



Vegetation Response to Hydrological Changes in Poyang Lake, China

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Abstract

Poyang Lake is the largest freshwater lake and area of alluvial wetlands in China. The vast, seasonally-inundated alluvial plain is internationally recognized for its rare and endangered species which was one of the first to be included in The Ramsar Convention's List of Wetlands of International Importance. Average lake stage (water level) has declined during both the summer wet season and dryer part of the year since the early 2000s, resulting in significant hydrological and ecological consequences. The purpose of this study is to describe changing spatial patterns for major vegetation types and relate vegetation response to changing hydrological conditions. The results suggest that vegetation patterns have shifted substantially in recent years. Most significant is spread of reed and sedge dominated plant communities to sites 1 m to 2 m lower in elevation. Reed communities that continue to dominate the highest elevations within the lake basin expanded across shallow regions of the lake previously too wet for regeneration. In contrast, sedges cannot tolerate dry conditions, and therefore, declined on higher sites. The dominance of aquatic plant communities doubled in area at low elevation sites in the absence of the severe floods that normally inhibit regeneration. We attributed the variation of vegetation patterns to the great water regime changes. However, lower lake stage has not resulted in a highly-degraded wetland ecosystem. Plant communities will continue to adjust to future long-term changes in lake hydrological conditions. The findings provide an important baseline in monitoring vegetation communities' shifts in Poyang Lake wetland from which future research can be compared but also for other international tropical wetlands also impacted by similar threats.

Keywords Wetland vegetation · Ramsar wetland · Hydrology · Reeds and sedge plant communities · Hydoperiod

Introduction

Poyang Lake is the largest freshwater lake in China. It occupies an area of low elevation immediately south of the middle Changjiang (Yangtze River), which it drains into through a narrow channel (Fig. 1). Poyang Lake includes the largest freshwater wetland area in China. The vast, seasonally-inundated alluvial

plain, with an area of 2845 km² (Liu et al. 2013), contain high species richness (551 wetland plant species and 236 bird species) and this region is internationally recognized for its rare and endangered species (eg. *Isoetes sinensis*, *Ceratopteris thalictroides*, *Myriophyllum ussuriensis*, *Ciconia nigra*, *Ciconia boyciana*, *Grus leucogeranus*, and *Grus monacha* etc.) (Ramsar Convention Secretariat 2010; OMDCJ 2015). During the summer wet season, June–September, the lake covers an area of 3752.7 km², inundating the low-lying alluvial plains surrounding the lake and flooding the lower sections of large rivers flowing into it (Liu et al. 2013; Shankman et al. 2006). During the autumn, lake stage (water level) falls eventually receding largely into channels created by its tributaries and shallow depressions. Lowest lake level occurs in the winter, and the lake drops to an area of 907.7 km² (Liu et al. 2013). During spring months preceding the summer monsoon, lake stage rises again.

Change in the hydrological conditions of Poyang Lake during the past few years presents a threat to the wetland ecosystem. Causes of lake decline have been attributed to lower Changjiang stage related to operation of the Three-

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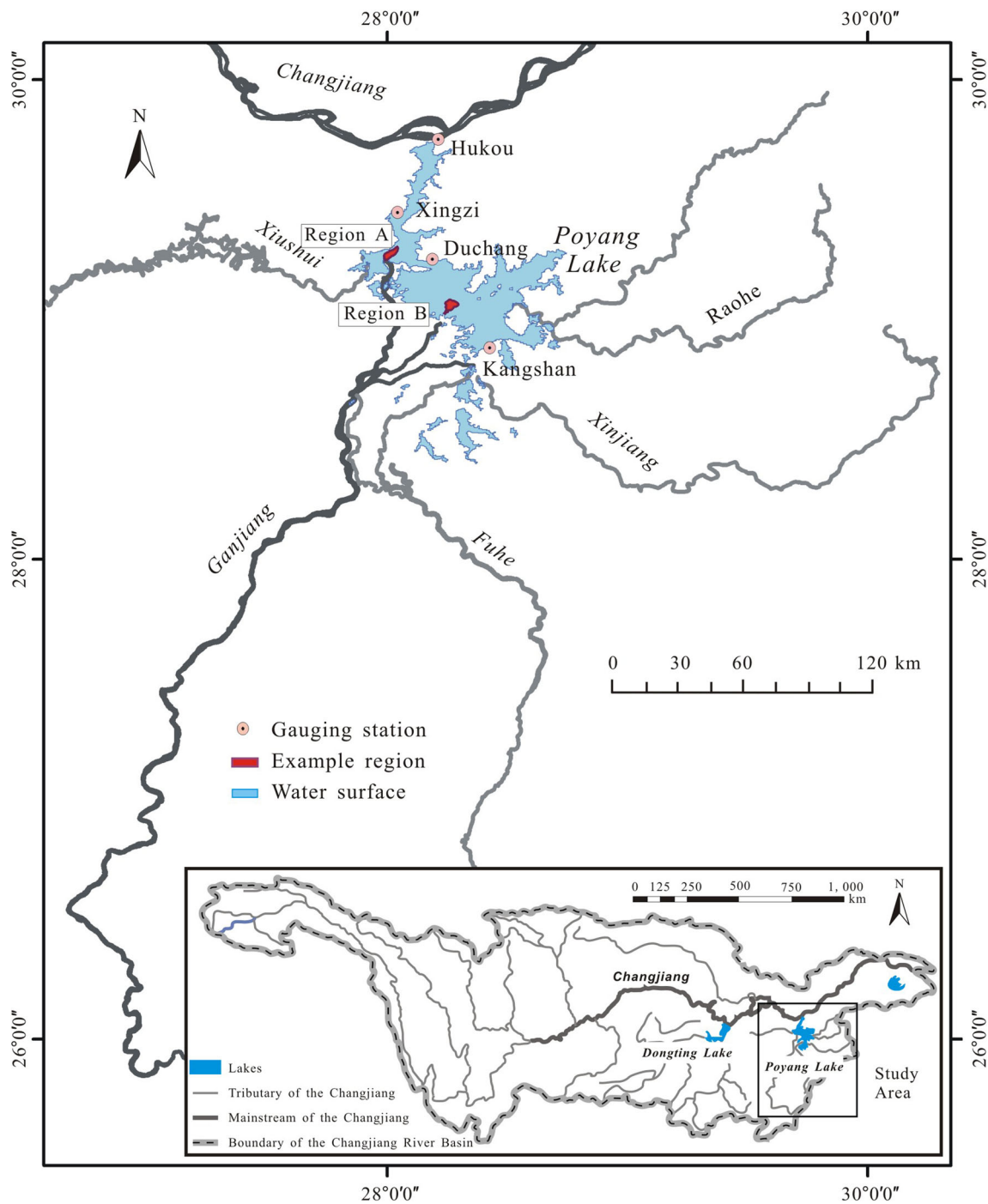


Fig. 1 Map of Poyang Lake with inset showing its location south of the Yangtze River. Plant community elevation zones for Regions A and B are shown in Fig. 3

Gorges Dam (Zhang et al. 2012b; Liu et al. 2013; Zhang et al. 2014; Dai et al. 2015), less precipitation in the Poyang Lake drainage basin (Gao et al. 2014; Zhang et al. 2015) and sand mining that enlarged the outflow channel connected to the Changjiang (Lai et al. 2014). Regeneration and distribution of wetland plants and formation of distinctive plant communities on seasonally-inundated sites is directly related to the depth, duration, and timing of inundation. Many wetland

plants have a narrow range of hydrological conditions necessary for regeneration and are likely to be vulnerable to drier conditions. How these plant communities respond to dramatically lower lake water level is not clear.

