WATER LEVEL FLUCTUATIONS DETERMINE THE SPATIAL AND TEMPORAL DISTRIBUTION OF MANCHURIAN WILD RICE (*ZIZANIA LATIFOLIA*) IN SIX YANGTZE RIVER FLOODPLAIN LAKES, CHINA

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Abstract. *Zizania latifolia* is a common emergent macrophyte in lakes along the lower reaches of the Yangtze River. To investigate the factors driving the expansion or decline of *Z. latifolia* populations, the spatial and temporal distribution patterns of *Z. latifolia* in six Yangtze floodplain lakes were analyzed from 2007 to 2016 using remote sensing and geographic information system tools. In combination with hydrological data and other environmental factors, the main influencing factors were determined. The results showed that distribution of *Z. latifolia* among the six lakes exhibited obvious differences. Plant cover was the highest in Wuchang and Huangda lakes, which had relatively stable water levels. Spearman correlation analyses showed that the lake morphological variables, climatic variables, and water quality variables had no significant effects on the distribution of *Z. latifolia*. Regarding variables related to hydrology, excluding the rate of water level change and timing of extreme water level annually, the other four groups of hydrological variables (a total of 20 indicators) all had significant effects on the distribution of *Z. latifolia*. At last, the reasons for difference in cover in different lake types were analyzed and appropriate strategies for the ecological management of *Z. latifolia* populations in different lake types were recommended.
Keywords: *hydrology, water level regulation, ecological restoration, emergent plant, remote sensing*

Introduction

The Yangtze River floodplain is one of the most important ecosystems globally. Thousands of shallow freshwater lakes are distributed in the ecosystem, with a total area of 15770 km^2 (Wang et al., 2016). Historically, all the lakes were freely connected with the Yangtze mainstream, and constituted the river-floodplain ecosystem, also known as the river-lake complex ecosystem (Wang and Wang, 2009). Aquatic plants, representing the major primary producers, are one of the most important structural and functional components in such complex ecosystems. They play important roles in nutrient cycling, energy flows, water purification, and provision of habitats for other aquatic organisms (Bornette and Puijalon, 2011; Zhang, 2013). In the course of evolution, such plants have gradually adapted to natural water level fluctuations (WLF), and formed various ecological groups with different WLF requirements (Lytle and Poff, 2004; Toogood et al., 2008; Yang et al., 2020). However, most lakes along the Yangtze River have been disconnected from the Yangtze mainstem by sluices over the recent decades to facilitate

aquaculture and flood control activities (Wang et al., 2016). River-lake disconnection has not only significantly altered the community structures of lake plants, but has also altered the WLF of these lakes to various degrees (Zhang et al., 2015; Wang et al., 2016).

Zizania latifolia (Griseb.) Turcz. ex Stapf is a tall emergent plant with well developed underground parts. It can reproduce sexually through seeds or asexually via rhizomes and tiller buds (Wang et al., 2014, 2018). In the Yangtze River basin, *Z. latifolia* has been extensively cultivated as an aquatic vegetable in association with *Ustilago esculenta*, an epiphyte (Guo et al., 2007). Due to its rapid growth rate and high competitive ability, the species is the dominant emergent macrophyte in most lakes along the Yangtze River (Zhang et al., 2016; Li et al., 2018). However, spatial and temporal distributions of *Z. latifolia* in the lakes have displayed different patterns following river-lake disconnection. In some lakes, considerable terrestrialization has occurred due to the overgrowth of *Z. latifolia* populations, while the decline or elimination of emergent macrophytes has been observed in other lakes (Li et al., 2018; Wang et al., 2018). Both situations have resulted in ecological management challenges in lakes in this region. To effectively manage and exploit such *Z. latifolia* populations, it is necessary to determine the major factors influencing their distribution, which could provide a theoretical basis for the ecological management of the *Z. latifolia* populations and lakes in the Yangtze River floodplain.

