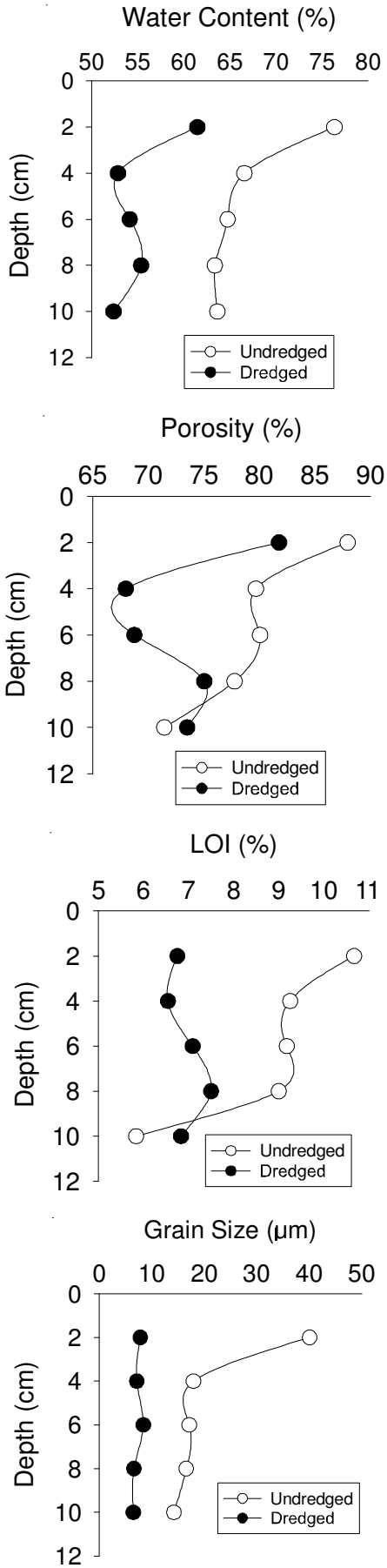

Fig. 2. Vertical profiles of sediment physical characteristics, including water content, porosity, organic matter content (calculated as loss on ignition, LOI) and grain size of the sediment cores

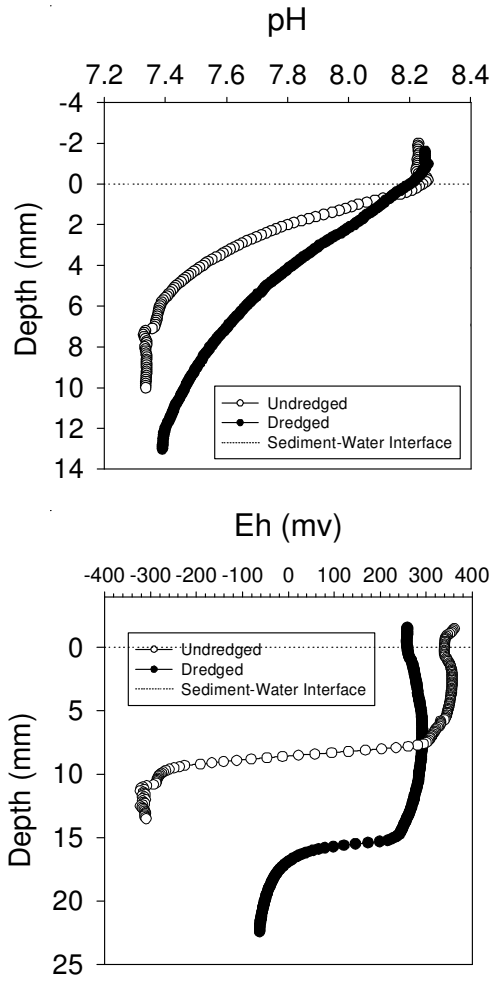

Fig. 3. Profiles of pH and Eh in the undredged and dredged sediment cores

dredged cores that the process taken place was deeper, estimated about at the 16 mm depth, although the lowest value only -60 mV. These results indicated that the dredged cores have a wider aerobic layer than the undredged ones and the undredged cores have more complex biogeochemistry activities than the dredged cores within upper few millimeters of the sediment.