Previous work has described or speculated about the effects of lower lake stage on vegetation patterns, and the potential for ecological degradation to the extensive wetlands of the seasonally-inundated alluvial plains (Barzen et al. 2009;

Zhang et al. 2012b). Zhang et al. (2012a) explored the influences of hydrological conditions on vegetation structure within the Poyang Lake National Nature Reserve and determined that difference in sensitivity to hydrological conditions among communities is the main reason of vegetation succession. More recently, Dai et al. (2016) investigated the distribution of spring sedges in response to water level fluctuations in Poyang Lake and revealed that continual presence of high water levels lasting up to 20 days during spring could trigger substantial changes in distribution of sedges. Hu et al. (2015), Tan and Jiang (2016) and Tan et al. (2016) analyzed the response of Poyang Lake wetland to water level fluctuations from 2000 to 2012 based on MODIS imagery and revealed that different vegetation communities can only survive a particular range of mean water depth and percent time inundated in Poyang Lake. However, aquatic plants communities were not mentioned in previous studies. Hence we still have no detailed, large-scale descriptions of vegetation changes in response to modified hydrological conditions. The purpose of this investigation is to describe changes in wetland vegetation patterns in response to a significant decrease in both average annual summer maximum stage since 1999, and average dry season lake stage that began in 2000. Specifically, we (1) describe changing spatial patterns for major vegetation types and relate vegetation response to changing hydrological conditions, and (2) discuss probable long-term effects of changes in seasonal water level fluctuations on wetland plant communities and future ecological threats.

Methods

Study Area

The Poyang Lake watershed area covers 162,000 km². The headwaters of the lake basin are located in the surrounding mountains. Forestland prevails and accounts for 57.1%, followed by cropland (29%), built-up land (6.2%), water body (5.6%) and other land (2.1%). The five major rivers flowing into Poyang Lake are the Xuishui, Ganjiang, Fuhe, Xinjiang, and Raohe (Fig. 1). Stream gradient decreases as these rivers flow onto the relatively flat region surrounding Poyang Lake. Sediment deposition from the Ganjiang, the largest river in the lake watershed and, to a lesser extent the Fuhe (the second largest river in the lake watershed) has created a large delta plain on the southern and western shores of Poyang Lake that is dissected by their distributaries. The Ganjiang contributes a larger discharge and sediment load than the flow and sediment contribution of the other tributaries combined.

Lake level depends on both Changjiang stage and discharge from the lake watershed. The rainy season in southern China typically begins in late spring and continues throughout the summer. Most years, discharge from the large rivers in the

lake watershed increases during spring to mid-summer, raising the level of Poyang Lake, which drains into the Changjiang at Hukou (Fig. 1). From July to early September, Poyang Lake tributary discharge steadily decreases, while at the same time, Changjiang discharge and water level increases (Fig. 1). If the level of Changjiang exceeds that of the lake, the previous flow of water from the lake into the Changjiang reverses, and the muddy water from the Changjiang flows into the lake. The highest annual lake stage generally ranges from about 18 m to 21 m above mean sea level (m.s.l) during the summer monsoon season in southern China, but may be higher or lower during unusually wet or dry years (Shankman et al. 2006). The lowest annual lake stage generally ranges from about 8 m to 9 m above m.s.l., but may be higher or lower during unusually wet or dry years (Shankman et al. 2006).

There are three major vegetation types (zones) in Poyang Lake wetland (Zhu and Zhang 1997) (Table 1). They are as follows: Zone 1 (reeds), semi-aquatic emergent tall vegetation (e.g., *Phragmites communis* and *Miscanthus sacchariflorus*); Zone 2 (sedges), emergent aquatic vegetation (e.g., *Carex cinerascens* and *Phalaris arundinacea*); and Zone 3 (aquatics), floating/submerged vegetation (e.g., *Potamogeton malainus* and *Vallisneria natans*). In the surrounding area of the lake (5 km buffer of the lake) cropland prevails and covers 67.7%, forestland, water body, grassland, built-up land and bareland take up 11.8%, 11.7%, 5.4%, 2.9 and 0.5%, respectively.

Data Sources

In this study, we utilized available daily water level data of Poyang Lake from Xingzi Station (Dai et al. 2014; 2015; Zhang and Werner 2015) from 1990 to 2014 to reveal fluctuating water regimes in the wetland. A Digital Elevation Model (DEM) with a resolution of 5.0 m, obtained from the Hydrological Bureau of Jiangxi Province (<http://www.jxsw.cn/>), was used to reveal the spatial pattern of vegetation distribution. Six Landsat TM/ETM⁺ images was applied to generate vegetation maps of the wetland in six different years, including 1995, 1999, 2001, 2004, 2006 and 2009. All these Landsat images were acquired at late autumn of the corresponding year (Landsat Scene Identifier: LT51210401995341CLT00, LE71210401999344SGS00, LT51210402001325BJC00, LT51210402004334BJC00, LT51210402006307BJC01, LE71210402009339EDC00), because the area of exposed grassland reaches a maximum in the end of the autumn in Poyang Lake wetland.

Processing of Remote Sensing Images

All the six Landsat TM/ETM⁺ images were processed by three steps: (1) Image preprocessing. We applied ENVI 4.7 software

Table 1 Three major vegetation types corresponding to elevation zones (Zhu and Zhang 1997). Dominant species for each vegetation type is shown

Zones	Vegetation Type	Dominant Species	Surface Elevation in Typical region A	Surface Elevation in Typical region B	Surface Elevation	Surface Exposure
1	Reeds	<i>Phragmites communis</i> <i>Miscanthus sacchariflorus</i> <i>Artemisia selengensis</i> <i>Artemisia rubripes</i> <i>Polygonum caespitosum</i> <i>Zizania caduciflora</i>	15–17 m	15.5–16 m	>15.5 m	>270 days
2	Sedges	<i>Carex cinerascens</i> <i>Carex brevicuspis</i> <i>Carex scabrifolia</i> <i>Carex argyi</i> <i>Carex doniana</i> <i>Carex unisexualis</i> <i>C. laticeps</i> <i>Phalaris arundinacea</i> <i>Polygonum orientale</i> <i>Polygonum japonicum</i> <i>Cardamine lyrata</i> <i>Potentilla limprichtii</i>	12.5–15 m	14.5–15.5 m	13.5–15.5 m	170–270 days
3	Aquatics	<i>Vallisneria natans</i> <i>Potamogeton malaianus</i> <i>Potamogeton crispus</i> <i>Trapa maximowiczii</i> <i>Hydrilla verticillata</i> var. <i>rosburghii</i> <i>Najas minor</i>	11.5–12.5 m	14–15 m	<13.5 m	0–100 days

