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Temporal changes in wetland plant communities with decades of cumulative water pollution in two plateau lakes in China's Yunnan Province

WANG Si-hai[1,2,3] http://orcid.org/0000-0002-4143-4919; e-mail: wangsh6688@163.com

WU Chao[2] http://orcid.org/0000-0002-8724-1434; e-mail: 1073895932@qq.com

XIAO De-rong[2] http://orcid.org/0000-0003-2311-4716; e-mail: xiaoderong1@163.com

WANG Juan[2,4*] http://orcid.org/0000-0002-2868-9175; e-mail: schima@163.com

CHENG Xi-ping[5] http://orcid.org/0000-0002-5461-6527; e-mail: xipingcheng2012@163.com

GUO Fang-bin[5] http://orcid.org/0000-0002-5540-5836; e-mail: guodelinlin@163.com

** Corresponding author*

1 Key Laboratory of the State Forestry Administration on Conservation of Rare, Endangered and Endemic Forest Plants, Yunnan Academy of Forestry, Kunming 650201, China

2 National Plateau Wetlands Research Center, Southwest Forestry University, Kunming 650224, China

3 State Key laboratory of Phytochemistry and Plant Resources in West China, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming 650201, China

4 Yunnan Provincial Key Laboratory of Cultivation and Exploitation of Forest Plants, Yunnan Academy of Forestry, Kunming 650201, China

5 Faculty of Ecotourism, Southwest Forestry University, Kunming 650224, China

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Abstract: Wetland plant communities in the plateau lakes of Yunnan Province, China, have decreased significantly over the past decades. To better understand this degradation, we analyzed the processes and characteristics of changes in wetland plant communities in two of the largest lakes in Yunnan Province, Dianchi and Erhai lakes. We collected records of native and alien plant communities in the two lakes from literature published from the 1950s to current period. We calculated plant community types and their area in some historical periods when related data were reported, and analyzed the relationship between changes in plant communities and water pollution. In Dianchi Lake, 12 community types of native plant communities, covering over 80% of the surface in the 1950s and 1960s, were reduced to four types covering 2.4% by the late 2000s. Alien plant communities started to appear in the lake in the late 1970s, and have since come to cover 4.9% of the lake surface, thereby becoming dominant. In Erhai Lake, 16 community types of native plant communities, covering 47.1% of the lake surface in the late 1970s, declined to 10 community types, covering 9.3% of the surface, by the late 2000s. Alien plant communities appeared in the middle 1980s, and at present cover 0.7% of the surface area. It was indicated that changes in plant communities were significant related to water eutrophication. The area occupied by native and alien plant communities was, respectively, negatively and

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positively related to the content of nutrients in water. This showed lacustrine pollution played an important role in native plant loss and alien plant invasion in the two plateau lakes.

Keywords: Dianchi Lake; Erhai Lake; Wetland plant community; Eutrophication; Alien plant

Introduction

Plateau lakes are water towers for downstream river basins, but they are ecologically very fragile and prone to human disturbances, for example, land reclamation and cumulative pollution, in terms of the lacustrine environment due to the geological formations and patterns of human habitation. Most of the lakes in Yunnan Province in Southwest China are sag ponds formed by land sinking along fault lines. In general the lakes are surrounded by mountains and forest, and have relatively steady water levels. These lakes are rich in plant communities and biodiversity (Yang et al. 2008). Around some of these large and fertile lakes, humans have been living for over 2000 years, and hence have been affecting the lacustrine environment. However, the effects of early human habitation, mostly resulting from traditional and small-scale agricultural activities, were minimal in comparison to the effects in recent decades, which are caused by industrial pollution and urban development. Lacustrine environments have experienced different magnitudes of change, and biodiversity has correspondingly degraded over the past decades (Wang et al. 2013). Plant communities are the basis of maintaining the structures and functions of plateau lakes (Li et al. 2014) and their changes may be subject to the dynamics in the lacustrine environment. The cumulative effects of the lacustrine environment on plant communities are rarely immediate and often require long-term regular monitoring to detect the changes. Processes of long-term changes (several decades) in the plant communities were rarely known owing to the lack of regular monitoring. This paper endeavors to study the processes and causes of plant community changes resulting from the cumulative impact of water pollution based on reviewing and analysis of historical data in the past decades.

