

Purification efficiency of two ecotypes of wetland plants on subtropical eutrophic lakes in China

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Research Article

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Abstract

The accelerated eutrophication rate of (sub)tropical lakes is a major environmental problem. Constructed wetlands are considered as an effective method to purify water bodies. However, the removal rate of nitrogen (N), phosphorus (P) and other nutrients by wetland vegetation is quite different, and the continuous observation of plants and water ecosystems is required. In this study, the growth curves of two subtropical wetland plants, *Phragmites australis* and *Zizania caduciflora*, and their absorption effects on N and P in constructed wetlands were studied. The results showed that the growth curves of the two wetland plants were similar, reaching the biomass peak in July to August, and the cumulative absorption of N and P by plants had the same trend with the change of biomass. The N and P concentration of plants reached the peak in March to April, with higher concentration in *P.australis* than that of *Z.latifolia*. At the end of the growing season, i.e. around October 20, the accumulated absorption of N and P by plants reached the maximum, which was the optimal time for harvest of subtropical wetland plants. Thereafter, the residues of plant litter entered the water, causing the recovery of N and P concentration in the water body, therefore affected the purification function of wetland. There is a strong correlation between the water purification efficiency and plant growth. With the increase of biomass, N and P accumulation in *P.australis* and *Z.latifolia*, the N, P content and chemical oxygen demand (COD) in the water of wetland showed a significant decreasing trend. The removal rates of N, P, COD and suspended substance (SS) in the constructed wetlands with *P.australis* and *Z.latifolia* as the main plants were 95%, 96%, 82% and 86%, respectively. In general, the purification capacity of *P.australis* is slightly higher than that of *Z.latifolia* and precipitation had positive effects on the pollutants concentration of wetland water. The results provide scientific basis for plant selection and management of subtropical constructed wetlands.

1. Introduction

Constructed wetlands are widely used in ecological restoration and environmental improvement. The effect of wetland on water purification is one of the important functions of wetlands. There are lots of experimental studies on the removal effect and mechanism of nitrogen and phosphorus in water by wetland plants (Zhuang et al. 2019; Tang et al. 2020; Wang et al. 2022). Different wetland plants may have divergent purification effects. Constructing a stable wetland plant community can improve the purification effect, while the climate factors will also affect the removal rate of pollutants (Hickey et al. 2018; Engida et al. 2020; Varma et al. 2021). The mechanism of wetland purification by plants is mainly in four aspects. The first is the physical blocking effect, which leads to the sedimentation of particles, changes of the solute movement and pathways (Jesus et al. 2018). Second, plants can change the dissolved oxygen (DO) content in water because the photosynthesis of submerged plants can directly increase DO in water while the emerged plants transport oxygen produced by leaves to roots through the rhizome ventilation tissues, and the oxygen nearby roots can be monitored by high-precision instruments (Pedersen, Colmer & Sand-Jensen 2013). Recent studies found that different plants have the different oxygen secretion intensities, i.e., *P.australis* > cattail > yarrow > cress > lotus (Du et al. 2020). As affected

by plant photosynthesis and respiration, the DO concentration in water changed periodically during day and night, and thus leading to the variations of aerobic and anaerobic microsites in the sediment, which is beneficial to the progress of nitrification and denitrification, and the removal of nitrogen in the wetland (Pedersen, Colmer & Sand-Jensen 2013; Jesus et al. 2018). Third, the root exudates were released during the plant growth and they provide microorganisms with a metabolic energy "carbon source" (Philippot et al. 2013), and the root environment has become a habitat for a large number of microorganisms growth and reproduction, and accelerates the organic degradation and consumption of nutrients (Garcia et al. 2010). Finally, plant growth absorbs nutrients from aquatic system (Wang et al. 2014).

Generally, the purification efficiency by constructed wetlands depends on the composition and diversity of wetland plants as well as the regional climate conditions. For example, Jiang et al. (2004) find that 17 plants accumulations of nitrogen and phosphorus ranged from 2.10 to 24.48 g m⁻² and from 0.23 to 1.95 g m⁻², respectively; Liu et al. (2015) find that *Canna indica* removal rates of TN and TP reached 29.61% and 74.7%, respectively. Yue et al. (2012) using *S. validus*, *P. australis* and *Z. latifolia* to remove nitrogen, the sewage N removal rates were 86.59%, 76.32% and 74.83%; the rates of N uptake were 23.81%, 8.55% and 11.30%; the conductivities were 1.136, 2.214 and 1.413; and the ratios of MDA were 0.962, 1.629 and 2.06. *S. validus* appeared to be most efficient in both of purification and stress resistance. Therefore, plant species and composition were the key factors determining the removal capacity of N and P pollutant of wetlands.

There are more than 6,700 species of wetland plants in the world, but only a few species have been used in wetland and have the purification effect. The plants of *P. australis* and *Z. caduciflora* are emerged plants that commonly grown in lakes, rivers and wetlands (Rodriguez & Brisson 2015; Zhang et al. 2018; Zheng et al. 2019; Wang et al. 2021). *P. australis* is a perennial aquatic or wet tall grass that grows beside the irrigation ditches, rivers, etc (Rodriguez & Brisson 2015). and it is tall and have well-developed creeping rhizomes underground. The stems of *P. australis* are erect, 1 to 3 meters high, with long, sturdy stoloniferous rhizomes, mainly rhizome propagation, extremely resistant to nitrogen, phosphorus and organic pollutants in water, and can also be found on coastal beaches and inland of saline soil (Wang et al. 2021). It has been found to be suitable for a humid ecological environment, and the tolerance to the pollutions increased as the plant grows (Hao, Huo & Wu 2017). *Z. caduciflora* is a perennial shallow herb of the family *Poaceae*, with stoloniferous rhizomes. The culm is tall and erect, 1–2 meters high. The ligule is membranous, about 1.5 cm long, with a pointed tip and the leaves are flat and broad, 50–90 cm long and 15–30 mm wide. It is a thermophilic plant and the growth temperature is 10–25°C, with no resistance to cold and high temperature and drought (Lu, Zhang & Cui 2010; Qiao 2019). Many studies have shown that *Z. caduciflora* has a strong absorption effect on nitrogen and phosphorus in sewage (Ge et al. 2011; Wu, Yu & Wang 2019). Under the premise of regular harvesting, it can directly remove nitrogen and phosphorus, and it has the promoting effects on restoring riparian vegetation community and improving the biodiversity of the riparian zones (Lu, Zhang & Cui 2010).