for the map registration through choosing ground-control points in a geo-referenced Landsat images of this area. The root mean square errors in image registration were < 0.3 pixel for all six images during 1995–2009. We then selected a spatial subset to extract the images that included the scope of the whole lake area. (2) Hierarchical classification. Wetland vegetation was mapped according to the following classes: water, mudflat, aquatics, sedges, reeds, and bare land. A hierarchical classification method was applied to delineate the vegetation (You et al. 2017). In this method, the first level consisted of water, vegetation, and land-water transition zone. Normalized Difference Vegetation Index (NDVI) was calculated using the calculation formula of $NDVI = (NIR - RED) / (NIR + RED)$ by ENVI 4.7 to obtain the vegetation coverage distribution. The second level included six types of wetland landscapes, which are water, mudflat, aquatics, sedges, reeds, and bare land. We utilized the Wetland Inventory data gathered by the Poyang Lake Marsh Field Station in each year as the ground surface reference to image the classification. Vegetation maps of the wetland were extracted from remote sensing images based on the spectral curve characteristics of different marks. (3) Accuracy assessment. A standard error matrix, overall classification accuracies, and Kappa chance correction statistics were used for the images to determine the accuracy of the hierarchical classifications. Finally, the overall classification accuracy of the remote sensing images was more than 80% compared with the ground truth.

GIS Analysis

Combining the two data set of DEM and vegetation maps, the coverage area of each vegetation types in different elevation ranges were calculated from overlapped vegetation and DEM maps on the platform of ArcGIS 10.2. It was then used to reveal the variation of vegetation distribution in different years with varying water regime conditions.

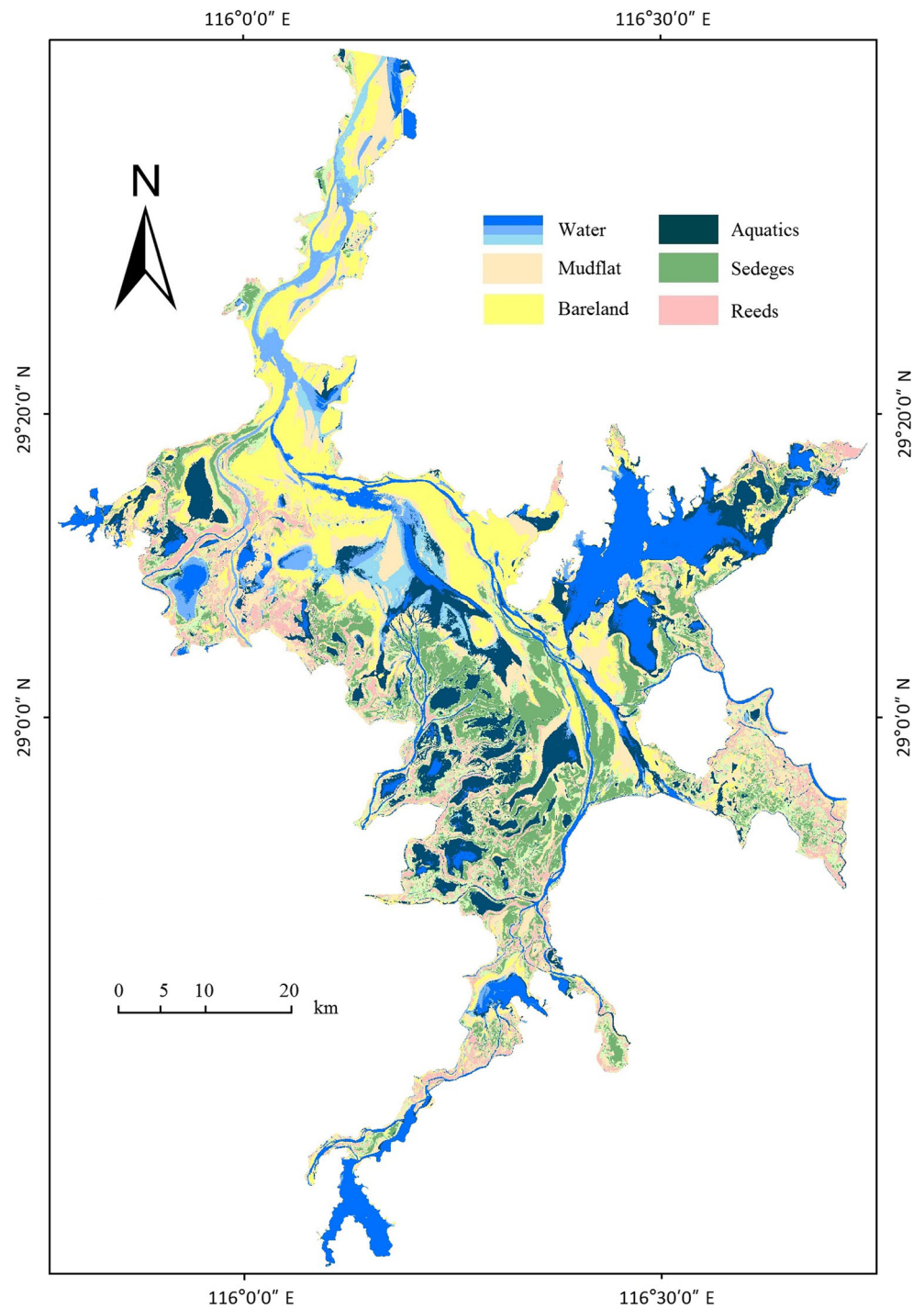
Results

Spatial Distribution of Vegetation Types

Wetland vegetation patterns within Poyang Lake depend on depth and duration of surface submersion and therefore occur in well-recognized elevation zones. Three major vegetation types (zones) distribute with gradient (Table 1).

Figure 2 showed the distribution pattern of the differing vegetation zones in 2006. Zone 1 (Reeds) occurs on the highest surfaces within the lake basin and may only be submerged during the summer floods. Reeds cannot tolerate long-term root submersion and occur on surfaces exposed for at least 270 days per year. This zone is generally above 15 m elevation, although the precise elevation varies depending on location within the lake (Fig. 3), and the average inundation depth of this zone is 0 to 2 m. The dominant vegetation type,

Fig. 2 The vegetation map of Poyang Lake wetland in 2006

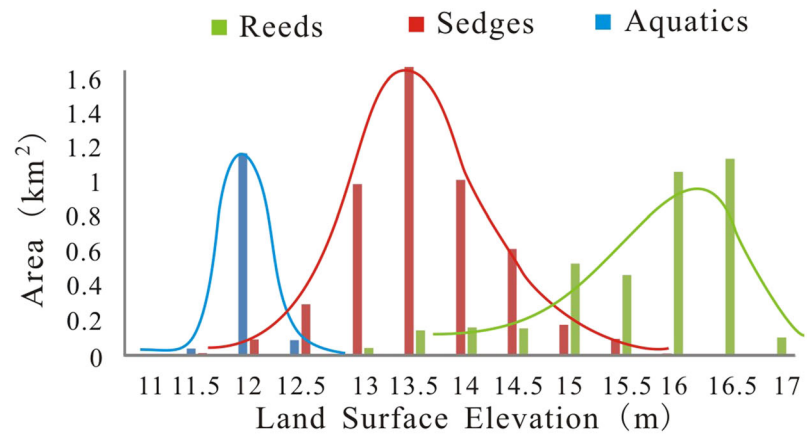


reeds, can reach up to about 3 m tall in summer and are the only communities on these surfaces that are partially above water during summer flood. *Carex spp.* and other minor components of these plant communities are less than 0.6 m tall and most years become completely submerged during summer.