Dianchi and Erhai lakes are the two largest plateau lakes in Yunnan province. Their lacustrine environment has rapidly changed in recent decades, most likely owing to human disturbance. In the 1950s there was still a high diversity of species, and many types of stable plant communities existed (Li et al. 1963; Dai 1986; Li and Shang 1989). After 1970s, great changes occurred in the species composition and community structure as a result of the deterioration of the lacustrine environment (Yu et al. 2000; Li et al. 2011; Lu et al. 2012; Xiang et al. 2013; Wang et al. 2013). Previous studies on the two lakes focused mainly on the short-term (several years) changes of plant composition and community structure. It is unknown how the lacustrine environment affects changes in plant communities. In this paper, we summarize the distribution patterns of plant communities and the changing water conditions from 1950s to 2000s, and analyze the relationship of plant community change with regard to water pollution.

1 Methods

1.1 Study sites

The drainage basin of Dianchi Lake has a northern subtropical monsoon climate with an annual rainfall of about 1000 mm. More than 20 large and small rivers run into the lake, of which, Panlong River, the largest and longest, traverses through Kunming City, the capital of Yunnan Province. Similarly, Erhai Lake is located in the subtropical monsoon climate zone with an annual precipitation of 1060 mm and there are about 25 main rivulets injecting into the lake. The population has multiplied ten-fold in Dianchi Lake basin (Lian 2011), and three-fold in the Erhai Lake basin (Liao & Zhou 1993; Liao et al. 2003) in the last 60 years. Rapid population growth was accompanied by fast agricultural expansion and intensification, industrialization and urbanization, posing enormous pressure on the water quality in both lakes. Table 1 gives brief information about the two lakes (Wang et al. 2013; Fu et al. 2013).

1.2 Data collection

We collected records of native and alien plant communities from literature from the 1950s to the

present (Table 2). The data for Erhai Lake were only available from the 1970s. The maps of community distribution from previous publications were scanned, imported into, and rectified in Auto CAD 2013. All maps of different scales from literature were scaled up or down so as to match the boundary of all maps. In the historical data of plant community distribution, the areas of individual plant communities in the maps were represented by the distribution of a single dominant species, we thus adopted the same mapping scheme. The boundary of each plant community was then redrawn on the basis of the background distribution maps and characteristics of plant distribution, and their areas were computed in the graphic software. We focused on the temporal changes of the plant communities represented by the single dominant species (Appendixes 1, 2) in different time periods, but companions of individual communities were not considered, as the communities are mostly dominated by single species.

As our data were from literatures published in various journals, rather than from direct long-term regular monitoring, the criteria for assessing community area were not consistent, and deviation existed among different publications. Furthermore, we redrew the boundary of the plant communities by graphic software based on small-scale illustration of community distribution published in literatures, so area measurement was not precise. In contrast to long-term and large-amplitude changes in plant communities, the effect of this inaccuracy was acceptable on our conclusion. Appendixes 1 and 2 show the estimated areas of plant communities over the past decades. In certain time periods, the areas of some communities were non-existent as the researchers at that time had not assessed it as reaching the level of a plant community due to scattered or insignificant distribution area.

We chose the easily available data of water pollution, the total nitrogen (TN) and total phosphorus (TP), as the indicators of water quality. Historical data of water quality were acquired from the collected literature (Table 2). Process of water pollution, and content of TN and TP were showed in Appendix 3. These water pollution data were matched with area of plant communities in the same period, in order to correlate the analysis.

1.3 Data analysis

We summed up the area of each plant community and the number of community types in each period (Appendixes 1 and 2) in which distribution of plant communities was reported by literature. Four quantified indicators were used to assess (1) the total area of all plant communities types; (2) changes in the number of plant community types; (3) the correlation coefficient between total area of all native plant community types, and TN and TP; (4) the correlation coefficient between total area of all alien plant community types, and TN and TP; All statistical analyses were conducted in Microsoft Excel 2010.

