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Four decades of wetland changes of the largest freshwater lake in China: Possible linkage to the Three Gorges Dam?

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ABSTRACT

Wetlands provide important ecosystem functions for water alteration and conservation of bio-diversity, yet they are vulnerable to both human activities and climate changes. Using four decades of Landsat and HJ-1A/1B satellites observations and recently developed classification algorithms, long-term wetland changes in Poyang Lake, the largest freshwater lake of China, have been investigated in this study. In dry seasons, while the transitions from mudflat to vegetation and vice versa were comparable before 2001, vegetation area increased by 620.8 km^2 (16.6% of the lake area) between 2001 and 2013. In wet seasons, although no obvious land cover changes were observed between 1977 and 2003, ~30% of the Nanjishan Wetland National Nature Reserve (NWNNR) in the south lake changed from water to emerged plant during 2003 and 2014. The changing rate of the Normalized Difference Vegetation Index (NDVI) in dry seasons showed that the vegetation in the lake center regions flourished, while the growth of vegetation in the off-water areas was stressed. Rapid NDVI increase was also found in the NWNNR in the wet seasons. The relationships between the water levels and vegetation coverage also showed two regimes in both dry and wet seasons for the pre-Three Gorges Dam (TGD) period (before 2003) and post-TGD period (after 2003). Analyses of long-term hydrological and meteorological data clearly indicated that while local precipitation remained stable, the water level of Poyang Lake decreased significantly after the impoundment of the TGD, which is likely the main reason for the wetland expansion in recent years.
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1. Introduction

Regardless of the valuable functions of manmade dams on flood control, power generation, agricultural irrigation, and many others, their potential environmental and ecological impacts received considerable concerns from the general public, governments, and the scientific communities (Graf, 1999). One typical example is the world's largest hydroelectric dam upstream the Yangtze River, the Three Gorges Dam (TGD, 30°49′ N and 111°0′ E) of China (see location in Fig. 1). Numerous studies have been conducted to find the potential linkages between the abrupt changes of the downstream ecosystems in recent years and the construction and/or operation of the TGD (Dai, Du, Li, Li, & Chen, 2008; Wu et al., 2004; Xie, 2003; Xu & Milliman, 2009; Yan et al., 2008; Yang et al., 2006). The Chinese government has also admitted the potential consequences of the TGD to the Yangtze River ecosystem recently (Lu, 2011), although scientific evidence is still generally lacking.

Connecting to the middle reaches of the Yangtze River, the environment of Poyang Lake, the largest freshwater lake of China, was not immune to the influence of the TGD. For example, observations through the use of the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite measurements between 2000 and 2010 showed a significant decreasing trend of the lake's inundation area since the impoundment of the TGD in 2003 (Feng, Hu, Chen, & Zhao, 2013). Consistent with this observation and based on hydrological modeling, Zhang et al. (2012) revealed a reduced water level of Poyang Lake over the dry seasons in the post-TGD period.

The Poyang Lake wetland is a complex system with the composition of water, sand, mudflat and numerous species of vegetation (Dronova et al., 2012; Dronova, Gong, & Wang, 2011). Although changes of the surface water area were understood through the above studies, the influence of the TGD to other types of wetland cover is generally unknown, making it difficult to conduct a comprehensive assessment of the ecological changes in the Poyang Lake wetland. The limited data coverage through traditional field surveys makes it difficult to monitor large-scale changes, not to mention understanding their responses to natural and/or anthropogenic impacts. Starting from the 1970s, satellite images collected by consecutive Landsat missions have provided >40-year continuous and frequent global observations with fine spatial resolutions, which have been widely used to investigate environmental changes in both terrestrial and aquatic systems all over the world (Wulder, Masek, Cohen, Loveland, & Woodcock, 2012). Thus, Landsat