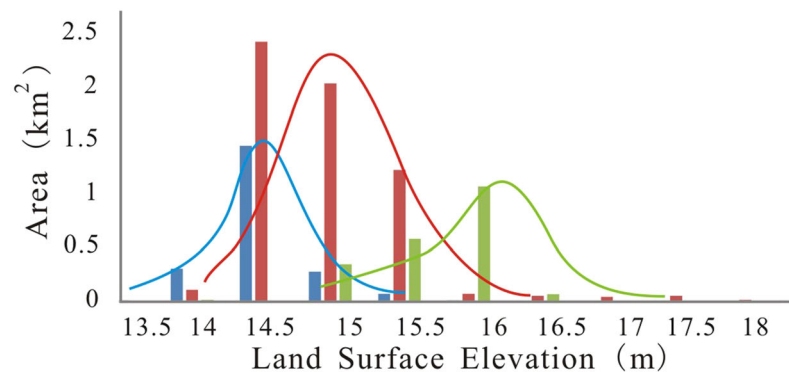
Zone 2 (Sedges) is located on lower surfaces compared to Zone 1, generally about 13 m to 15 m elevation at the lower (northern) section of the lake and at slightly higher elevation with distance to the south (Fig. 2, Fig. 3). These sites have a

long inundation period during summer, and the average inundation depth is 2 m to 6 m. Surface exposure ranges from 170 to 270 days per year and compared to Zone 1, experiences greater flood depth. Sedges spread vegetatively (Editorial board of Wetland Vegetation in China 1999) and to a lesser extent by seeds. In the seasonally submerged area of Poyang Lake, sedges have developed the distinctive feature of initiating growth twice within a year, in spring and fall (Guan et al. 1987). They become dormant during summer and winter.

Fig. 3 Area of dominance for reed, sedge, and aquatic plant communities for different elevations in Regions A and B (2006)



Region A: The wetland surrounding the main branch estuary of the Ganjiang River



Region B: The wetland surrounding the south branch estuary of the Ganjiang River

Zone 3 (aquatics) includes low surfaces within the lake, generally about 10 m to 13 m elevation (Fig. 2, Fig. 3). Aquatic plants grow on sites that are submerged much of the year, but require periods of exposure for establishment of a seedbed. Therefore, they do not generally occur in or near channels created by lake tributaries, which are the lowest surfaces within the lake and are continuously under water. The highest sections of this zone occasionally include sedges, but long-term submersion and water depth, in almost all cases, preclude reeds. This zone is occupied by floating/submerged aquatic plants. Submerged plants spread vegetatively and by seeds (Chen et al. 2006; Jarvis and Moore 2008). Aquatic plants germinate in late spring when lake stage is increasing, and grow vigorously in summer when the lake typically reaches its highest stage. These plants blossom during late summer and yield fruit in August which matures in October.

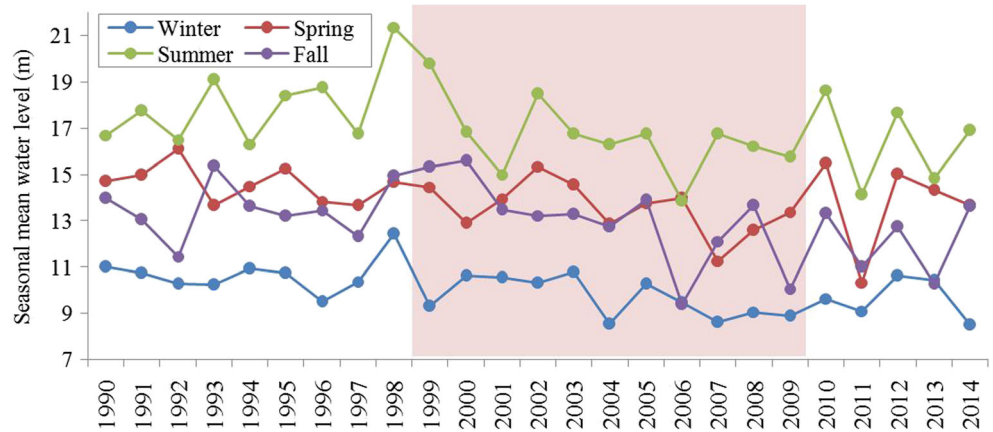
Decreasing Lake Stage

Average lake stage has decreased significantly ($p = 0.003$) during the past few years (Fig. 4). The frequency of severe floods that occurred during the summer monsoon and average

annual maximum lake stage reached historical highs during the 1990s. However, since the 1998 flood, which was the most severe ever recorded on Poyang Lake, no severe floods have occurred (Shankman et al. 2009, 2012, and later gauging station data) and the average annual maximum lake stage has declined greater than 2 m (from 20.73 m before 2000 to 18.27 m during the later years). Although maximum annual stage has decreased, almost every year during the summer monsoon, the lake extends from the eastern shore to the levees protecting low lying areas to the west. So the total lake area at this time remains largely unchanged, but depth and duration of floods for large areas within the lake basin have decreased.

Lake stage during the drier time of year has also decreased significantly. Average annual minimum lake stage (usually occurring during the winter months) for the years 1953–2002 was 8.0 m and for the 1990s was 8.5 m. This value, however, decreased to 7.7 m during the most recent decade (2003–2014). The duration of low lake stage, defined by Min and Zhan (2012) as periods at less than 11.8 m, has increased from 137 days (1952–2000) to 175 days (2001–2010). The low lake period during the most recent decade began earlier during the fall and continued later into the spring. Average

Fig. 4 Average lake stage (1995–2014) for (a) spring and summer and (b) winter and fall. The period of dramatic lake decline is shaded



lake stage during both (1) fall months, a period during which lake stage declined from 13.8 m (1990–2002) to 12.2 m (2003–2014), and (2) spring months, when lake stage increases, fell from 14.5 m (1990–2002) to 13.4 m (2003–2014). Although average lake stage during these times of year has decreased significantly ($p < 0.05$), the annual variability of lake stage remains high.

Hydrological Changes and Shifting Vegetation Patterns

Zone 1 (Reeds)

Deep water during the summer flood season and surface inundation during the spring and fall months is detrimental to growth of reeds. Average summer maximum lake stage greatly increased over the period 1950s–1990s. During the mid-late 1990s, reeds dominated a relatively small area compared to more recent years. During the early-mid 1990s, Zone 1,

covered an area of 150 km² (Fig. 5a). The reed-dominated area decreased to 135 km² in 1999 because of a series of floods (the most severe during 1995 and 1998). Reeds distribution contracted until they occurred mostly on higher surfaces nearer the lake margins, including the Ganjiang and Fuhe deltas at the southern end of the lake, and near the mouth of the Xiushui to the west (Fig. 6).