Table 1 Characteristics of Dianchi and Erhai lakes

Character	Dianchi Lake	Erhai Lake
Co-ordinates	24°29'-25°28' N, 102°29'-103°01' E	25°35'-25°58' N, 100°05'-100°17'E
River basin	Yangtze River	Mekong River
Lake-surface area	297.9 km^2	249.8 km^2
Catchment area	2920 km^2	2565 km^2
Lake elevation	1886 m	1974 m
Average water depth	4.4 m	10.5 m
Water volume	1.17×10^9 m^3	2.88×10^9 m^3

Table 2 Literature assessed to estimate community distribution and water quality

Type	Dianchi Lake	Erhai Lake
Community distribution	Ley et al. 1963; Li 1980; Dai 1985, 1986; Zhao et al. 1999; Yu 2000; Shen et al. 2010; Xiang et al. 2013; Xie et al. 2013	Ley et al. 1963; Li 1980, 1989; Li and Shang 1989; Qian 1989; Dai 1989; Dong et al. 1996; Hu et al. 2005; Li et al. 2001; Fu et al. 2013
Water quality	Ley et al. 1963; Wang et al. 2004; Su 2011; Lu et al. 2012	Wang et al. 1999; Li 2001; Ni 2003; Zhao 2003; Han 2005; Fu et al. 2013

2 Results

2.1 Changes in the area of native and alien plant communities

Most of the surface area of Dianchi Lake was covered by native plant communities in the 1950s and 1960s, reaching over 80%. In the late 1970s, the coverage of plant communities rapidly shrank to 20.9% of the lake surface. In the late 2000s, native plant communities covered 2.4% of the lake surface only (Figure 1). In Erhai Lake, 47.1% of the lake surface was covered by native plant communities in the late 1970s. The coverage subsequently decreased to 9.3% in the late 2000s (Figure 1). Alien plant communities were initially recorded in Dianchi and Erhai Lake in the late 1970s and the middle 1980s, respectively. The spread of these alien communities was rapid. In the late 2000s, 4.9% of the surface of Dianchi Lake was covered by alien communities, equaling twice the area of native communities, while in Erhai Lake only 0.7% of its surface was covered by alien communities (Figure 1).

2.2 Changes in the types of plant communities

The types of plant communities were reduced in recent decades. In Dianchi Lake there were 12 and 13 types of native plant communities respectively in the 1950s and the 1960s, and 12 types still remained in the late 1970s, while the area of communities substantially decreased during the 1970s (Figure 1 & Figure 2), and the number of community types had decreased to 4 by the late 2000s. In Erhai Lake the process of degradation followed the same pattern, with the number of community types decreasing from 16 in the late 1970s to 10 in the late 2000s (Figure 2). The types of alien plant communities increased from one in the late 1970s to four in the late 2000s in Dianchi

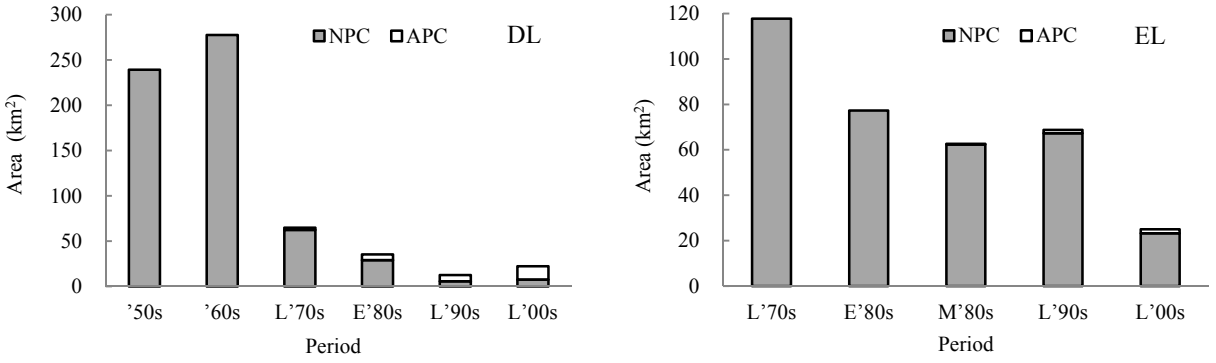

Figure 1 Changes in the total area of vascular plant communities in Dianchi Lake (DL) and Erhai Lake (EL) over the past decades. NPC, Native plant communities; APC, Alien plant communities; '50s, 1950s; L'70s, the late 1970s; E'80s, the early 1980s; M'80s, the middle 1980s, and so forth.