WLF maintain ecological integrity and regulate ecological processes in floodplain lakes, which are usually described using amplitude, water depth, frequency, timing, and rate of change (Deegan et al., 2007; Yuan et al., 2017). Previous studies conducted in the region have reported that aquatic plant communities are structured considerably by the WLF components (Zhang et al., 2015, 2018). Therefore, alteration of WLF could be the major factor influencing temporal and spatial differences in *Z. latifolia* populations in the Yangtze floodplain lakes. In the present study, six typical floodplain lakes were selected as model ecosystems in the lower reaches of the Yangtze River. Remote sensing and geographic information system (GIS) technologies were used to determine the distribution of *Z. latifolia* populations in the six lakes from 2007–2016. The aims of the present study were: 1) to determine the temporal and spatial distribution patterns of *Z. latifolia* populations in different lakes; 2) to determine the key WLF parameters influencing the distribution of *Z. latifolia* populations; and 3) to develop water level regulation strategies for the effective management of *Z. latifolia* populations in different lakes. The results of the present study could not only have significant implications for the management of floodplain lakes, but also provide an eco-hydrological basis for the regulation of regional water resources.

Materials and methods

Study area

The six typical floodplain lakes selected in the present study, including Shengjin Lake, Caizi Lake, Pohu Lake, Huangda Lake, Wuchang Lake, and Pogang Lake, which are located in the lower reaches of the Yangtze River, China. The six lakes are also in a key region of floodplain wetlands along Anqing city, Anhui province. The region, which experiences a subtropical monsoon climate, has adequate rainfall and four distinct seasons. The annual average rainfall and air temperature among the six lakes have minimal differences, ranging from 16.1–16.6°C and 1241.3–1554.4 mm (*Table 1*).

Table 1. *Locations and environmental parameters of the six study lakes*

Lakes	Location	Lake area (km²)	Lake bottom elevation (m)	Catchment area (km²)	Shoreline length (km²)	Average water depth (m)	Annual average rainfall (mm)	Annual average temperature (℃)
Shengjin Lake	N: 30°15′-30°28′, E: 116°58′-117°14′	126.6	8.4	1554	217.5	2.54	1554.4	16.1
Caizi Lake	N: 30°43′-30°58′, E: 117°01′-117°09′	181.2	8.5	3234	276.1	1.94	1241.3	16.5
Pohu Lake	N: 30°04′-30°15′, E: 116°19′-116°33′	151.9	10	4941	202.4	2.97	1291.3	16.6
Huangda Lake	N: 29°56′-30°08′, E: 116°14′-116°33′	266.5	10.5	7849	212.4	2.38	1291.3	16.6
Wuchang Lake	N: 30°14′-30°20′, E:116°36′-116°53′	100.6	10	1083.7	96.4	2.13	1299.6	16.5
Pogang Lake	N: 30°33′-30°42′, E: 117°04′-117°13′	28.4	8.7	346	46.3	2.49	1389.1	16.5

The lake with the largest surface area is Huangda Lake, at 266.5 km², followed by Caizi Lake, Pohu Lake, and Shengjin Lake, at 181.2, 151.9, and 126.6 km², respectively. Wuchang Lake and Pogang Lake have the lowest surface areas, at 100.6 and 28.4 km², respectively (*Table 1*). In the past, all the six lakes were freely connected with the Yangtze mainstem, and the water regime in the Yangtze mainstem greatly influenced WLF in the lakes. However, all the six lakes have become river-lake disconnected lakes due to the building of sluices, to facilitate aquaculture and flood control activities. The overgrowth of *Z. latifolia* in the Wuchang and Huangda Lakes has caused serious ecological problems, while relatively poor distribution has been observed in the other four lakes following the construction of sluices. The geographical location and basic environmental parameters of the six lakes are presented in *Fig. 1* and *Table 1*.
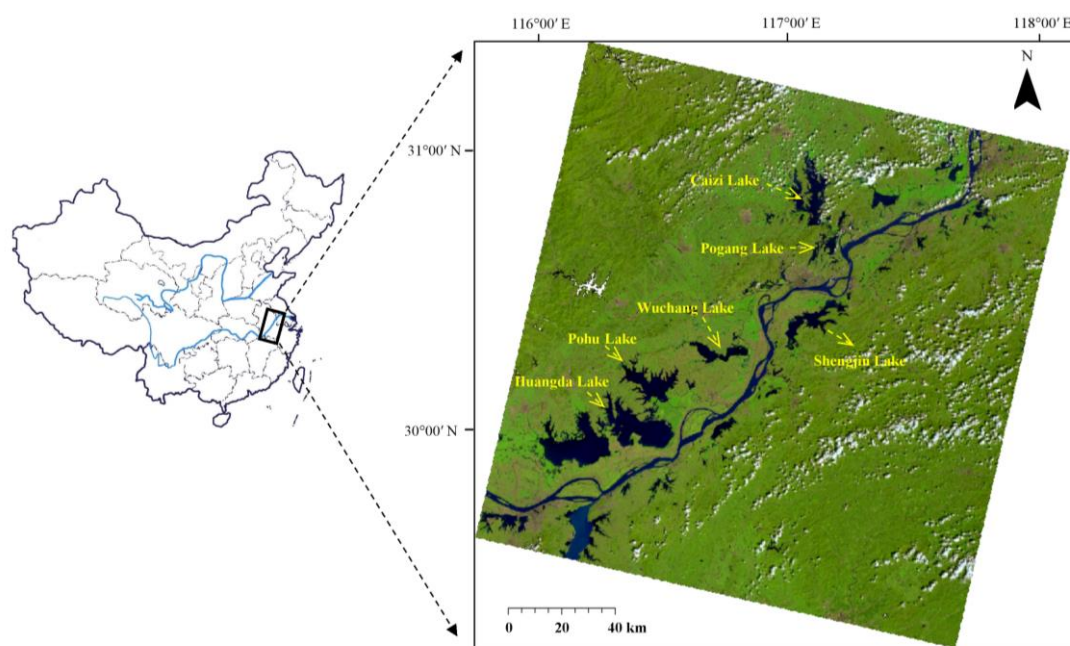
Figure 1. *Locations of the study lakes along the Yangtze River*