Since the early 2000s, however, decreasing average lake stage throughout the year has facilitated expansion of reed-dominated sites. No severe floods occurred since 1998 and both spring and fall months, critical periods for reed growth and regeneration, became much drier. Since 2001, Zone 1 covers an area usually greater than 300 km², which is an increase of 50% since the 1990s. Maximum area of reed dominance since the 1990s was 390 km². An exception occurred during fall 2006, when unusually dry conditions and low soil moisture content reached a critical threshold for reeds on many sites they previously dominated. Reed distribution that year shrank to an area of 268 km², a 26%

Fig. 5 Area of dominance for reed (a), sedge (b), and aquatic (c) dominated communities

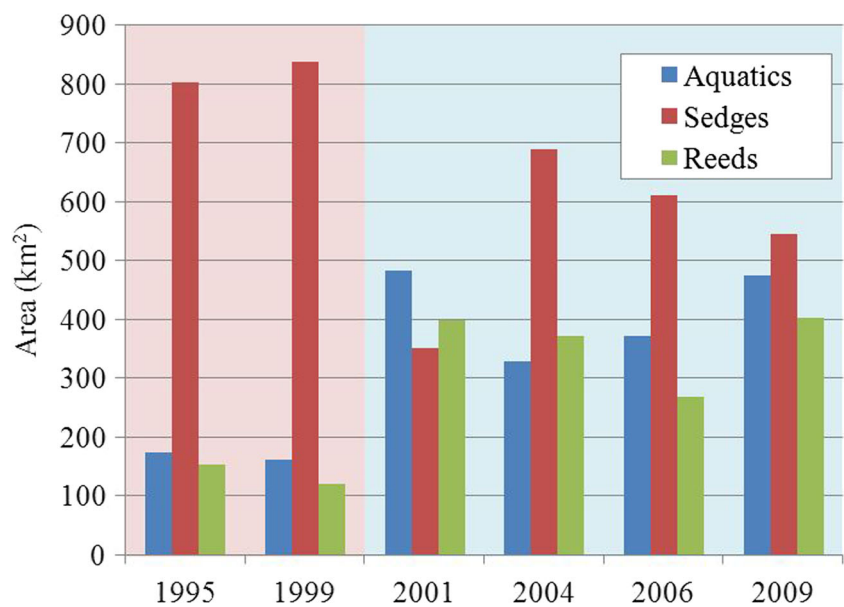
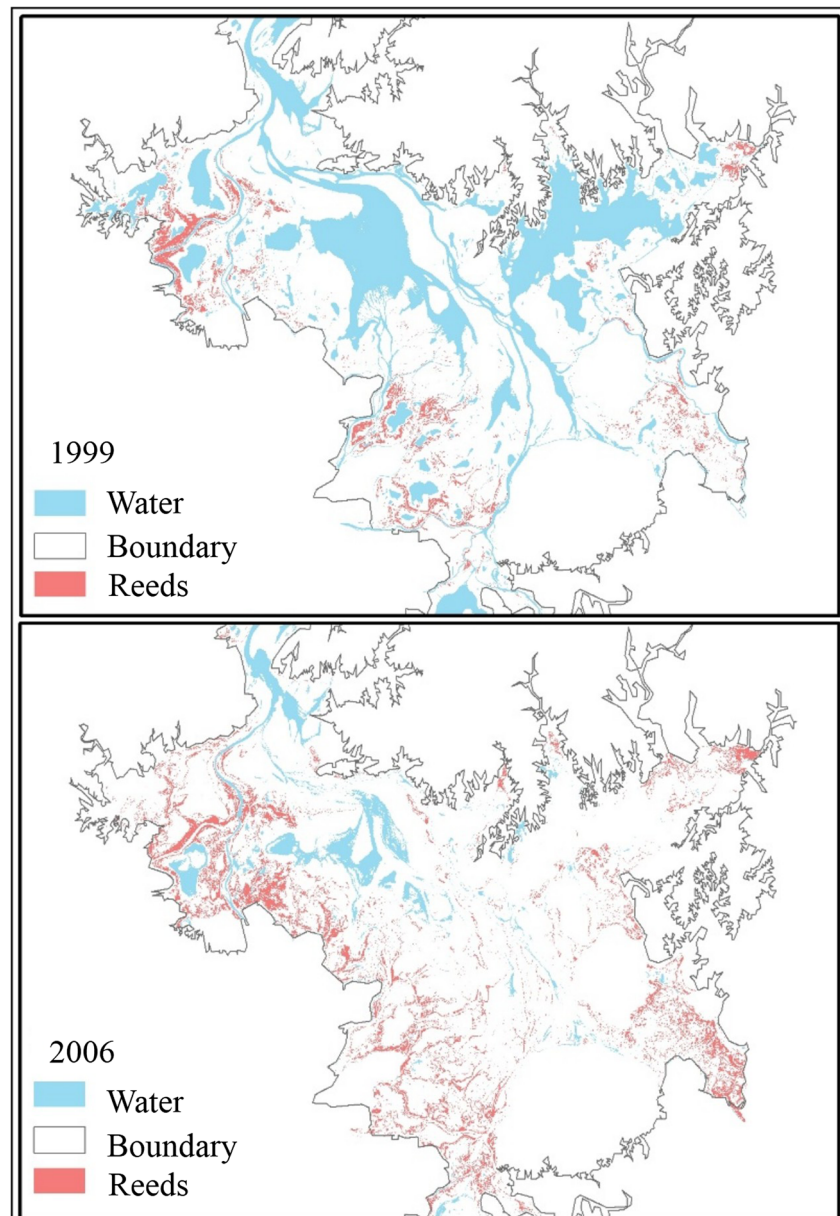


Fig. 6 Maps showing distributions of reed dominated communities (1999 and 2006)