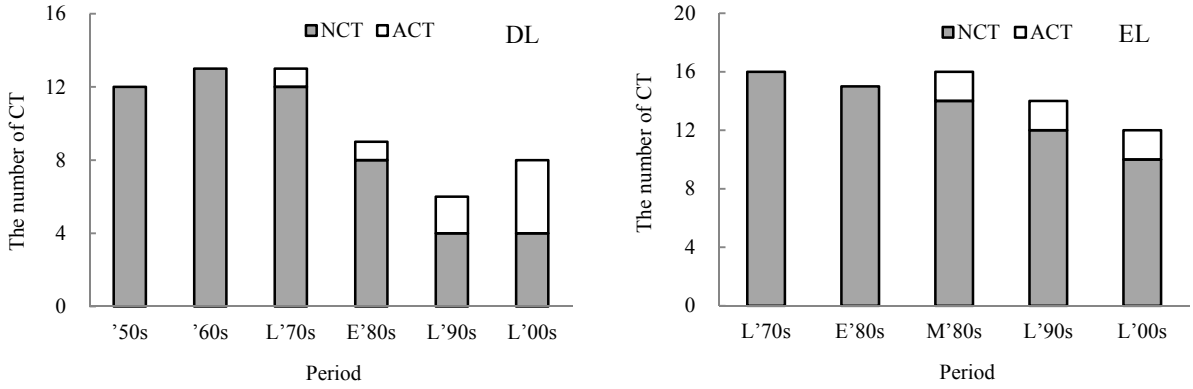

Figure 2 Changes in the number of the vascular plant community types in Dianchi Lake (DL) and Erhai Lake (EL) over the past decades. NCT, native plant community type; ACT, alien plant community types; CT, community types; '50s, 1950s; L'70s, the late 1970s; E'80s, the early 1980s; M'80s, the middle 1980s, and so forth.

Lake, while in Erhai Lake only two alien communities were present beginning from the middle 1980s (Figure 2). Even though there were few alien plants at present, these invasive species had occupied much of the lake surface (Figure 1), and had posed serious ecological impacts on lakes.

2.3 Relationship between the area of native plant communities and nutrient contents s in water

The area of native plant communities was significantly affected by nutrient load (TN and TP)

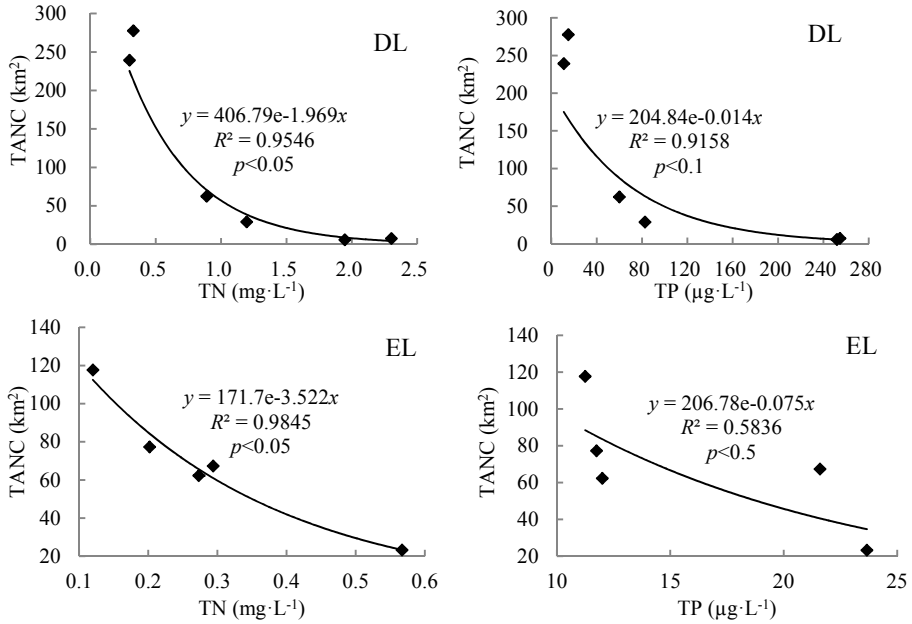

Figure 3 Relationship between the area of native plant communities and the content of nutrients in water in Dianchi Lake (DL) and Erhai Lake (EL). TANC, total area of native plant communities; TN, total nitrogen; TP, total phosphorus.