Study methods and data analyses

To determine the spatial and temporal distribution patterns of *Z. latifolia* in the six lakes, MSS/TM/ETM+/OLI remote sensing images from 2007–2016 were obtained from the US Landsat satellite. All the Landsat images were downloaded from the US Geology Survey site (http://glovis.usgs.gov). The track numbers of the MSS and TM/ETM+/OLI sensors are 130–39 and 121–39, respectively, with resolutions of 80×80 m and 30×30 m, respectively. Considering the coverage of *Z. Latifolia* reaches the maximum in autumn, autumn images with no more than 30% cloud cover were selected in each year. To improve the accuracy of image interpretation, the ENVI v.4.7 (ITT Visual Information Solutions) was used to perform geometric correction, band combination, image fusion, and enhancement for the 10 scene remote sensing images. The images were then interpreted and classified, and the spatial distribution and areas of distribution were calculated using ArcGIS 10.2 (http://www.esri.com/software/arcgis). To verify the accuracy of plant coverage detection, field survey was conducted in May, 2017.

The environmental factors used for analyses were in four categories, including lake morphological variables, climatic variables, water quality variables, and water level fluctuation related hydrological variables. The lake morphological variables include lake surface area, lake bottom elevation, shoreline length, and catchment area. The lake bottom elevation and catchment area were derived from available literatures (Wang and Dou, 1998; Compilation Commission of Anhui Local Records, 1998; Jin, 2008), and the lake area and shoreline length were measured. The climatic variables included annual average rainfall, annual average temperature, and annual average sunshine hours, while the water quality variables included total nitrogen, total phosphorus, and transparency. All the climatic and water quality data were obtained from available literatures (Wang and Dou, 1998; Gu et al., 2014; Wu et al., 2016; Wu, 2018). The WLF variables can be divided into six groups, i.e. G1 (Fluctuating amplitude), G2 (Monthly mean water depth), G3 (Annual extreme water depth), G4 (Timing of annual extreme water level), G5 (Rate of water level changes), and G6 (Frequency of water level changes). A total of 28 indicators were included in the six groups (*Table 2*). The water level data of the studied lakes during the study period were obtained from the Hydrology Bureau of Anqing city or downloaded from the flood and drought information network of Anhui province (http://61.191.22.157/Default.aspx) (water level data for several lakes were missing in some years). The hydrological data were used to classify the six lakes into different categories using Two-Way Indicator Species Analysis (TWINSPAN), which was performed using PC-ORD for Windows (McCune and Mefford, 1997). Life history information on *Z. latifolia* was obtained from published studies (Zhang et al., 2016).

In the present study, the water level data from 2007–2016 in the six lakes were analyzed first, and then the spatial and temporal distribution patterns of *Z. latifolia* were determined based on the remote sensing images. Indicators of Hydrologic Alteration software (The Nature Conservancy, Charlottesville, Virginia) was used to calculate the related 28 indicators of the six groups. Spearman correlation was used to determine the effects of lake morphological variables, climatic variables, water quality variables, and WLF related variables on the distribution of *Z. latifolia,* and the cover data was used in the analysis. Factors influencing the variable cover in the different lake categories were also analyzed, and appropriate recommendations were provided for the ecological management of *Z. latifolia*.