Dianchi Lake is the largest freshwater lake in the Yun-Gui Plateau and Southwest China. It is known as the "Pearl of the Plateau" and is of great significance to maintaining the urban climate environment, water

resources security, and social and economic development. Due to its superior climate and geographical conditions, the Dianchi Lake Basin has transformed traditional agriculture into intensive agriculture and facility agriculture since the 1980s (Wang et al. 2017), resulting in the continuous increase in the amount of chemical fertilizer application, which has become the most serious and eutrophication in China except for Taihu Lake (Wang et al. 2016; Wang & Yang 2021). On the other hand, the semi-closed structure of Dianchi Lake and the long exchange cycle of the inflowing rivers lead to long retention time of water pollutants and aggravate the eutrophication of the water (Zheng et al. 2019). Nitrogen and phosphorus are not only the main nutrients that cause eutrophication, but also the limiting factor of eutrophication. As a model of plateau lake management, dozens of large-scale artificial wetlands have been built around Dianchi Lake, focusing on improving the water quality of Dianchi Lake and restoring and giving play to the key ecosystem functions of Dianchi Lake wetlands. However, studies on water purification by constructed wetlands rarely focus on plateau lakes, and there are lacking the researches on the characteristics of wetland vegetation growth and seasonal changes in water quality. Therefore, understanding the biogeochemical process of Plateau lake wetlands, the influence of wetland vegetation on eutrophication status and the temporal changes are the critical way to carry out scientific governance of plateau wetland pollution and eutrophication. Therefore, we proposed three hypotheses based on the previous studies: 1) The removal rate of N and P in water planted by *P.australis* is higher than that of *Z.caduciflora* due to the higher biomass of *P.australis*; 2) At the end of the growing season in October, the amount of nitrogen and phosphorus remove by the plants reaches the maximum value, and the nitrogen and phosphorus content and COD value in the water are the lowest; and 3) Temperature had the positive effects on the removal of wetland water pollutants whereas precipitation had the negative effects. To answer these questions, we selected a typical wetland around Dianchi Lake - Xihua Wetland, and conducted the continuous observation of plant and water for 10 times a year. The aims of this study were: 1) to compare the nitrogen and phosphorus removal effects of two typical wetland plants in subtropical plateau lakes; 2) to reveal the correlations between the seasonal variations of nitrogen and phosphorus concentrations in constructed wetlands and the growth of wetland plants; 3) to get the optimal time period for plant harvesting in subtropical plateau wetlands, and thus supply the scientific guidance for wetland management.

2. Materials And Methods

2.1 Site description

Dianchi Lake, located in the southwest of Kunming City, Yunnan Province, is the largest freshwater lake in Southwest China and the drainage area is 2920 km². The Lake is 40 km long from north to south and the average width from east to west is 7 km with the widest point of 12.5 km. The altitude of the lake is 1886 m.s.l. and the shoreline is about 150 km long (Xu et al. 2016; Ma et al. 2020). The drainage area has a subtropical plateau monsoon climate, with an average annual temperature of 14.4°C, the sunshine duration of 2371 hours, a frost-free period of 227 days, and an annual precipitation of 1036 mm (Fig. 1). The emerged plant community in the lake area were mainly *Z.caduciflora*, *P.australis*, *Typha orientalis*

Presl, *Himalayan balsam* and *Polygonum lapathifolium*, among which *Z.caduciflora* and *Paustralis* are the predominant species. The observation wetland, Xihua Wetland, is located in the west of Dianchi Lake and the area is approx. 52 hectare (ha), of which 20 ha as the ecological constructed wetland planted with 1,225 arbors, including willows, Dianchipu, peach, etc., as well as more than 250,000 clumps of aquatic plants (Deng et al. 2016).

2.2 Observation of wetland plant growth

The Xihua wetland, in the lakeside of Dianchi Lake was selected, and the plant biomass, plant height and leaf area of the *Z.caduciflora* and *Paustralis* in the wetland were observed. During the observation period from March to December 2011, five of the 1m × 1m plots were randomly selected in the *Z.caduciflora* and *Paustralis* area, and ten plants were randomly selected from each quadratic to measure the plant height and leaf area, after that the plants were cut from the water surface, brought back to the laboratory, and placed in the oven at 80°C to constant dry weight as the aboveground biomass of each plot. The accumulation of the above-ground biomass is estimated by the formula of the difference in above-ground dry matter from March to December: $\Delta W = \sum_{i=3}^{12} (W_{i+1} - W_i)$

Whereas, W_i and W_{i+1} represent the aboveground biomass of W_i and W_{i+1} in January and February, respectively. The plant samples were air-dried and then pulverized, and the total nitrogen content of plants was determined by the method of sulfuric acid digestion-sodium salicylate. Detailed information can be found in previous study (Cole, Brooks & Wardrop 2001; Kansime et al. 2003).

2.3 Determination of nitrogen and phosphorus in water

Water samples in the growth area of *Z.caduciflora* and *Paustralis* were simultaneously collected as the parallel observation parameters to measure total nitrogen, total phosphorus, and COD, and the temporal characteristics were analyzed. The TN content in water was monitored by the method of potassium sulfate oxidation-UV spectrophotometry, and the TP content in water was monitored by the method of ammonium molybdate spectrophotometry (Lu, Zhang & Cui 2010).

2.4 Statistic analysis

The data in this study were firstly analyzed for normal distribution by using the Kolmorov-Smirnov test, and then the homogeneity of variance was checked by using the Levene test. One-way ANOVA and Fishers Least Significant Difference (LSD) were used to explore the significant differences of TN, TP, COD and the removal efficiency of N and P among the study sites. The Polynomial Equations and the Logistic Equations were used to determine the dynamic changes of nutrients in water. Statistical analysis was performed by using SPSS 21 (SPSS Inc., Chicago, USA), and data processing and drawing was used by Origin 2021 software (Origin Lab Inc., Northampton, USA).

3. Results And Discussion

3.1 Growth dynamics of wetland plant

The growth of *P.australis* and *Z.caduciflora* followed the Logistic curve and was shown in Fig. 2. The *P.australis* entered the rapid growth period in mid-April, and the aboveground biomass was 665 g m^{-2} (Fig. 2a). The period of mid-June to late June is the fastest growing period when the dry matter weight reached to 50% of the cumulative weight during the whole growing season (Fig. 2a). From the mid-September to the late-September, the growth of *P.australis* entered a slow period and in late October, the biomass reached the maximum value of 4138 g m^{-2} (Fig. 2a). The absolute growth rate of *P.australis* had two peaks, which were in early June and early August (Fig. 2b). The growth of *Z.caduciflora* showed similar curve with *P.australis* but lower biomass and few peak. The *Z.caduciflora* entered the rapid growth period in early-April, and the aboveground biomass was 512 g m^{-2} (Fig. 2a). The fastest growing period was approx. 100 days when the dry matter weight reached to 50% of the cumulative weight during the whole growing season (Fig. 2c). The growth of *Z.caduciflora* entered a slow period and in late October, the biomass reached the maximum value of 3092 g m^{-2} (Fig. 2c). There was only one peak of absolute growth rate of *Z.caduciflora*, which was in early June (Fig. 2d).