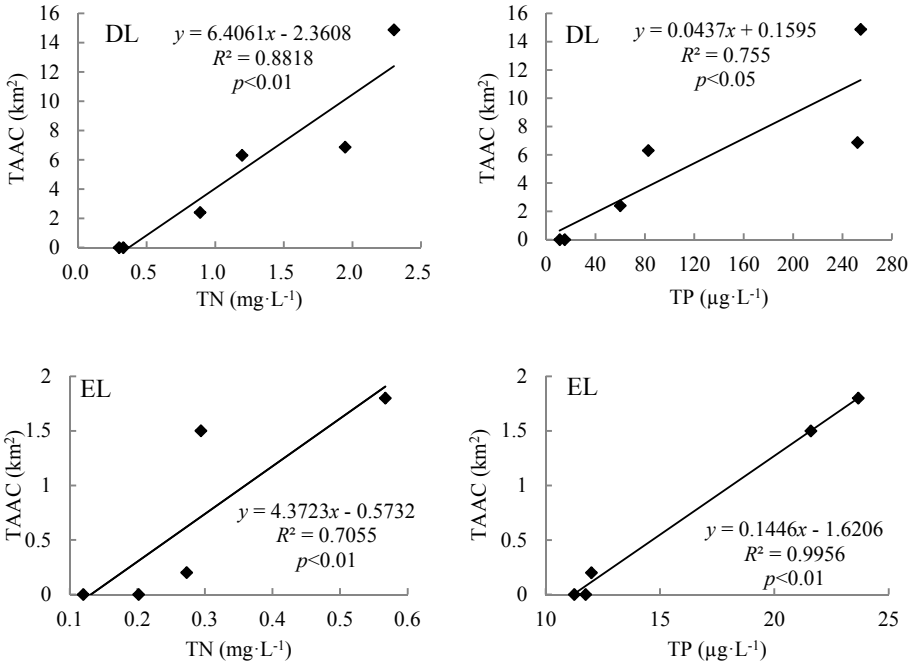

Figure 4 Relationship between the area of alien plant communities and the content of nutrients in water in Dianchi Lake (DL) and Erhai Lake (EL). TAAC, total area of alien plant communities; TN, total nitrogen; TP, total phosphorus.

in the two lakes. In Dianchi Lake the negative correlation was significant for both TN (R^2=0.9546, p<0.05) and TP (R^2=0.9158, p<0.1); similarly, in Erhai Lake negative correlation occurred with TN (R^2=0.9845, p<0.05) and TP (R^2=0.5836, p<0.5) (Figure 3).

2.4 Relationship between the area of alien plant communities and content of nutrients

The spread of alien plant communities was positively correlated with the nutrient load (TN and TP) based on the observation of the time span of 30-40 years. In Dianchi Lake the area covered by communities was strongly correlated with TN (R^2=0.8818, p<0.01), and with TP (R^2=0.755, p<0.05; similarly, in Erhai Lake, the area is strongly correlated with TN and TP (R^2=0.7055 and R^2=0.9956 respectively, p<0.01) (Figure 4).