The measured profiles of O_2 in the undredged cores and dredged cores are shown in Fig. 4, together with the calculated net rates of O_2 production and consumption in the sediment cores. The O_2 was produced by photosynthetic activity from the microorganism inhibited the sediment surface and consumed by the respiration and diffusion. The O_2 concentrations in the overlying water of the undredged and dredged cores were *ca.* 240 and 250 μM, respectively. O_2 fluctuated in the overlying water near the sediment surface of undredged cores due to the microbial activities, but in the dredged cores, O_2 only had a slight increasing above the surface. And then, O_2 decreased to anaerobic state with the depth in the sediment both in the undredged cores and dredged cores. O_2 penetrated 5.7 mm into the undredged sediment cores, less than half deep of the dredged sediment cores (12.7 mm). It was probably due to the different grain size particle attribution of the sediment leading to the different diffusion rate. The photosynthetic activity was detected at the upper 1.5 mm of sediment surface in undredged cores, the net rate value reached to maximal (0.23 nmol/cm^3/s)

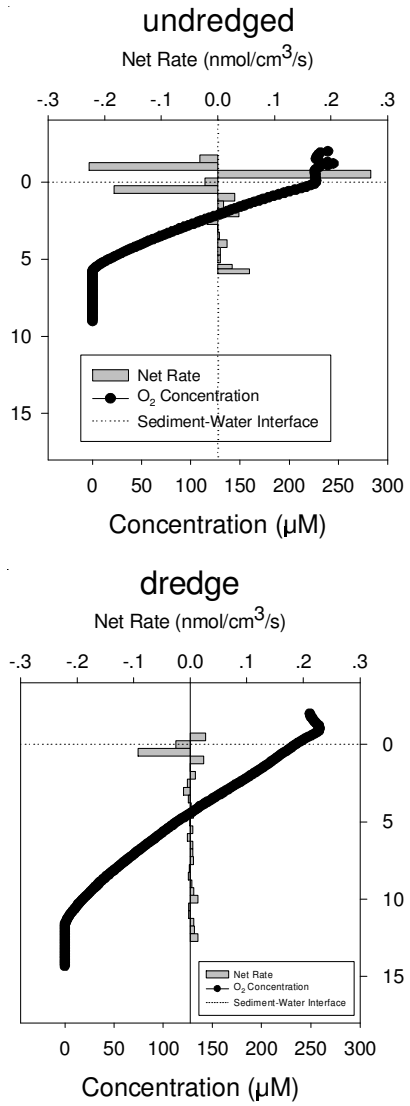

Fig. 4. Steady-state O_2 concentration profiles and calculated net rates of O_2 production and consumption in the undredged and dredged sediment cores. Positive and negative values indicate O_2 consumption and O_2 production rates, respectively

at the upper 1 mm. The O_2 production rate was 0.18 nmol/cm^3/s at the 0.5 mm depth in the undredged cores. In the deeper layers of the sediment cores, the photosynthetic activities were disappeared and the consumption increased with the depth. Until to the 5.8 mm depth, the consumption rate approached 0.06 nmol/cm^3/s at the bottom of the aerobic layer. The fluctuated net rate indicated that there was abundant in microbe which can make photosynthesis or not at the sediment-water interface of the undredged cores. Whereas for the dredged cores, the photosynthetic activities were detected just at the sediment surface and the maximum production rate was only 0.1 nmol/cm^3/s at the 0.5-mm depth, which was less than half of that in the undredged cores. The lower net rate in the dredged cores indicated that there were few microbes at the sediment surface. Therefore, we estimated from the results that the microbial community structure can not be restored in 15 months of incubation after lake dredged.

Effect of light intensities on O_2 concentration profiles and photosynthesis in the sediment: Many physical and chemical factors affect O_2 distribution in the sediment in nature and the O_2 concentration affected the microzonation of O_2 production, respiration, denitrification and so on[19]. In order to figure out the influence of sunlight to the long-term effect of sediment dredging on biogeochemistry, the effect of light intensities on O_2 concentration profiles and photosynthesis in the sediment was investigated. Three different light intensities were chose by the filed measurement of the diurnal cycle of sunlight intensities on the surface of the sediment (Fig. 5). The light intensity increased as the sun rose and reached its maximum just at noon on sunny days. The light intensity then gradually decreased during the afternoon. While on raining days, the light intensity kept only *ca.* 1000 μEinst/m^2/s, great less lowly than the light intensity on sunny day. According to the study of Nakamura *et al.*[20], the light intensities on cloudy days showed the same trend, but were less than half of the light intensities on sunny days. From the research of Revsbech *et al.*[14] on the photosynthesis in the microbial mat, the efficiency of the photosynthesis was highest at low light intensities up to about 120 μEinst/m^2/s and the light intensities at 1670 μEinst/m^2/s would be approached photosaturation in the microbial mat. Considering above factors, three different light intensities were chose at 0.8, 300 and 1030 μEinst/m^2/s, finally.