A polynomial model was established to show the dynamic variation of the leaf area of *P.australis* and *Z.caduciflora* (Fig. 2e). The *P.australis* entered the fast growing period since mid-March and the leaf area was $1.28 \text{ m}^2 \text{ m}^{-2}$ with the growth rate of $0.05 \text{ m}^2 \text{ m}^{-2} \text{ d}^{-1}$ (Fig. 2f). The growth rate of leaf area reached the maximum value ($0.13 \text{ m}^2 \text{ m}^{-2} \text{ d}^{-1}$) in early June, and the leaf area was $5.02 \text{ m}^2 \text{ m}^{-2}$. The leaf area continued to increase to $7.54 \text{ m}^2 \text{ m}^{-2}$ until early August while with the weakened growth rates of $0.02 \text{ m}^2 \text{ m}^{-2} \text{ d}^{-1}$. It is worth noting that after mid-August, the growth rate of leaf area was negative, indicating that mid-August is a critical period for *P.australis* management and needs to be harvested. The dynamic curve of the leaf area of *Z.caduciflora* was similar with *P.australis*, but showed the higher peak value of $9.99 \text{ m}^2 \text{ m}^{-2}$.

3.2 Dynamics of N and P contents in wetland plants

The temporal variation of total N (TN) and total P (TP) contents of *P.australis* and *Z.caduciflora* were significant (Fig. 3). In general, plant the nutrient content is relatively high in the early growing season and gradually decreased with the extension of the growing season, and the amount of N and P absorbed by *Z.caduciflora* is higher than that of *P.australis* (Fig. 3). The average values of TN and TP in *P.australis* were 14.51 g kg^{-1} and 1.86 g kg^{-1} respectively, and in *Z.caduciflora* the values were 17.00 g kg^{-1} and 2.65 g kg^{-1} respectively (Figs. 3a and 3b). The peak of N and P absorption of *P.australis* and *Z.caduciflora* appeared in the budding and leaf-spreading stages from March to April, when a large amount of N and P was absorbed from the water and sediment to meet the needs of rapid growth, and meanwhile the N and P in the water was reduced. In autumn, the *P.australis* and *Z.caduciflora* were at the end of their growing stage, when the plants rarely or completely stop absorbing nutrients, and part of the N and P released into the water through the dropped branches and leaves.

The cumulative uptake of N and P by *Paustralis* was higher than that of *Z.caduciflora* in the growing season (Figs. 3c and 3d). The cumulative absorption of N and P in *Paustralis* and *Z.caduciflora* gradually increased during the growing season until October (Figs. 3c and 3d). In the late-October, the cumulative N uptake of *Paustralis* reached a maximum of 45.622 g m^{-2} , and that of *Z.caduciflora* reached a maximum of 61.433 g m^{-2} ; after then, the cumulative N uptake of the two plants decreased rapidly (Fig. 3c).

3.3 Dynamics of N, P, COD and LAF content in wetland water

The temporal variation of TN in wetland water in the growth area of *Paustralis* and *Z.caduciflora* was shown in Fig. 4a. The TN content in the growing area of *Paustralis* was $1.44\text{--}4.40 \text{ mg L}^{-1}$ with an average of 2.70 mg L^{-1} , while the TN content in the growing area of *Z.caduciflora* was $1.44\text{--}5.10 \text{ mg L}^{-1}$ with an average of 2.65 mg L^{-1} (Fig. 4a). The TN content in the water was highest in winter, then gradually decreased and reached the lowest in summer, followed by the gradually recovery in autumn, which was closely related to the plant growth in wetlands. The highest value of TN content of water in winter ($4.02\text{--}5.10 \text{ mg L}^{-1}$) might be due to the plant nutrient variations during the growing season, i.e., the wetland plants stop absorbing nutrients from the water in winter, and decompose the organic matter through anaerobic reaction, resulting in increases of the TN content in the wetland water. In contrast, in summer, the TN content in wetland water gradually decreased due to the increase of the absorption of nutrient by plants. From April to early June, the TN content in the wetland water reached the lowest value ($1.44\text{--}1.74 \text{ mg L}^{-1}$) and decreased by 50–60% compared with winter (Fig. 4a). With the growth of wetland plants in autumn, the photosynthetic function gradually declined combined with the decrease of the absorption capacity of nutrients, and the plant residues fall into the water, resulting in a gradual increase in the content of TN in the water (Fig. 4a). There were significant differences in TN content in water of *Paustralis* and *Z.caduciflora* planting areas in different periods. Before mid-May, the TN in the *Paustralis* water was higher than that in *Z.caduciflora* water (2.38 vs 2.09 mg L^{-1} for *Paustralis* water and *Z.caduciflora* water, respectively). After late May, the TN in the *Paustralis* water was lower than that in *Z.caduciflora* water (3.19 vs 3.49 mg L^{-1} for *Paustralis* water and *Z.caduciflora* water, respectively) (Fig. 4a). As for the TP content and COD_{Mn} variation in different seasons, the pattern of TP in the water of the *Paustralis* and *Z.caduciflora* wetlands was consistent with that of TN (Figs. 4b and 4c), but the TP content in *Paustralis* water was consistently higher than that of *Z.caduciflora* water during the entire observation period (Fig. 4b). Likewise, there was temporal dynamics of TN/TP ratio and the patterns of the *Paustralis* and *Z.caduciflora* were pronounced different (Table 1). The COD_{Mn} in *Paustralis* water was lower than that of *Z.caduciflora* water before April (8.61 vs 9.76 mg L^{-1} for *Paustralis* water and *Z.caduciflora* water, respectively), while the opposite pattern was observed after April (11.37 vs 8.61 mg L^{-1} for *Paustralis* water and *Z.caduciflora* water, respectively) (Fig. 4c).

Table 1
TN/TP Ratio of water in constructed wetland planting with *Paustralis* and *Z.caduciflora*

Date (mm-dd)	Dec-15	Jan-15	Feb-15	May-3	Jun-17	Jul-18	Aug-22	Sep-22
<i>Paustralis</i>	7.70 ± 0.87a	3.13 ± 1.66b	16.57 ± 2.35a	4.12 ± 0.35b	5.02 ± 0.86b	5.07 ± 1.41b	4.37 ± 1.94a	2.61 ± 0.49a
<i>Z.caduciflora</i>	8.59 ± 0.54a	7.32 ± 1.17a	10.86 ± 3.22a	8.31 ± 0.70a	18.92 ± 7.58a	18.11 ± 11.79a	4.52 ± 1.16a	4.50 ± 1.23a

The dynamic of TP, TN, COD, and LAF in the water of the two plants are standardized equations, as shown in Fig. 4d, from late September to late October, there is an important intersection, when the cumulative absorption of nitrogen and phosphorus by the two plants and the biomass of the plants reached the maximum value. During this period, harvest of the wetland plants can maximize the function of removing N and P in wetland. However, if it is not harvested in time, the input of wetland plant residues and the release of N and P into water will aggravate the pollution, thus it should be paid attention by the wetland management.