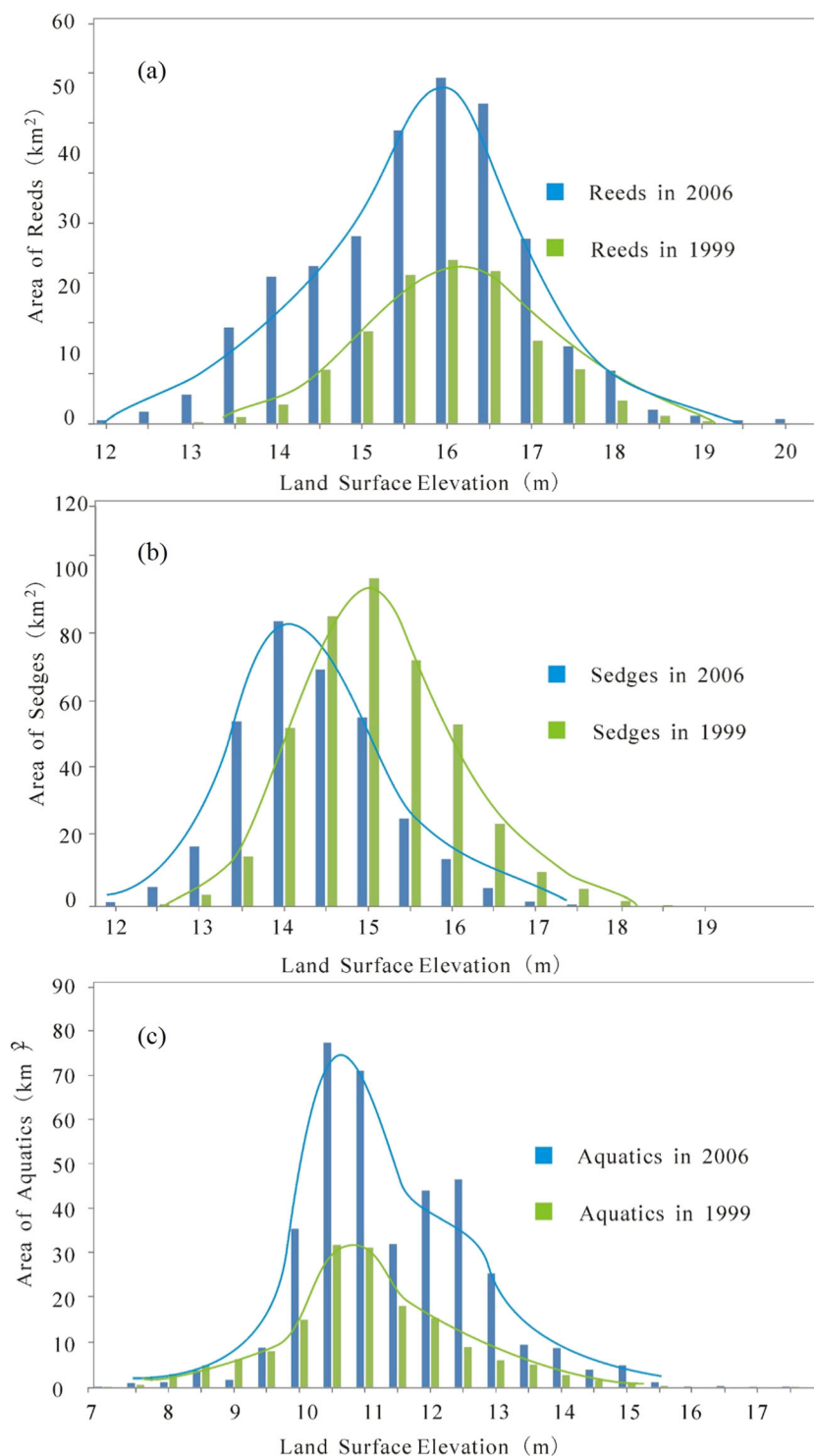
reduction and by far the lowest area of reed dominance compared to all other years since 2001 (Fig. 5a). A comparison of reed dominance during 1999 and 2006 at different elevations within the lake basin shows (1) little change on sites greater than 17 m elevation, which are at the lake margins, (2) a dramatic increase in dominance on sites 14 m to 17 m elevation, and (3) a significant expansion onto surfaces less than 14 m elevation that were previously too wet for reeds (Fig. 7a).

Zone 2 (Sedges)

The severity of flood affects distribution of sedges in an indirect but significant way. Sedges are submerged and;

therefore, dormant during summer floods. But the most severe floods results in expansion of sedges on to sites occupied by reeds. Besides high lake stage in summer, sedges are also sensitive to dry soils during their spring and fall periods of rapid growth. The area of sedge dominance significantly decreased from the 1990s to the late 2000s (Fig. 8). Sedges during the mid-late 1990s dominated an area of 800 km² (Fig. 5b). This was a period of successive wet years with high summer lake stage (Fig. 4) which led to expansion of sedges into the upper lake basin formally occupied by reeds. Reeds declined because they were unable to survive the long and deep submergence in summer floods. Affected areas include the Ganjiang-Fuhe delta on the southwestern lake

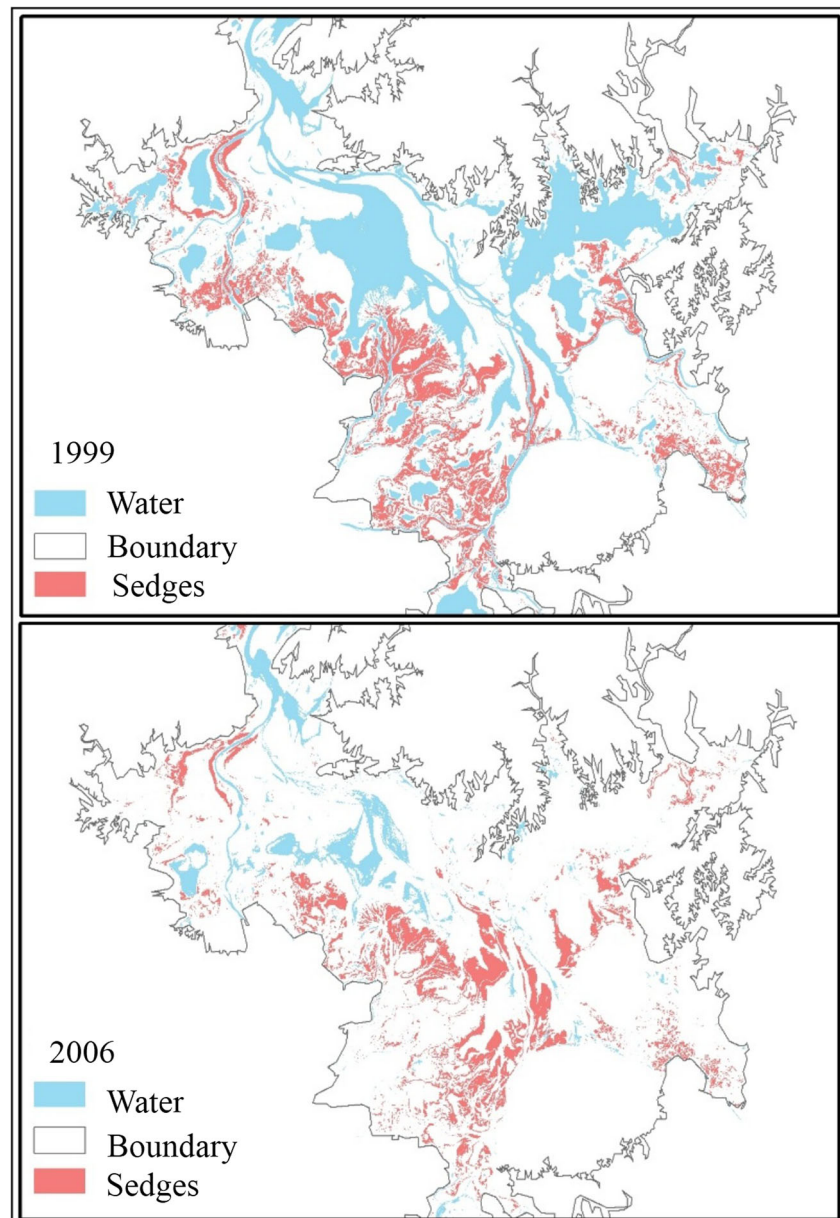
Fig. 7 Area composition of reeds (a), sedge (b), and aquatic (c) dominated communities at various elevations between 1999 and 2006



margins and the areas near the Xuishui to the west. During 2001, high lake stage during fall months inhibited growth and regeneration of sedges which retreated from the western lake basin (Fig. 8). Their area of dominance that year was 350 km², less than 50% of the area during earlier years. During the mid-late 2000s, average lake stage throughout the year was low. Low

stage during summer and fall months facilitated a dramatic expansion of sedges, most notably in the western lake basin (Fig. 8). Average annual area of sedge dominance during these years was 614 km² (Fig. 5b). A comparison of sedge dominance during 1999 and 2006 at different elevations within the lake basin shows a 1 m to 2 m shift toward lower elevation because of generally