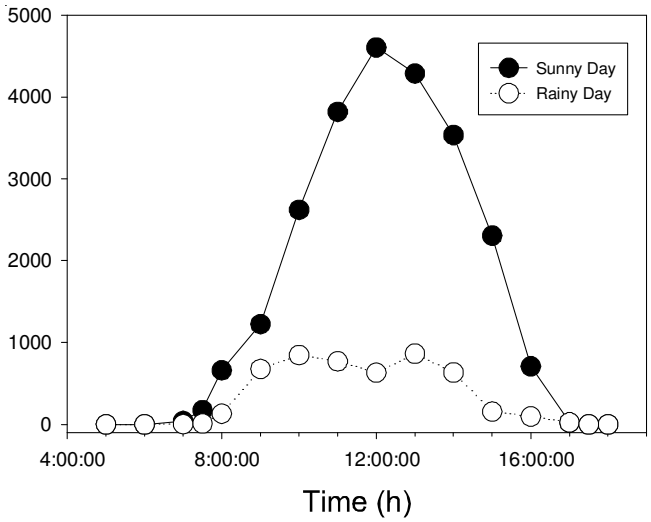

Fig. 5. Diurnal cycle of sunlight intensity in the open air in Jiangsu Province of China. The measurements were conducted in May 2010

Mean steady-state O_2 concentration profiles measured at three different light intensities and calculated net rates of O_2 production and consumption in the undredged and dredged sediment cores are shown in Fig. 6, respectively. The oxygen microsensor was introduced into the same point in the sediment surface for each determination. The photosynthetic activities were detected just on the sediment surfaces of the undredged and dredged cores when the light intensity was at 0.8 μEinst/m^2/s. As light intensity increased, net rate of O_2 production in sediment-water interface increased, resulting in increases in maximal O_2 concentration in the overlying water. The maximum concentrations of O_2 in the bulk liquid of the undredged and dredged cores were 292 and 323 μM at 1030 μEinst/m^2/s, respectively. The O_2 concentrations in the overlying water of the dredged core even had been oversaturation. A comparison of the net rates of O_2 consumption with depth showed that most of the O_2 consumption occurs just below the net O_2