The results of the removal rate of N and P in water by *Paustralis* and *Z.caduciflora* are shown in Fig. 5. From January to May, the contribution rate of *Paustralis* to TN removal was 28.9–74.3%, and the average removal contribution rate was 51.1% (Fig. 5a). After June, the demand for nutrient elements of wetland plants weakened, and the contribution rate to N removal was negative. Figure 5b shows the contribution rate of P removal in the water body of the water body of the *Z.caduciflora*. From January to June, the contribution rate of *Paustralis* to TP removal was 0.3–52.3%, and the average removal contribution rate was 18.6% (Fig. 5b). After July, the N removal contribution rate of *Paustralis* and *Z.caduciflora* to wetland water body was negative. From January to May, the contribution of *Z.caduciflora* to TN removal was 28.9–74.3% with the average of 51.1%, and the contribution of *Z.caduciflora* to TP removal was 0.3–52.3% with the average of 18.6%. After July, the contribution rate of N and P removal was negative (Figs. 5a and 5b).

3.4 Correlations between the climatic parameters and wetland water pollutants

Correlation analysis revealed that precipitation, rather than temperature, had strong positive effects on the increase of phosphorus ($P < 0.01$, Fig. 6e), nitrogen ($P < 0.05$, Fig. 6f) and COD ($P < 0.05$, Fig. 6g) in the water bodies of wetland either planted with *Paustralis* or *Z.caduciflora*. In addition, both temperature and precipitation had the significant positive effects on the leaf areas, which was consistent with the previous studies (Liang et al. 2011; Hu et al. 2021; Lindborg et al. 2021). Although study by Lindborg et.al (2021) found that the leaf area of wetland plants at high altitude responded more strongly to temperature than that of wetland plants at low altitude, our research shows that there is a significant positive correlation between leaf area of subtropical plateau wetlands and temperature ($R^2 = 0.947$, $P < 0.001$, Fig. 6d). This is mainly due to the influence of the climate characteristics of the subtropical plateau, such as distinct

seasonal temperature changes and sunshine radiation, which affect the leaf trait of wetland plants. This effect may lead to changes in the composition of plant communities, increase the rapid growth and quantity of large leaf and polyclonal plants, and thus affect plant competition and ecological functions, such as decomposition and nutrient retention in the wetland ecosystems (Lindborg et al. 2021).

Interestingly, our study indicates that the concentrations of N, P and COD in wetland water bodies were significantly positively correlated with precipitation (Figs. 6e-f), which was inconsistent with our hypothesis. We assumed that precipitation might dilute pollutants in waters and thus negatively correlated with pollutants. This phenomenon is mainly related to the special location and management of Dianchi Lake. Dianchi Lake is located in the center of the provincial capital Kunming. Since the 1980s, the rapid economic development has ignored the impact on the environment, resulting in the domestic sewage and agricultural non-point source pollution around Dianchi Lake far exceeding the sewage purification capacity (Xu et al. 2016; Li et al. 2019). When rainfall comes, especially moderate and strong rainfall, the precipitation will bring these untreated domestic sewages into wetland and lake, and the pollutant concentration will increase (Xu et al. 2016); In addition, the agriculture around Dianchi Lake is mainly facility agriculture, with large amount of chemical fertilizer and low utilization rate. Rainfall accelerates the leaching of N and P, which flows into the lake with the runoff and soil leaching solution (Guo et al. 2017; Ma et al. 2020). Our research suggests that even though wetland plants have strong purification capacity, when pollutants flow into the wetland with rainfall, they exceed the purification capacity of wetland plants and the key step to reduce eutrophication are to increase the interception capacity of sewage of Dianchi Lake inlet in rainy season.

3.5 Effect of subtropical constructed wetland on water purification

In order to test the wetland effects on the purification of water in subtropical plateau lakes, the concentrations of N, P, COD_{Mn}, and SS in wetlands and Dianchi Lake were monitored (Fig. 7). The results showed that the concentrations of TN, TP, COD_{Mn} and SS in the wetland were significantly lower than those in Dianchi Lake. The TN and TP content were 2.27 mg L⁻¹ and 2.84 mg L⁻¹, respectively in the water inlet of the wetland, while after the purification of wetland, the TN and TP content reduced to 0.118 mg L⁻¹ and 0.108 mg L⁻¹, respectively in the water outlet of the wetland (Table 2). These results showed that subtropical wetland plants of *P.australis* and *Z.caduciflora* can absorb a large amount of N and P nutrients from the water, and after the purification effect of the wetland, the water quality flowing into Dianchi Lake has improved significantly (Table 2).

Table 2
Purification effect of Dianchi wetland

Sampling site	TN (mg L ⁻¹)	TP (mg L ⁻¹)	COD _{Mn} (mg L ⁻¹)	SS (mg L ⁻¹)
Inlet of wetland	2.27	2.84	56.4	36.5
Wetland	0.359	0.205	53.6	40.8
Outlet of wetland	0.118	0.108	10.4	5.1
Removal ratio	94.8%	96.2%	81.6%	86.0%
TN: total nitrogen, TP: total phosphorus, COD _{Mn} : potassium permanganate index of chemical oxygen demand, SS: Suspended Substance				

For wetlands, vegetation plays an important role in filtration and adsorption, and is conducive to microbial activities, creating a better metabolic environment.(Garcia et al. 2010; Zhuang et al. 2019). Different wetland vegetation has different adsorption and purification effects. By planting vegetation with special emphasis, specific pollutants can be effectively removed, thus to improve the effect of water purification (Wang et al. 2017; Engida et al. 2020). In particular, the mixing of different vegetation can significantly enhance the comprehensive treatment level of sewage, effectively balance its nutrients, facilitate the exchange of wetland material and energy, promote the development of aquatic organisms, and promote the ecological balance of wetlands (Hickey et al. 2018), leading to the ultimate improvement is the comprehensive purification capacity of the wetland (Li et al. 2014; Zhuang et al. 2019; Colares et al. 2020). Our results showed that although there were differences in the growth of the two plants (*Paustralis* and *Z.caduciflora*), they have played a good role in the process of water purification (Fig. 4). *Z.caduciflora* has better purification effect for TP, and similar purification effect for TN and COD by the two plants (Fig. 4). For the removal of COD, it is mainly through the adsorption and utilization of roots and the decomposition of microorganisms, which cannot be separated from the support of oxygen, while the root system of *Z.caduciflora* is less developed than that of *Paustralis*, especially in the early growth season (Hao, Huo & Wu 2017; Qiao 2019), thus leading to the relatively lower COD content in the *Paustralis* wetland water (Fig. 4).