Fig. 8 Maps showing distributions of sedge dominated communities (1999 and 2006)



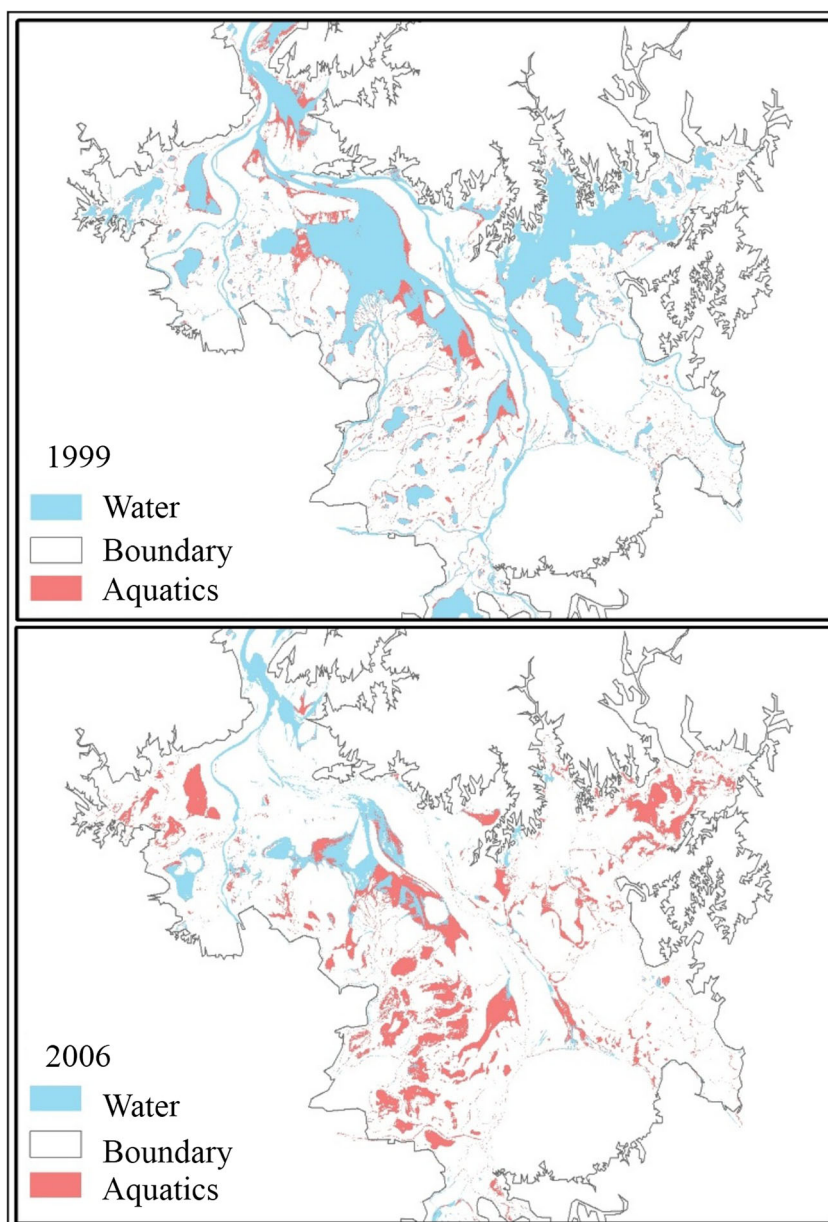
lower lake stage (Fig. 7b). Specifically, (1) sedge dominance declined on sites at 15 m to 17 m elevation and (2) increased dominance at 12 m to 14 m (Fig. 7b).

Zone 3 (Aquatics)

Extremely high lake stage during the summer flood season is detrimental to growth of aquatics. Increasing average lake stage and a series of severe floods during the 50 year period, 1950s- 1990s reduced coverage of aquatics. During the mid-late 1990s, aquatics dominated a relatively small area compared to more recent years. During the early-mid 1990s, aquatics covered an area of 100–150 km², mostly west of the Ganjiang lake channel (Fig. 5c, Fig. 9). Since the early

2000s, decreasing average summer lake stage has facilitated a dramatic expansion of aquatics into Ganjiang delta to the southwest, lake sub-basins to the west, and near the mouth of the Raohe to the east (Fig. 5c, Fig. 9). During this period, average annual coverage of aquatics was greater than 440 km² and attained a maximum area of almost 500 km². A comparison of aquatic dominance during 1999 and 2006 at different elevations within the lake basin shows (1) little change on sites 7 m to 9 m and 14 m to 15 m that are at the extremes of their elevational range, but (2) a dramatic increase in dominance on sites 10 m to 13 m elevation (Fig. 7c). Minimal elevation shift in their distribution shows that aquatics have a narrow range of conditions necessary for regeneration and are limited primarily to a narrow elevational band.

Fig. 9 Maps showing distributions of aquatic dominated communities (1999 and 2006)



Discussion

Hydrological Demands of Vegetation Types

The hydrological conditions most conducive for growth and reproduction of reeds vary during the year and at different stages of growth. Rhizomes of reeds sprout most actively in spring as the lake stage and area increases (Xie and Yang 2009). At this time, exposed surfaces with high soil moisture content provide ideal conditions for growth. Springtime submersion that occurs during unusually wet years suppresses growth (Xie and Yang 2009). The most vigorous growth of reeds occurs in summer. Maximum annual lake stage is highly variable. Sites dominated by reeds are gradually inundated only during severe summer floods. Reeds cannot tolerate

long-term and deep root submersion. So extreme floods in summer result in high mortality rates of reeds (Deegan et al. 2007; Xie and Yang 2009), while low flood stage favors growth of reeds. During fall months, as the lake recedes, reeds enter the booting stage in early September and heading stage in late October and early November (Feng et al. 2009). Surface submersion at this time of year is not conducive to growth. During the winter dry season, above ground stems wither and die, while the underground rhizomes become dormant. Water level fluctuations during winter months have no direct influence on distribution of reeds.

Sedges grow best on exposed sites with wet soils. Precipitation increases from early spring until summer and the rise of soil moisture, absent submersion, promotes tillering of sedges (Wang et al. 2009; Dai et al. 2016). During the

summer flood season, sedges that grow to a height of 40 cm to 60 cm are submerged. Above ground shoots wither and the plants become dormant (Wu et al. 2012; Zhang et al. 2013). During the fall water levels recede and sedges initiate growth as sites are exposed. The upper limits of lake stage during spring and fall controls the lowest elevation sites for sedges. Hence, unusually high water level during fall (typically a period of rapid growth) limits the growing space exposed for sedges, while a drier condition in fall leads to a larger exposed area for growing sedges. As noted earlier, a very high summer lake stage kills reeds. Sites previously dominated by reeds will be occupied by sedges after initiating a second growth period during the fall. During the winter dry season (a dormancy period), water level fluctuation and differences in soil moisture have no direct influence on the growth or distribution of sedges. Overall, sedges prefer severe summer floods, dry falls, and wet springs.