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Table 2. *Comparison of the water level fluctuations in six floodplain lakes. The values in the table are the average values for 2007-2016.*

Items	Shengjin Lake	Caizi Lake	Pohu Lake	Huangda Lake	Wuchang Lake	Pogang Lake
G1: Fluctuating amplitude (m)						
Amplitude	7.02	6.52	4.31	3.90	3.40	1.89
G2: Monthly mean water depth (m)						
January	0.67	0.41	2.01	1.56	0.90	2.06
February	0.49	0.39	1.85	1.47	0.93	2.10
March	0.71	0.62	1.87	1.50	1.20	2.08
April	1.48	1.00	2.31	1.68	1.36	2.20
May	2.72	1.74	2.81	2.02	1.73	2.23
June	4.02	2.86	3.80	2.77	2.48	2.55
July	5.36	4.77	5.00	3.70	3.59	3.29
August	5.12	4.50	4.96	3.88	3.68	3.24
September	4.43	3.50	4.00	3.56	3.40	3.06
October	2.75	1.96	2.89	2.77	2.87	2.71
November	1.82	0.84	2.02	1.96	2.09	2.27
December	0.86	0.67	2.10	1.72	1.32	2.11
G3: Annual extreme water depth (m)						
1-day min	0	0.27	1.30	1.18	0.83	1.86
3-day min	0	0.28	1.30	1.19	0.84	1.89
7-day min	0	0.29	1.32	1.20	0.85	1.91
30-day min	0.28	0.40	1.48	1.29	0.87	1.95
90-day min	0.65	0.50	1.71	1.45	1.00	2.02
1-day max	6.31	5.74	5.26	4.13	4.23	3.63
3-day max	6.28	5.72	5.24	4.13	4.23	3.62
7-day max	6.23	5.64	5.23	4.12	4.20	3.60
30-day max	5.87	5.30	5.19	4.07	4.07	3.49
90-day max	5.16	4.47	4.84	3.81	3.68	3.27
G4: Timing (Julian date) of annual extreme water level						
Date 1-day min	32.4	50.0	169.0	146.0	153.4	153.3
Date 1-day max	214.6	213.8	218.3	231.6	218.2	219.2
G5: Rate of water level changes (cm/d)						
Rise rate	12.59	7.76	4.27	3.68	4.16	3.08
Fall rate	-11.70	-6.25	-3.87	-2.97	-2.81	-2.32
G6: Frequency of water level changes						
Reversals	81.4	43.7	67.3	48.7	48.6	83.0

Results

WLF in the study lakes

WLF in the six study lakes varied greatly (*Fig. 2*; *Table 2*). Shengjin Lake and Caizi Lake had the highest fluctuation amplitudes, which were 7.02 and 6.51 m, respectively. In addition, the mean water depths in the two lakes were lower than 1.0 m from winter to early spring, while they were more than 5.0 m in summer. Water level change rate