4. Conclusion

The subtropical wetland plants *Paustralis* and *Z.caduciflora* have significant removal effects on N, P, COD and SS in the eutrophic plateau lakes, and the removal rate of the constructed wetland can reach 82–96%. The N and P concentrations of the two wetland plants are the highest at the beginning of the growing season (April to April), and the content in *Paustralis* is higher than that in *Z.caduciflora*. Pprecipitation, rather than temperature, had stronger correlation with the pollutants variation of wetland waters. With the development of the growing season, the N and P concentrations in the two plants gradually decreased, but the accumulation of N and P in the plants continued to increase until late

October. At this time, plants should be harvested to prevent the water bodies from being polluted again by falling litter. Although wetland plants have different demands and absorption capacities for nutrients in water, the two typical subtropical wetland plants we selected have great water purification effects and can be planted alone or in combination. In the future work, we suggest considering how to reuse these subtropical wetland plants, such as preparing compost, biochar or returning liquid fertilizer to the field, so as to realize the recycling of wetland plants.

Declarations

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Author Contribution

YZ participated in sample collection, optimization of analysis and manuscript writing. KZ participated in sample collection and provided field data. ZC participated in development of ideas and optimization of analysis. All the authors read and approve the final manuscript.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information file.

Ethical approval

This study did not involve any protected or endangered species, and no specific permissions were required for the sampling on the collection localities.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Figures

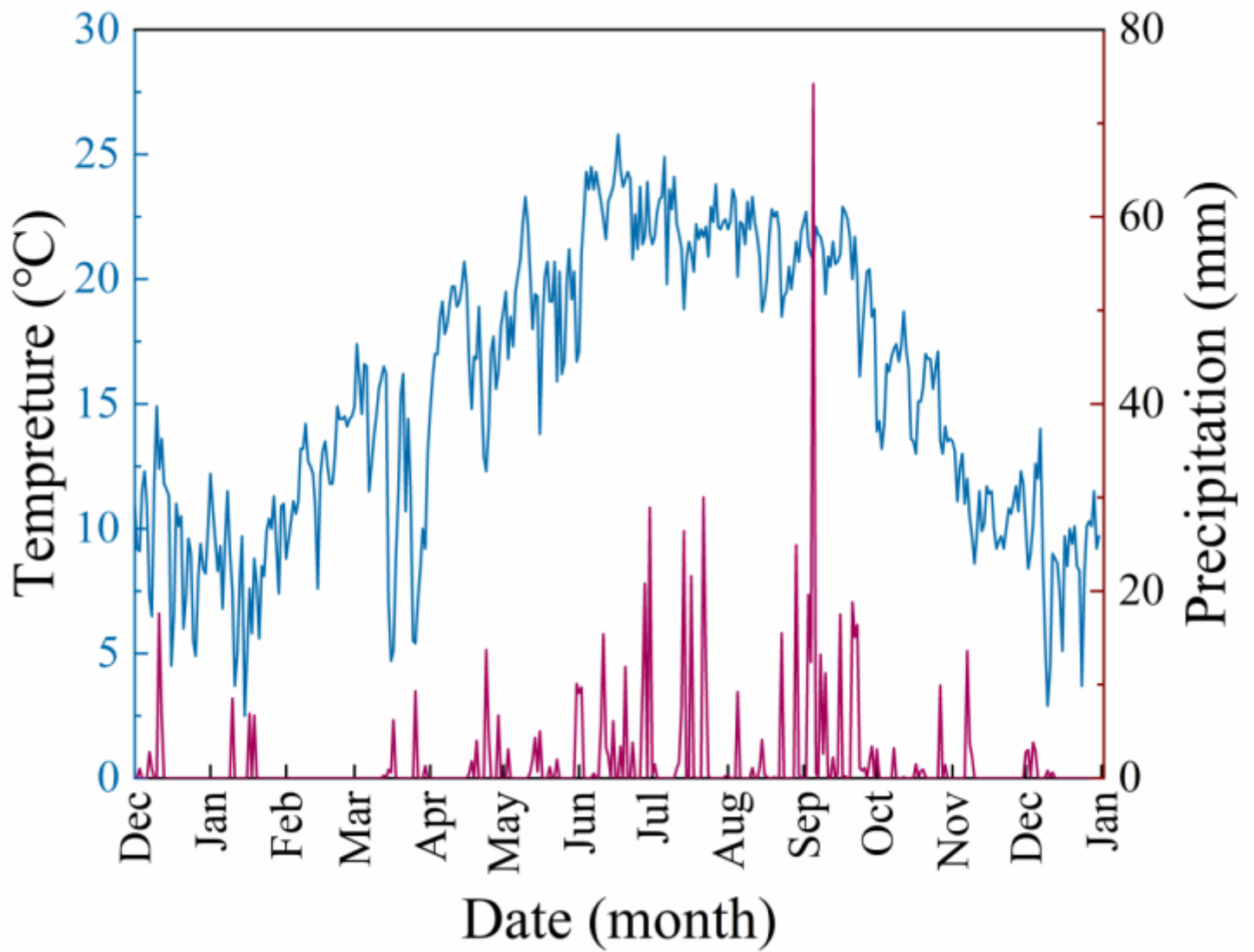


Figure 1

The temperature and precipitation around Dian Lake during the research year.