The hydrological demands of submerged plants in Poyang Lake vary greatly in different growth stages. Submerged plants germinate during spring in shallow water, not on exposed surfaces. Unusually dry conditions precludes regeneration (Li and Lian 1996; Chen et al. 2006). Under normal summer flood conditions, submerged plants receive optimal sunlight for growth. But during severe floods, progressively higher lake stage reduces sunlight and slows growth (Chen et al. 2006; Yuan et al. 2008; Wu and Li 2012; Yang et al. 2014). A wet fall, producing shallow water, is favorable for aquatics. Aquatics are dormant during the winter dry season, and are susceptible to unusually dry conditions that kill rhizomes buried in shallow mud (Liu et al. 2012).

Poyang Lake includes about 100 shallow sub-basins, covering a total area of 800 km², in the western part of the lake near the mouth of the Xiushui and in the Ganjiang delta. These basins are submerged during summer floods. They become detached from the main body of the lake during the fall months as lake stage declines and lake area shrinks. Shallow water in these sub-basins during late fall and winter months provides ideal habitat for aquatics and migratory water birds. Aquatics are the main food sources for migratory water birds. Water depth less than 60 cm is suitable for migratory water birds to forage (Burnham 2007; Barzen et al. 2009; Xia et al. 2010). Some sub-basin lakes in Poyang are controlled to maintain an average water depth of 20 cm to 60 cm during fall and winter months to meet the needs of aquatics and water birds (Guo 2005; Chen et al. 2013).

Long-Term Vegetation Changes and Future Ecological Threats

Water regime changes in Poyang Lake in recent decades have been revealed by many scholars (Liu et al. 2013; Shankman et al. 2009; Zhang et al. 2012b, 2014, 2015). The continuation of low lake stage, as opposed to reverting to wetter conditions

that existed before 2000, is not certain. Precipitation in the Changjiang basin that covers much of southern China is the dominant control of Poyang Lake stage. Severity of summer floods is directly linked to Changjiang stage that controls lake discharge (Shankman et al. 2012). Severe floods do not occur if Changjiang stage is low regardless of precipitation in the Poyang Lake basin. During drier months Changjiang discharge and stage are much lower, but still have an effect on lake stage because of changes in water surface gradient in the lake's outlet channel. Decadal-scale rainfall variability in this region has been noted, but future rainfall cannot be determined by examination of the historic records (Liu et al. 2013). Some argue low lake stage can be attributed to the Three-Gorges Dam that affects Changjiang discharge (Liu et al. 2013; Zhang et al. 2014; Dai et al. 2015), or sand mining that enlarged the lake's outflow channel (Lai et al. 2014). Both factors might be significant, but can also be viewed as secondary to changes in rainfall.

Previous work has also revealed many effects of water regime variation on wetland vegetation (Dai et al. 2016; Zhang et al. 2012a, 2013). If dry conditions of the past few years continues, major changes in vegetation patterns are unlikely. The area of reed dominance could increase slightly. Reeds, that are moderately drought tolerant, can maintain themselves at the highest elevation sites within the lake, areas generally above 17 m, and are likely to spread to lower elevation in the absence of severe summer floods. Sedge distribution is unlikely to change significantly. Sedges cannot tolerate dry conditions on high lake surfaces were they previously dominated. On the other hand, lowest elevation sites for sedges correspond to the upper limits of lake stage during spring and fall. If dry conditions continue and the water surface retreats towards the lake center, sedges will spread to lower sites as they follow the water surface. These two shifts can maintain the area of sedges even under a drier condition. Aquatics are highly sensitive to severe summer floods. In the absence of severe floods, aquatics will maintain dominance on lower elevation sites, 10 m to 13 m. Many sub-lake basins have small dams designed as water control structures to prevent their drainage during dry winter months to protect aquatic species. In some cases, a shift toward dryer conditions allows upland species to invade. But those species are unable to do so in the Poyang Lake basin. Every year summer floods, even in the driest years, cover the entire lake basin precluding non-wetland species that cannot tolerate root submersion.

If, during the next decade, high precipitation and lake stage rivals wet conditions during the 1980s and 1990s, vegetation patterns will be similar to what occurred at that time. The area of reed dominance will contract. Reeds will mostly disappear on low elevation surfaces which they colonized since 2000. Reeds cannot survive on sites less than 14 m because of their intolerance to surface submersion during spring and increasing water depth during summer floods. Sedges will shift

toward higher elevation. Similar to reeds, sedges will no longer occur on sites less than about 13 m, but will expand on sites 15 m to 17 m. Near their upper elevation limits, sedges and reeds share dominance on some sites, but with progressively drier conditions, reed dominance increases. Aquatics are restricted to a narrow elevational range of 10 m to 13 m. An increasing frequency of major floods will lead to a significant reduction in aquatic dominance on these sites because of their intolerance to low light under deep water. If, during the next decade, rainfall levels will be high but not higher than the 1990s, the vegetation pattern will be situated between the two cases discussed above.

A dam proposal on the outlet channel of Poyang Lake, often referred to as the Poyang Lake water control structure is now being considered. The dam will be 2.8 km long with sluice gates, 27 km upstream of the Changjiang (Wang et al. 2015). Its purpose is to slow lake discharge into the Changjiang and increase lake stage during dry months. It will have no effect during the summer wet season. Planned minimum lake stage is 12 m.

The dam will effect lake vegetation. Reeds and sedges are uncommon on sites below 12 m, so inundation up to that height will have minimal effects on their distributions. For aquatic plant communities, however, the effects of year-round inundation will be significant. Regeneration of aquatic plant communities requires surface exposure that allows seeds and winter buds contact with the lake bed (McFarland 2006; Jarvis and Moore 2008). Aquatics are most common on sites 10 m to 13 m elevation. Year-round surface inundation at 12 m precludes regeneration and aquatic plant communities will be unable to regenerate on the majority of sites they now dominate.

Conclusion

In this study, we revealed that vegetation patterns in China's largest freshwater wetland have been strongly affected by long-term changes in lake stage. Many wetland plants have a narrow range of physical/hydrological conditions necessary for regeneration. For the 10 year period 2000–2009, average Poyang Lake stage dropped dramatically during both the summer wet season and dryer parts of the year. Vegetation patterns have shifted substantially during these years. Most significant is the spread of reeds to sites 1 m to 2 m lower in elevation and a much greater area of dominance. Sites dominated by sedges have also shifted 1 m to 2 m lower in elevation. Aquatic vegetation communities have more than doubled the area of growing season dominance within a narrow elevational range, but have not expanded significantly to higher or lower sites.

We attributed the variation of vegetation patterns to the great water regime changes. Specifically, drier conditions since 1999 preclude regeneration of some vegetation communities on sites previously occupied, and have resulted in a

dramatic shift in plant communities' distributions. Lower lake stage has not, however, resulted in a highly-degraded wetland ecosystem. Plant communities have shifted to lower elevation sites in recent years, but still occur on some previously occupied sites, and summer floods that are less severe than those during the 1990s still preclude invasion of upland plant communities. Lake stage is primarily dependent on rainfall, but human activities should also be considered. These include land-use change, dams, and sand mining. Stable hydrological conditions should not be assumed, and plant communities will continue to adjust to future long-term changes in lake stage.

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