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was also highest in the two lakes, which were more than 11 cm/d and 6 cm/d, respectively. The fluctuation amplitude was also high in Pohu Lake (4.31 m), but the lake maintained a high mean water depth of 2.0 m from winter to early spring. WLF in Wuchang Lake and Huangda Lake were similar, and the fluctuation amplitudes were 3.4 m and 3.9 m, respectively. In addition, the mean water depths in the two lakes were approximately 1.1 m and 1.5 m, respectively, from winter to early spring. Water level was relatively stable in Pogang Lake, and the fluctuation amplitude was only 1.89 m. However, the lake also maintained a high mean water depth of 2.0 m from winter to early spring. Otherwise, the highest water level was observed in 2016 in all the six lakes from 2007–2016, followed by 2010. However, the lowest water levels were observed in different years in the six lakes.
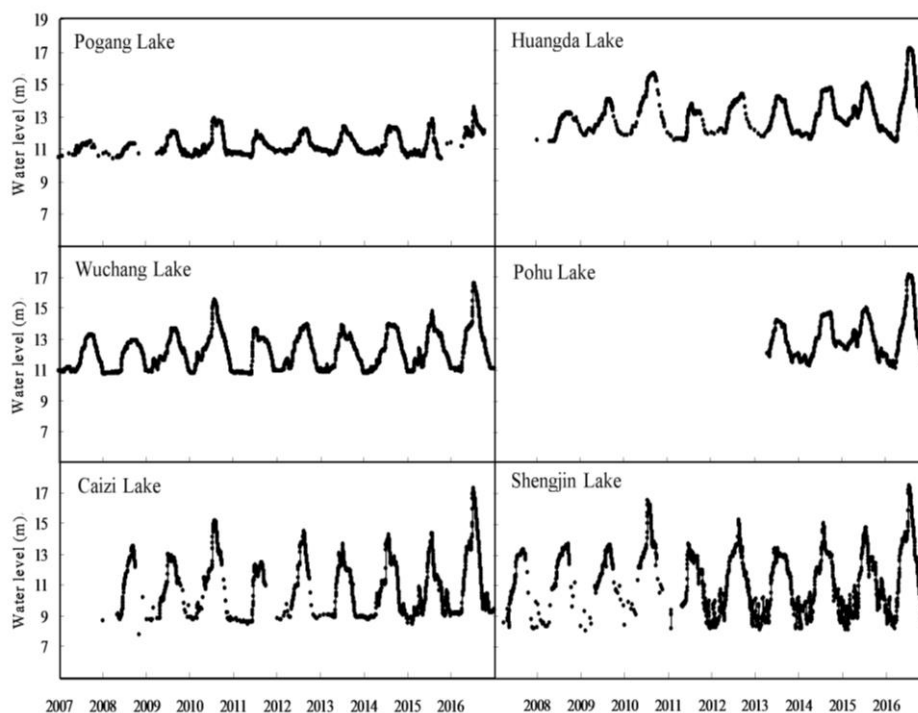
Figure 2. *Water level fluctuations in six floodplain lakes from 2007–2016*