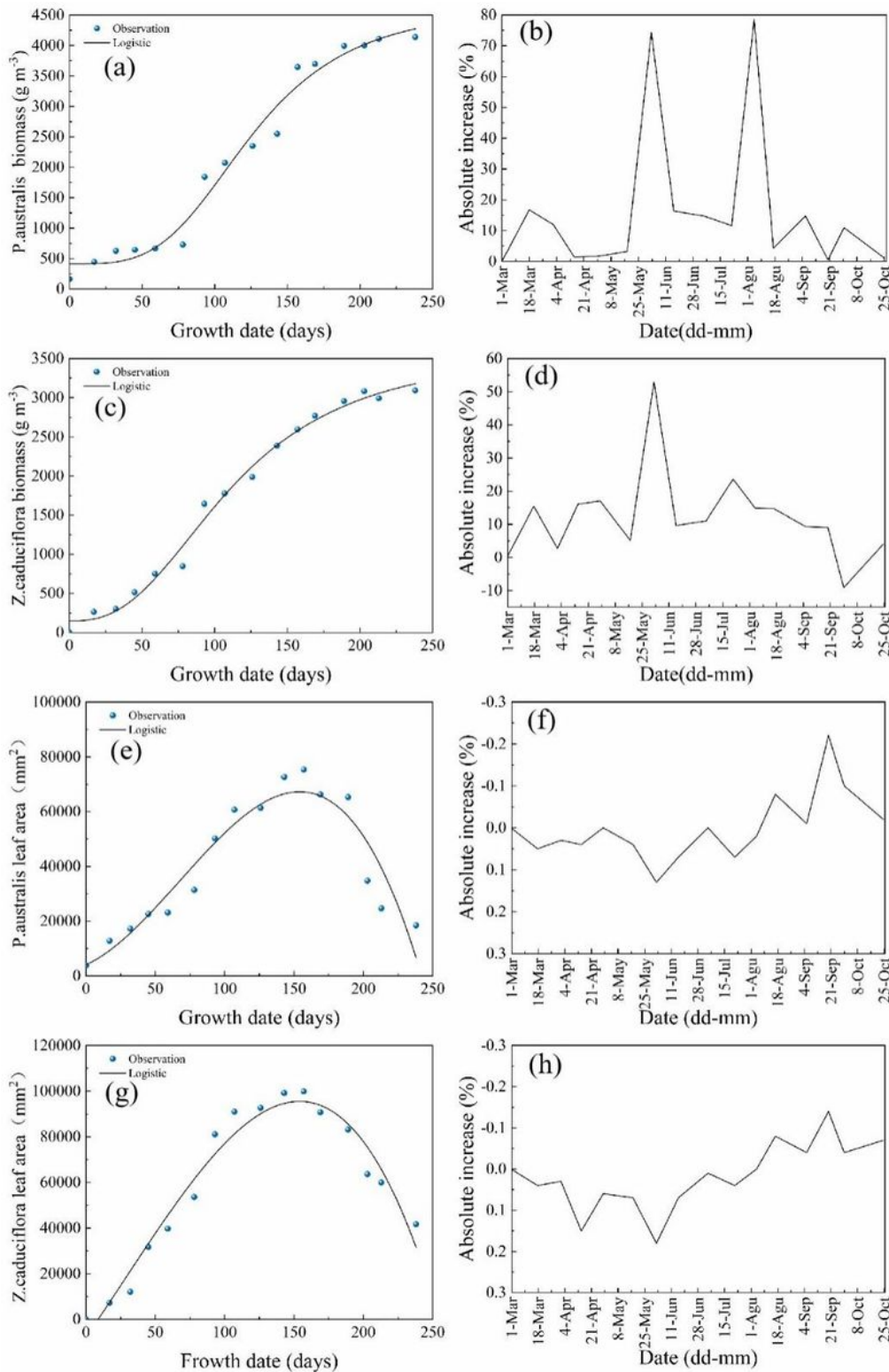


Figure 2

Growth curve of *P.australis* and *Z.caduciflora*. a) Temporal dynamics of *P.australis* biomass; b) Absolute increase ratio of *P.australis* biomass; c) Temporal dynamics of *Z.caduciflora* biomass; d) Absolute increase ratio of *Z.caduciflora* biomass; e) Temporal dynamics of *P.australis* leaf area; f) Absolute increase ratio of *P.australis* leaf area; g) Temporal dynamics of *Z.caduciflora* leaf area; h) Absolute increase ratio of *Z.caduciflora* leaf area.

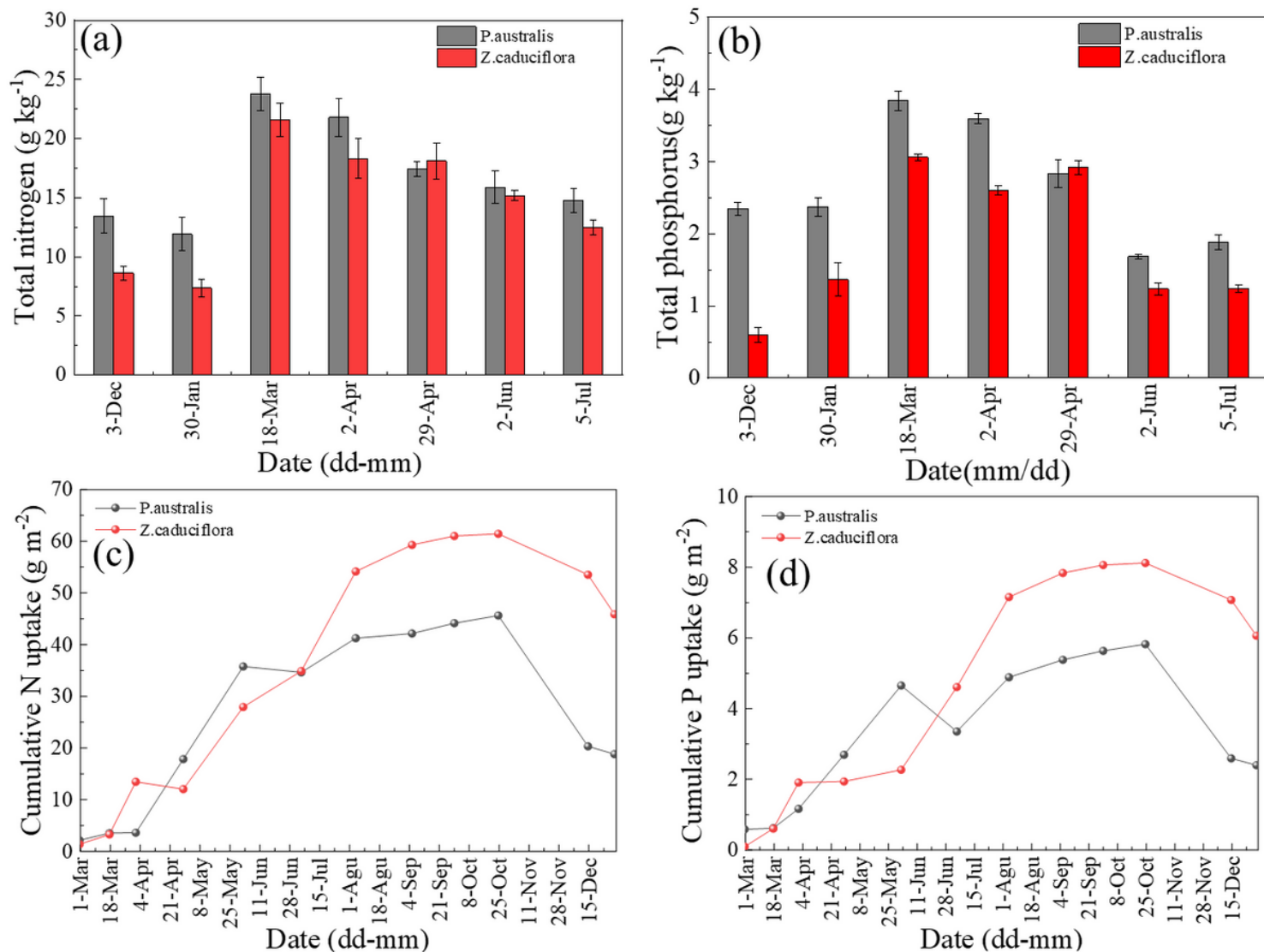


Figure 3

The nitrogen (a) and phosphorus (b) content of *P.australis* and *Z. caduciflora*; and the cumulative N uptake (c) and P uptake (d) of *P.australis* (grey) and *Z. caduciflora* (red).