3 Discussion

3.1 Impacts of cumulative pollution on native plant communities

Many abiotic and biotic factors interact to influence the performance and abundance of species in the plant community. Anthropogenic pollutant enrichment is a specific stressor on wetland systems that alter these abiotic and biotic interactions, potentially altering species composition (Mahaney et al. 2005; Porter et al. 2013). Dianchi and Erhai Lake experienced a large amount of accumulating pollutant input over the past decades. Dianchi Lake has undergone a process of rapid eutrophication since the 1960s, deteriorating from being oligotrophic to mesotrophic by the 1970s, and reaching a hypertrophication level by the middle 1990s, which continued until today (Wang et al. 2013). Similarly, Erhai Lake received increasing nutrient input since the middle 1970s, and became mesotrophic by the late 1980s. Subsequently, eutrophication continued to worsen, and while Erhai Lake is still mesotrophic, it is very close to becoming eutrophic (Wang et al. 2013). A significant negative correlation between lake area covered by plant communities, and the nutrient load of the water implies eutrophication is a key factor for shrinking native plant communities. Area and types of native plant communities diminished rapidly during the period in which the two lakes changed from mesotrophic to eutrophic. This perhaps indicates that it was difficult for plants living in oligotrophic water to cope with a eutrophic environment. For example, *Ottelia acuminata* covered 40% of the Dianchi Lake surface in the 1960s, but disappeared completely in the late 1970s (Dai 1986). The areas of native plant communities shrunk rapidly from 1960s to 1970s in Dianchi Lake from over 80% to 20.9%, and from 1970s to 1980s in Erhai Lake from 47.1% to 24.9%, whereas the types of native plant communities remained relatively stable, maintaining at 12-13 types in Dianchi Lake, and 14 to 16 types in Erhai Lake, during the corresponding time periods. The drastic loss of large plant community areas preceded the rapid disappearance of plant community types. The period of imminent disappearance of a large number of plant communities is critical in terms of interventions for plant community restoration, as it would be very difficult to restore the plant community after it has disappeared completely.

3.2 Role of alien plants in deteriorating lacustrine environment

Wetland is extremely vulnerable to plant invasions. Many wetland invaders form monotypes, which alter habitat structure, reduce biodiversity, disrupt nutrient cycling and productivity, and modify food webs (Zedler & Kercher 2004). Human impact on global nutrient cycles can benefit invasive species; many native plant communities are susceptible to invasion by undesirable species under elevated nutrients (Ostertag & Verville 2002; Perry et al. 2004). Increased nutrient availability may change the outcome of competitive interactions to favor invaders, resulting in their rapid spread (Kettenring et al. 2011). Pollution-tolerant alien plants, e.g. *Eichhornia crassipes*, *Alternanthera philoxeroides,* and *Pistia stratiotes,* could better adapt to eutrophic water, so these alien plants could quickly increase in abundance in the two lakes since the 1970s. The area of their spread had significant correlation with water pollution (Figure 1 & Figure 4). The area of alien plant communities

has surpassed that of native plant communities in Dianchi Lake (Figure 1), and alien plants have become dominant. Nutrient inflow contributed to invasion success, and the expansion of invasive plants further suppressed the native species (Currie et al. 2013). This showed lacustrine pollution played an important role for these pollution-tolerant alien plant species in invasive success.

3.3 Possible trend of change in plant community

China has witnessed rapid economic growth driven by industrialization and urbanization since the 1950s, especially since the 1970s. Accompanying this fast development, eutrophication has become an ubiquitous problem for lakes in China (Jin et al. 1990; Xiong et al. 2010). Such a trend of degrading lacustrine ecosystems was paid more attention under the pressure of water pollution. It is more difficult to control the pollution of plateau lakes with smaller catchment area and long cycle of water replacement in the event of increasing water pollution. Great changes (lacustrine eutrophication, extinction of native plants and increasing abundance of alien plants) have occurred in Dianchi Lake in the recent five decades. With the deteriorating water quality, it can be expected that alien plant species will continue to increase in abundance in Dianchi Lake and the coverage of their respective communities will further expand.

Although Erhai Lake has remained mesotrophic until today, the water quality is gradually deteriorating. If this problem is not dealt with in time, Erhai Lake will likely face the same destiny as Dianchi Lake, and alien plant species will come to dominate the flora in the lake.

4 Conclusions

In both investigated lakes, the surface area covered by native plant communities shrank rapidly over the recent three decades. Furthermore, many native plant community types were lost, while alien plant species became more abundant rapidly. At the date of publication, alien plant species have mostly displaced native species and have become the dominant flora in Dianchi Lake.

Changes in plant communities were more drastic in Dianchi Lake than in Erhai Lake, which was probably due to differences in water pollution levels of the two lakes. Changes in plant communities have significant correlation with water pollution. The surface area covered by native plants in the two lakes is negatively correlated with the eutrophication level, while the surface area covered by alien species is significantly positively correlated.

Considering the ongoing deterioration of the environmental conditions of the two lakes, we have to assume that native plant will continue to decrease, and that alien species will continue to expand their area of coverage in the two lakes. Erhai Lake is under serious threat of alien plant, which in the worst case scenario will eventually dominate the lake in the future.

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