Spatial and temporal distribution of Z. latifolia

The spatial and temporal distribution of *Z. latifolia* in the six lakes varied considerably, and the mean cover of *Z. latifolia* in Shengjin, Caizi, Pohu, Huangda, Wuchang, and Pogang Lakes were 1.54%, 1.41%, 2.93%, 17.85%, 26.01%, and 3.56%, respectively (*Fig. 3*). The distribution of *Z. latifolia* in Huangda Lake and Wuchang Lake was obviously higher than in the other four lakes, and the cover in the two lakes was more than 40% in 2007, 2008, and 2011, while it was lower than 2% in both lakes in 2016. Shengjin Lake had a patchy distribution in the southern area of the lake in 2007, 2008, and 2015, while Caizi Lake had minimal distribution in the northern area of the lake area in 2007, 2008, and 2011. However, in the other years, the two lakes had nearly no distribution of *Z. latifolia*. Pogang Lake had relatively high distributions in 2007 and 2008, which were 12.17% and 9.71%, respectively. In the other years, cover in Pogang Lake was lower than 5%.
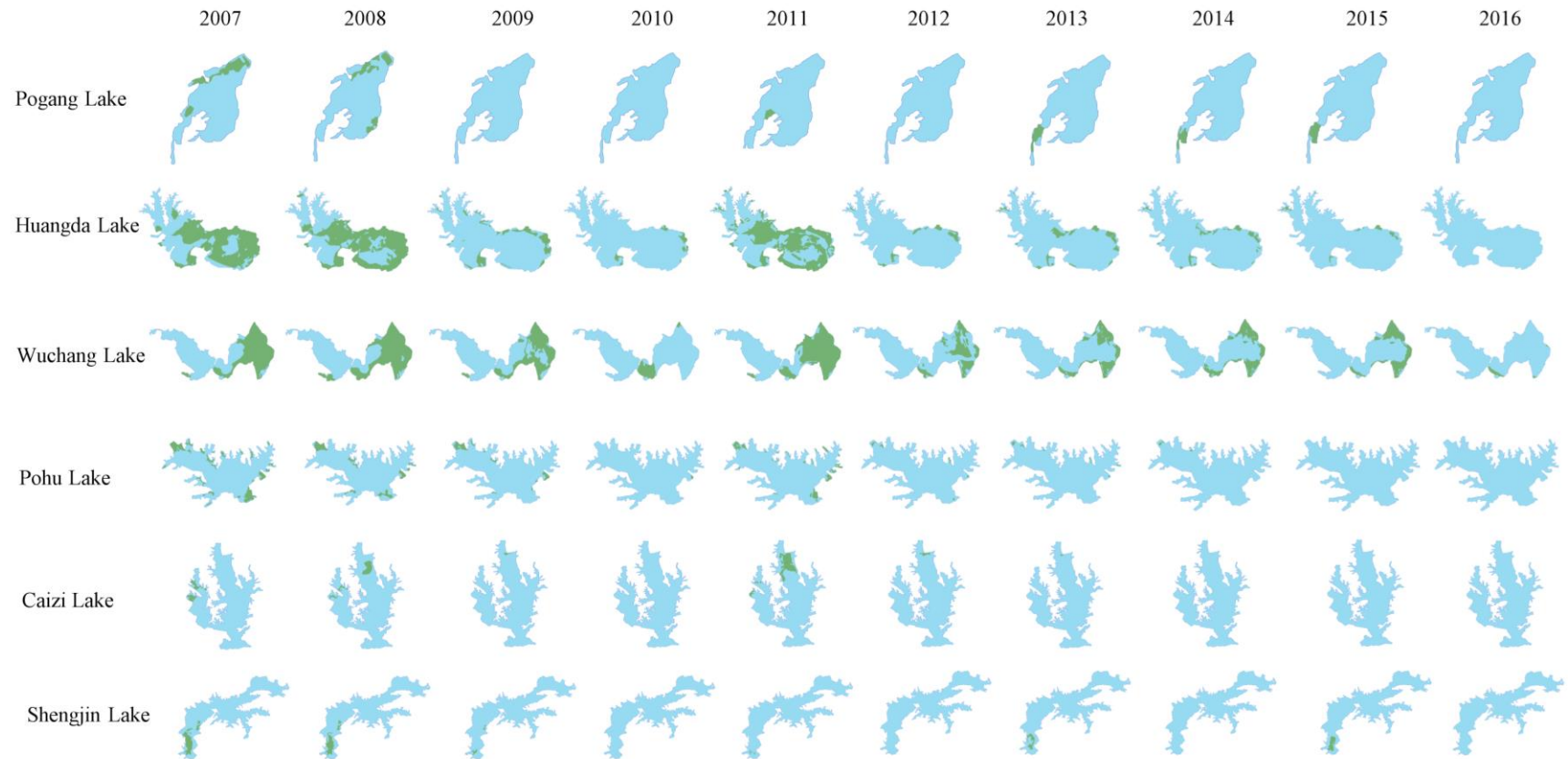
Figure 3. *Spatial and temporal distribution patterns of Z. latifolia in the study lakes from 2007-2016*

Major factors influencing distribution

Spearman correlation analyses revealed that the lake morphological variables, climatic variables, and water quality variables had no significant effects on the distribution of *Z. latifolia*. With regard to the WLF related variables, all the four groups (a total of 20 indicators) except the G4 and G6 groups had significant effects on the distribution of *Z. latifolia* (*Table 3*).

Table 3. *Spearman correlation between WLF variables and Z. latifolia cover. Only the WLF and cover data in Wuchang and Huangda lakes were used in the analysis*

| Items	*R*	*P*
G1: Fluctuating amplitude (m)		
Amplitude	-0.700**	**0.0078**
G2: Monthly mean water depth (m)		
January	-0.561*	**0.0297**
February	-0.810***	**0.0004**
March	-0.393	0.1069
April	-0.792 ***	**0.0001**
May	-0.933***	**0.0000**
June	-0.852***	**0.0000**
July	-0.743***	**0.0003**
August	-0.839***	**0.0000**
September	-0.665***	**0.0019**
October	-0.022	0.9302
November	0.259	0.2834
December	-0.038	0.8846
G3: Annual extreme water depth (m)		
1-day min	-0.665*	**0.0132**
3-day min	-0.657*	**0.0146**
7-day min	-0.694**	**0.0084**
30-day min	-0.720**	**0.0055**
90-day min	-0.645*	**0.0174**
1-day max	-0.777***	**0.0001**
3-day max	-0.782***	**0.0001**
7-day max	-0.782***	**0.0001**
30-day max	-0.819***	**0.0000**
90-day max	-0.837***	**0.0000**
G4: Timing (Julian date) of annual extreme water level		
Date 1-day min	0.073	0.8045
Date 1-day max	0.145	0.5540
G5: Rate of water level changes (cm/d)		
Rise rate	-0.415	0.1581
Fall rate	-0.705**	**0.0071**
G6: Frequency of water level changes		
Reversals	-0.264	0.3826