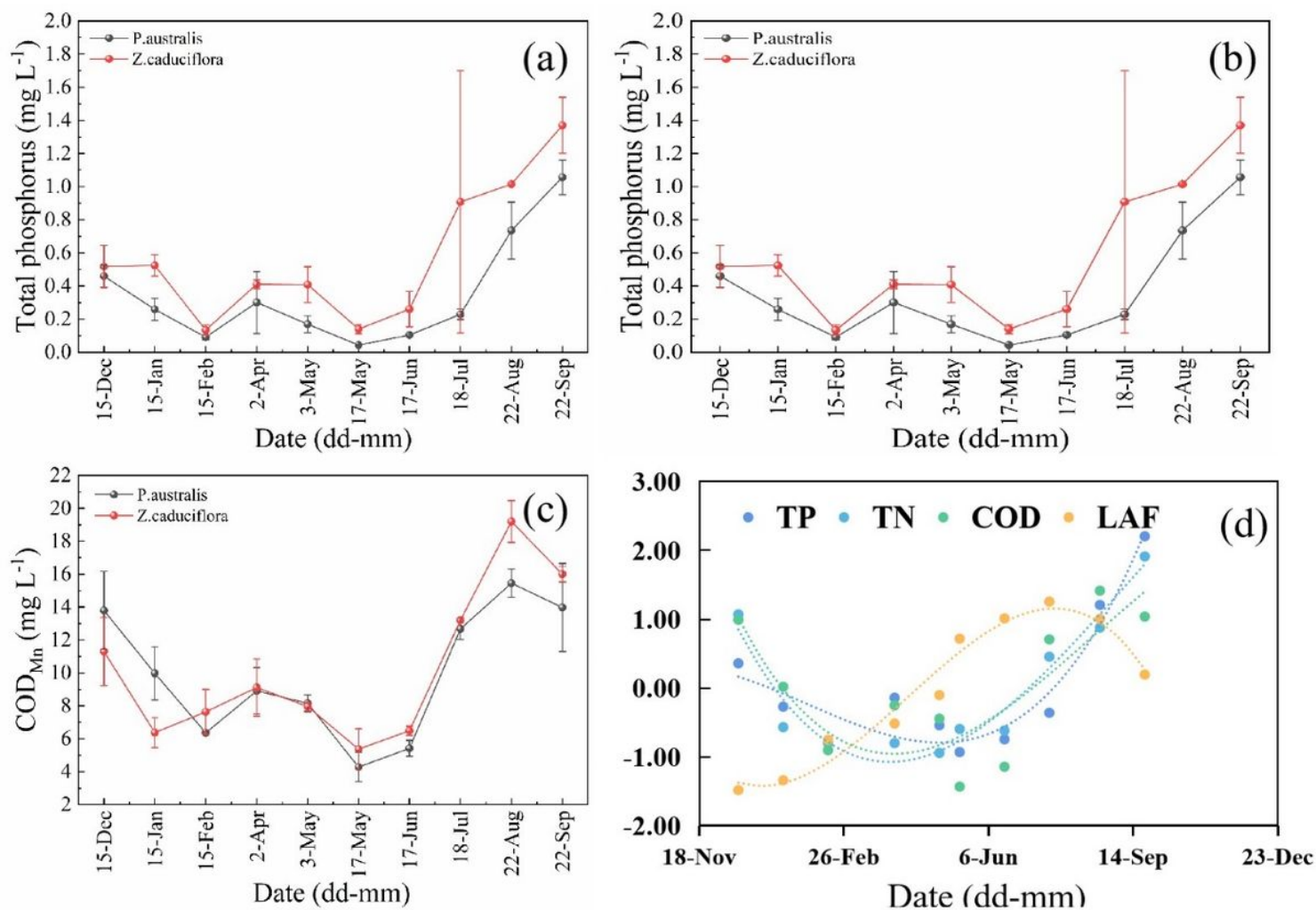


Figure 4

Changes of N (a), P (b), COD_{Mn} (c) and combination curve (d) in wetland waters planted with *P.australis* (grey) and *Z. caduciflora* (red).

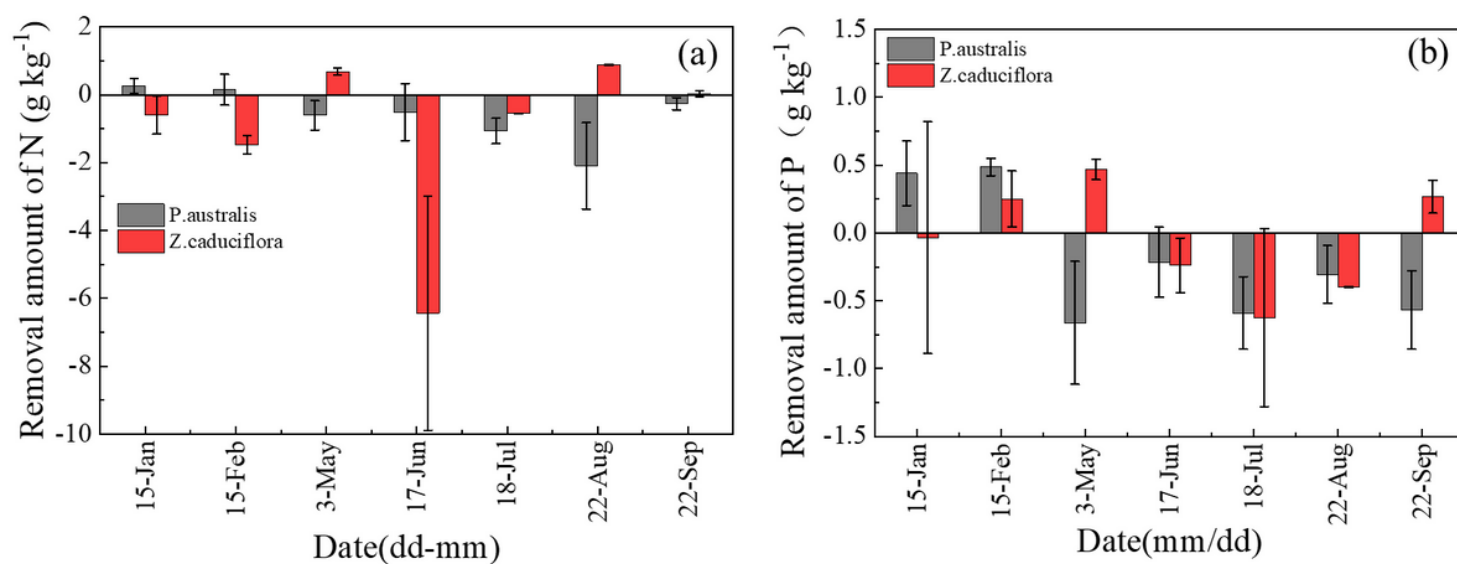


Figure 5

Removal amount of N (a) and P (b) in wetland waters planted with *P.australis* (grey) and *Z.caduciflora* (red), respectively