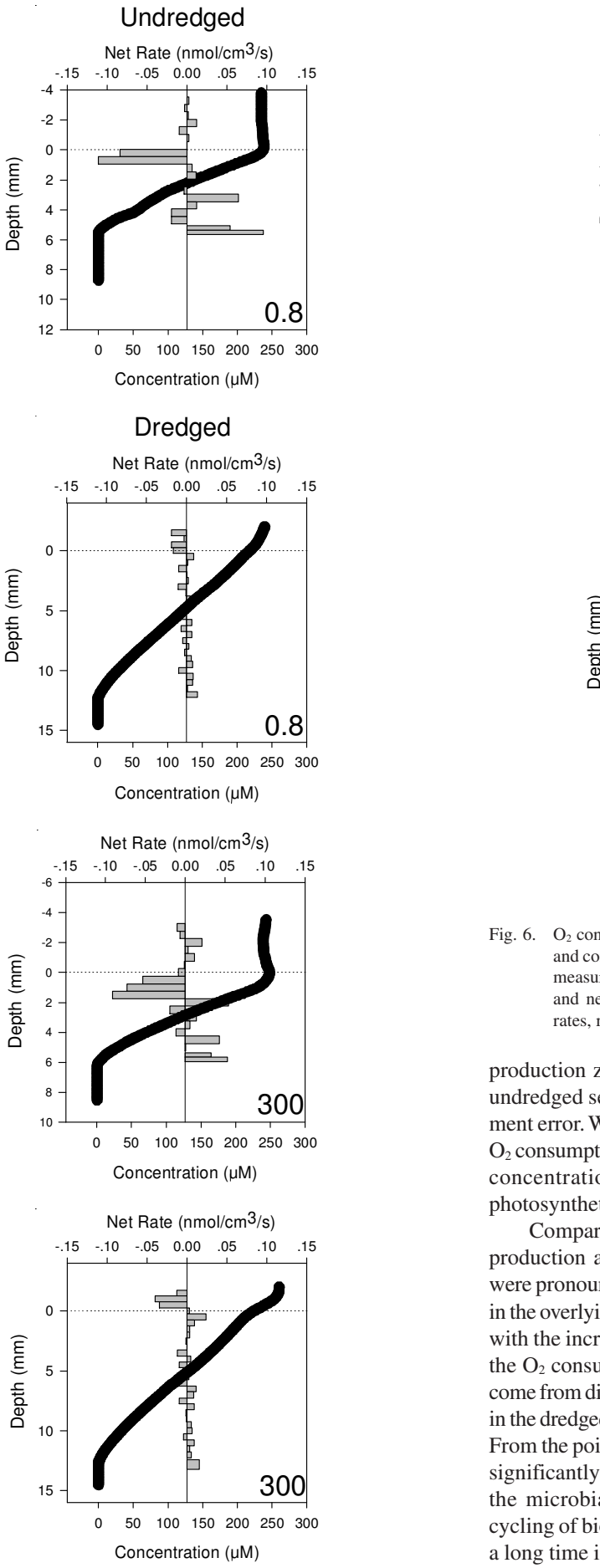

Fig. 6. O_2 concentration profiles and calculated net rates of O_2 production and consumption in the sediment cores. The O_2 concentrations were measured at light intensities of 0.8, 300, 1030 μEinst/m^2/s. Positive and negative values indicate O_2 consumption and O_2 production rates, respectively

production zone. There were some catastrophe points in the undredged sediment at 0.8 μEinst/m^2/s because of the experiment error. With increasing light intensity, the mean net rate of O_2 consumption increased. This was probably due to increasing concentrations of O_2 and organic carbon provided from photosynthetic zone in this zone.

Compared with the undredged cores, the net rates of O_2 production and consumption in the dredged sediment cores were pronounce lower at the same depth and O_2 concentrations in the overlying water of the dredged cores had a larger variation with the increasing light intensities. The results indicated that the O_2 consumption in the dredged sediment cores primarily come from diffusion. The fragile microbial community structure in the dredged cores made them more vulnerable to disturbance. From the point of view of microbial action, sediment dredging significantly reduced benthic diversity and density. Moreover, the microbial community could not be recovered and the cycling of biogenic elements in sediment would be affected in a long time in the future. Consequently, it suggested that lake

dredging may be not a satisfied measure for rehabilitating the aquatic ecosystem to control water eutrophication.

Conclusion

Despite that the *in situ* conditions could not be completely simulated in the laboratory, the experimental results indicated that dredging the uppermost 30 cm sediment layer could effectively control the phosphorus release, but not reduce the nitrogen pollution in long-term effectiveness. Profiles of pH, Eh and O_2 were determined in the sediment-water interfaces of the undredged and dredged cores at high spatial resolution by microsensors. The net rates of O_2 production and consumption in the sediment cores were also measured at different light intensities. By use of the microelectrode technique it was possible to get the detailed information about the biogeochemical processes. Comparisons of the microprofiles in undredged and dredged cores showed that the undredged cores have more complex biogeochemistry activities than the dredged cores within upper few millimeters of the sediment, although the latter have much more deeper O_2 penetration depth. The dredged cores were vulnerable to disturbance and the microbial community of surface sediment was hard to recover in a long time. It would affect the cycling of biogenic elements in sediment. Consequently, differ from the perspective of Zhong[21], we considered that lake dredging may be not a satisfied measure for rehabilitating the aquatic ecosystem to control water eutrophication.

ACKNOWLEDGEMENTS

The authors thanks to our colleagues, Z.J. Fang, H.Q. Gao, L. Xu, X.L. Yao, F. Yan, L.Y. Chen and L.T. Wang for their assistance. The study was supported by the National Natural Science Foundation of China (50879018), Graduate Student Scientific Research Innovation Plan of Jiangsu Province (CXZZ11_0436).

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