Reasons for varied cover

After the first level division using TWINSPAN, the six lakes were split by 1-day max into two groups (Shengjin, Pohu, and Caizi lakes with high 1-day max water depth, and the other three lakes with low 1-day max water depth) (*Fig. 4*). Further analyses divided all the six lakes into four groups based on January mean water depths (Pohu Lake and Pogang Lake with high water depth in January, and the other four lakes with low water depth in January) (*Fig. 4*).
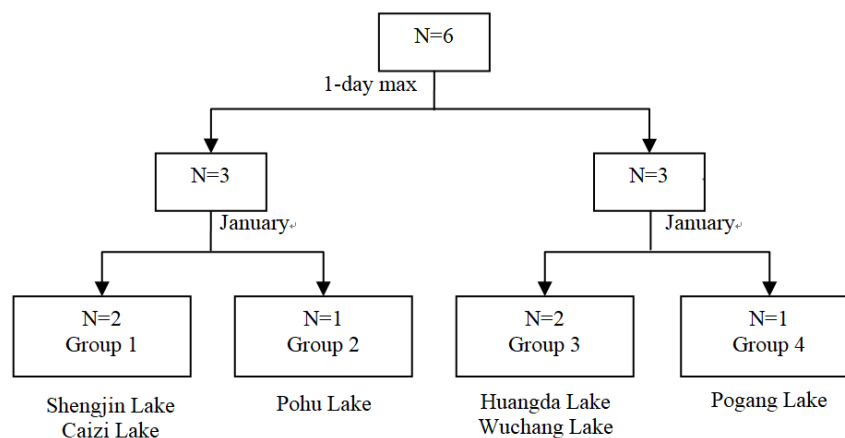
Figure 4. TWINSPAN dendrogram of the study lakes based on water level fluctuation parameters

The life history of *Z. latifolia* can be divided into germination period, rapid growth and expansion period, dispersal period, and dormancy period (*Fig. 5*). Combined with the major hydrological indicators (*Table 3*), the reason for low *Z. latifolia* cover in Pogang Lake could be the high water depths in winter to early spring limiting germination. In addition to the high water depth in the germination period, the high fluctuation amplitude could be a key reason for the low *Z. latifolia* cover in Pohu Lake. With regard to Caizi Lake and Shengjin Lake, although the water depth was low in the germination period, the high fluctuation amplitude and water level change rate was unfavorable for the growth and dispersal of *Z. latifolia*. WLF in Huangda Lake and Wuchang Lake were relatively adequate and met the requirements of *Z. latifolia*, which facilitated the maintenance of relatively high cover.
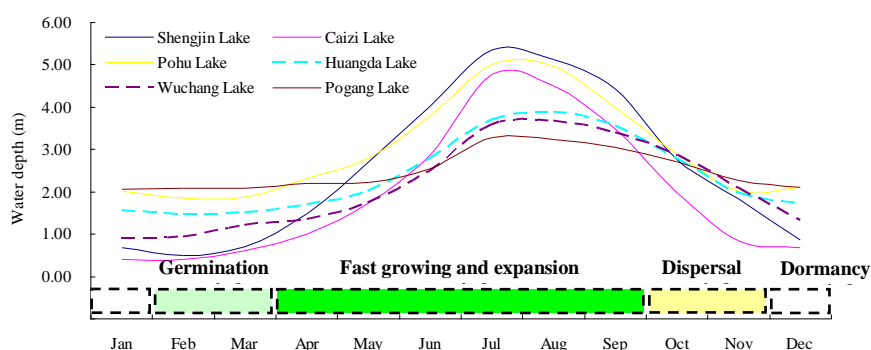
Figure 5. Life history of Z. latifolia and monthly mean water depth in six floodplain lakes

Discussion

The Yangtze River floodplain lakes play important roles in the maintenance of regional species diversity and sustainable economic development (Fang et al., 2006; Wang and Wang, 2016). Although most floodplain lakes have become river-lake disconnected over the past few decades, WLF in the lakes are different largely due to different aquaculture and flood control activities. For instance, Pogang Lake is mainly used for aquaculture, and water level is high and stable throughout the year following the construction of a sluice, while annual mean water level has decreased in Wuchang Lake due to flood control activities (Zhang et al., 2016). In addition, the catchment area and number of tributaries could affect WLF. In Shengjin Lake and Caizi Lake, which had high fluctuation amplitudes, the catchment areas were 3234 km^2 and 1554 km^2, respectively, while in Pogang Lake, which had the lowest fluctuation amplitude, the catchment area was only 346 km^2 (Wang and Dou, 1998).