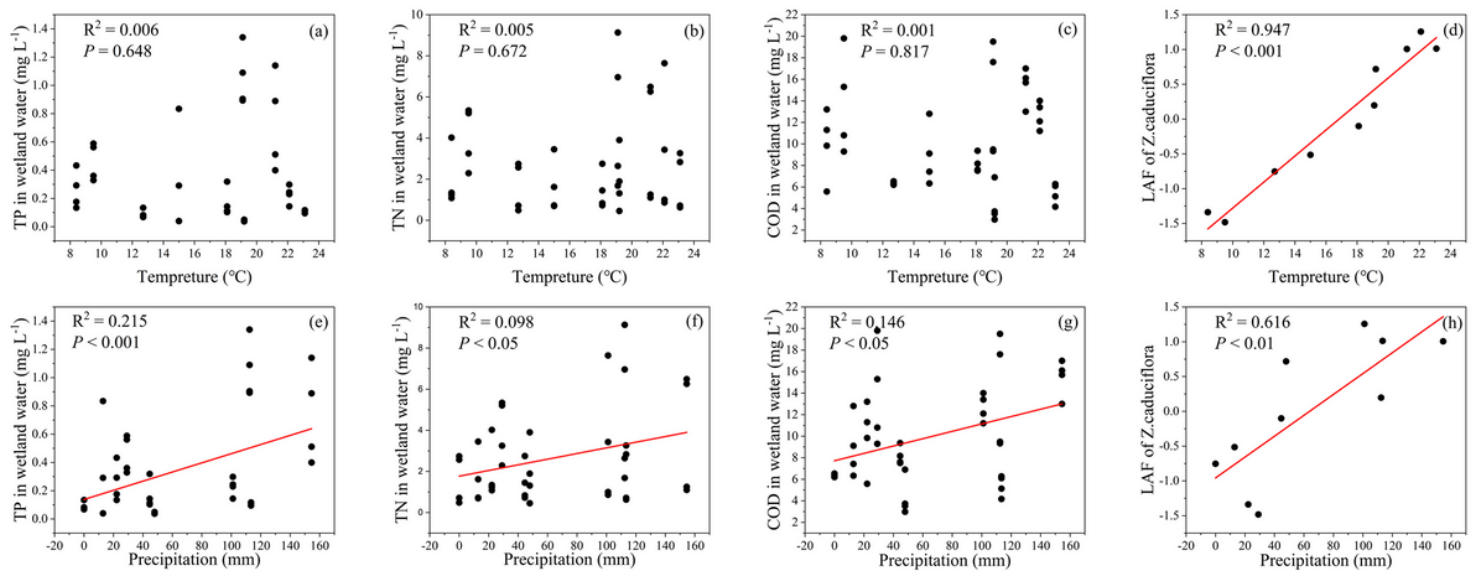


Figure 6

Correlations of temperature with TP (a), TN (b), COD (c) and LAF (d) content in wetland water; correlations of precipitation TP (e), TN (f), COD (g) and LAF (h) content in wetland water. TP: total phosphorus; TN: total nitrogen; COD: chemical oxygen demand; LAF: normalized leaf area.

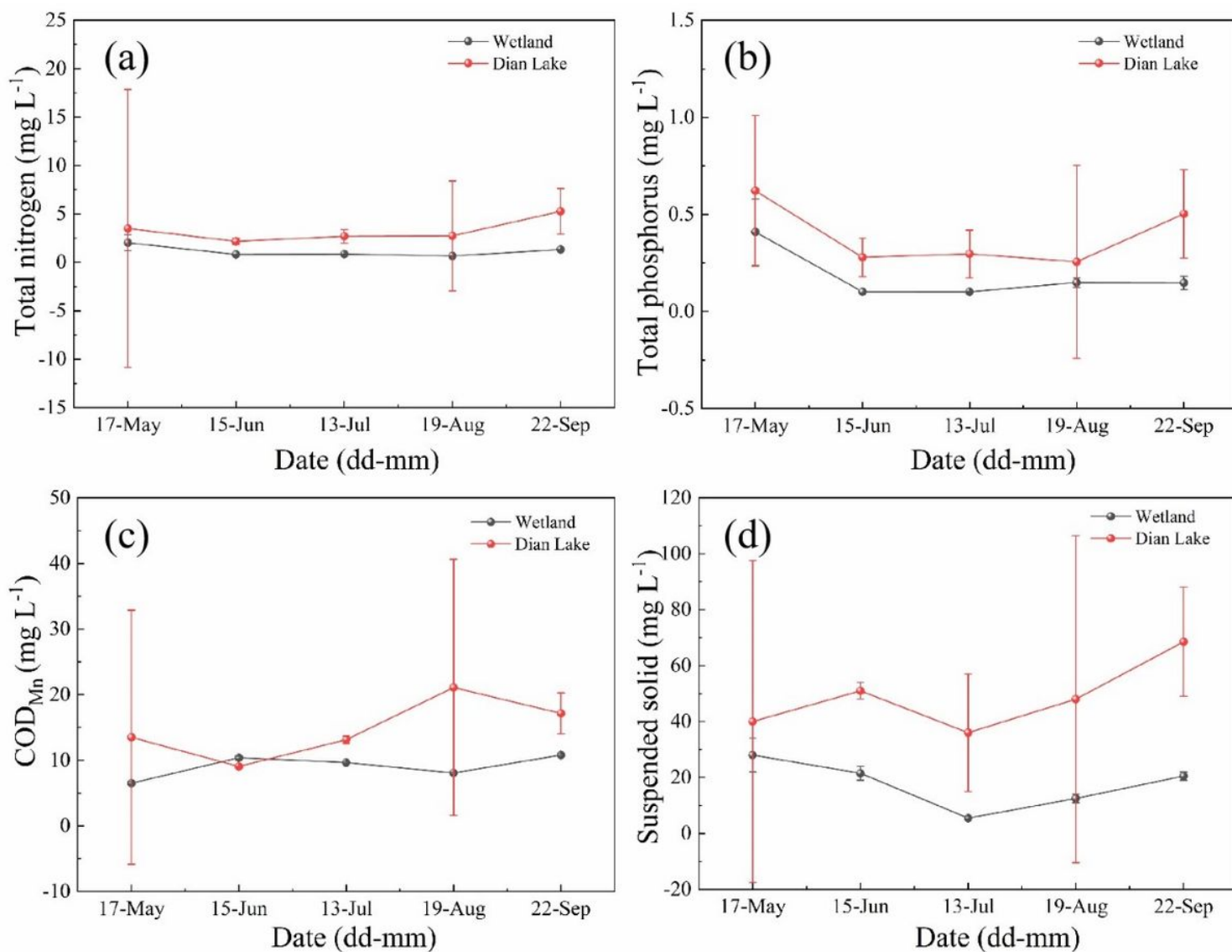


Figure 7

Temporal dynamics of total nitrogen (a), total phosphorus (b), COD_{Mn} (c) and suspended solid (d) in waters of wetland (grey) and Dianchi Lake (red)