Spearman correlation analyses revealed that the lake morphological variables, climatic variables, and water quality variables had no significant effects on the distribution of *Z. latifolia.* This could be largely because the variables changed minimally from 2007–2016. Among the six groups of WLF parameters, excluding the frequency of WLF (G4) and the timing of annual extreme water level (G6), the other four groups of water level parameters had significant effects on the distribution of *Z. latifolia*. The frequency of WLFs in lakes are generally low compared with the frequency of WLF in rivers; therefore, the frequency of WLF in lakes has minimal effect on species distribution, and other studies have reported similar findings (Zhang et al., 2015, 2018). The timing of annual extreme water level had no significant impact on the distribution of *Z. latifolia* potentially because the maximum water level of all the lakes was observed in summer, while the lowest water level was observed in winter. In the present study, the fluctuation amplitude was significantly negatively correlated with the distribution of *Z. latifolia*, which indicated that water bodies with relatively stable fluctuation amplitudes could be more appropriate for the growth and development of *Z. latifolia*. Some studies have shown that habitat heterogeneity in lakes decreases with decrease in fluctuation amplitudes, while intraspecific and interspecific competition among plants increases (Zhang, 2013). *Z. latifolia* is often the dominant species under such conditions due to its high competitive ability and its capacity to tolerate flooding (Zhang et al., 2016).

In addition, mean water depths in January–February and April–September were significantly negatively correlated with the distribution of *Z. latifolia*. The low water depth in January–February could significantly improve the underwater light conditions and physico-chemical properties of the sediment (Yang et al., 2020a,b), in turn promoting the germination of *Z. latifolia* individuals. The mean water depth in April-September may have considerable influences on the growth and development of *Z. latifolia*, since numerous studies have shown that the high water depths are not conducive for growth and biomass accumulation in *Z. latifolia* (Wang et al., 2014, 2018; Li et al., 2018). The annual extreme water depths also had significant effects on the distribution of *Z. latifolia*, and the distribution of *Z. latifolia* considerably declined with increase in maximum or minimum water depth. This could be mainly due to increasing stress on growth of *Z. latifolia* with increase in water depth (Mauchamp et al., 2001; Wang et al., 2007; Yang et al., 2020a). In the present study, plant cover in all the six lakes was the lowest in 2010 and 2016, which had the highest water levels, which is consistent with the observation that growth decreases with increase in water level.

The rate of change in water levels is also one of the key hydrological factors influencing the distribution of wetland plants (Yuan et al., 2017). Studies have shown that aquatic plants tolerate rapid changes in water levels to a certain degree; however, when the water levels change too rapidly, aquatic plants may not have adequate time adapt morphologically, and the plants would maintain intermediate and suboptimal states (Vretare et al., 2001). In the present study, the distribution of *Z. latifolia* was significantly negatively correlated with the rate of decline in water level, indicating that a high rate of decline was not conducive for the growth and spread of *Z. latifolia*.

Conclusion

This study showed that the lake morphological variables, climatic variables, and water quality variables had no significant effects on the distribution of *Z. latifolia* in lakes along the lower reaches of the Yangtze River. The WLF was the main factor determining the spatial and temporal distribution of *Z. Latifolia*. The results of the present study have significant implications for the ecological management of *Z. latifolia* in the Yangtze River floodplain lakes. We suggest that in lakes that require the restoration of *Z. latifolia* populations, water levels should be regulated. We recommend the maintenance of a low fluctuation amplitude and a low rate of change in water level. In addition, it is critical to consider that low water depth promotes germination. Conversely, in lakes with *Z. latifolia* overgrowth, we propose the increase of the fluctuation amplitude within a growth year, and the increase of water depth to limit germination. In addition, increasing the rate of change in water level would inhibit seedling growth and spread of *Z. latifolia* in environments in which they are overgrown. Finally, it is highly recommend that future researches carry out more studies to determine the specific WLF requirements of *Z. latifolia*, so as to provide a theoretical basis for the quantitative regulation of lake water levels.

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