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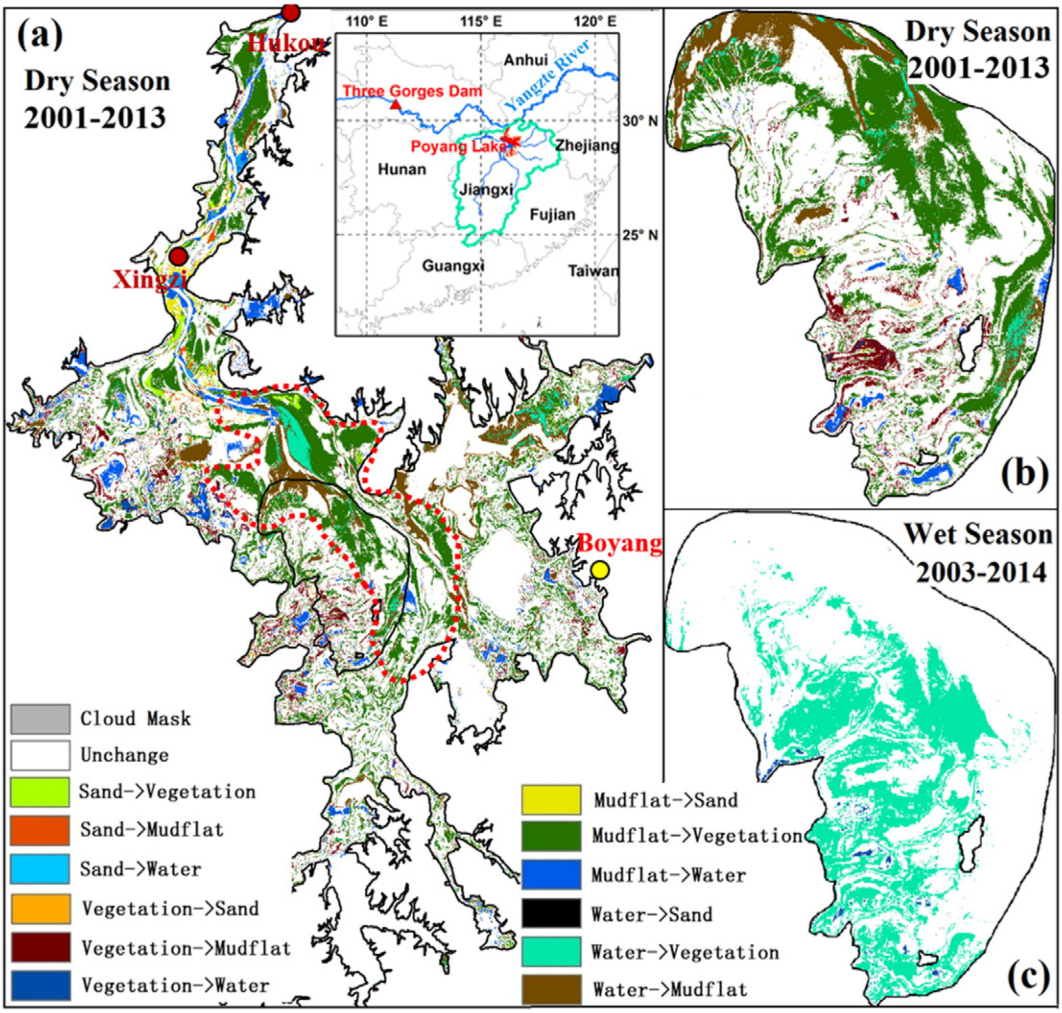


Fig. 1. (a) Transition map of Poyang Lake wetland between 2001 and 2013 in dry seasons. The locations of two hydrological stations (Hukou and Xingzi) and one meteorological station (Boyang) are annotated. The red circled region is the lake center area where significant amount of mudflat transitioned into vegetation during this period. The details of the NWNNR (outlined in black) reserves are enlarged in (b). (c) Transition map of NWNNR between 2003 and 2014 in wet seasons. The inset in (a) shows the location of Poyang Lake and the Three Gorges Dam.

observations appear particularly suitable for large scale wetlands studies.

In this study, we combined wetland classification maps from Landsat images and hydrologic and meteorological measurements to study the long-term changes in the Poyang Lake wetland, with the following two objectives: 1, to document major wetland changes of Poyang Lake in the last four decades in both dry and wet seasons, with particular focus on the changes after the impoundment of the TGD in 2003; 2, and to understand whether the wetland changes could be attributed to local climate variability, regional human or animal activities, or the TGD.

2. Study area and datasets

Located in the north of Jiangxi Province (28°22′–29°45′N and 11°47′–116°45′E, Fig. 1), Poyang Lake is the largest freshwater lake in China. The lake receives water from five tributaries in the south and discharges into Yangtze River at Hukou in the north. The precipitation of the Poyang Lake drainage shows great seasonality due to subtropical monsoons, leading to significant runoff variability of the tributaries every year. April to September is the wet season of the lake, when the inundation area reaches to >3000 km^2; and October to March is the dry season, with the inundation area shrinking to <1000 km^2 (Feng et al., 2012; Guo, Hu, Zhang, & Feng, 2012). During low-water stages, a large area of the lake's bottom emerged, serving as the habitat for most of the water birds from Siberia (Kanai et al., 2002). The critical ecological functions of Poyang Lake make it one of the most important wetland in the world, as recognized by the International Union for the Conservation of Nature (Finlayson, Harris, McCartney, Lew, & Zhang, 2010). The Chinese government has established two national nature reserves to protect the endangered migratory birds and the wetland ecosystem of Poyang Lake, and the largest one is the Nanjishan Wetland National Nature Reserve (NWNNR, ~370 km^2) in the south (see locations in Fig. 1). The Poyang Lake boundary used in this study is the same as that defined in Feng et al. (2012), which was delineated through the largest inundation in the wet season.

Long-term remote sensing images during both wet and dry seasons of Poyang Lake were used in this study to investigate the wetland changes under different hydrological conditions. The data collected by the Landsat instruments (i.e., MSS, TM, ETM+ and OLI) were obtained from the United States Geological Survey (USGS) (http://www.usgs.gov/) and the Remote Sensing Data Sharing Center of China (http://ids.ceode.ac.cn/). In total, 11 cloud free images in dry seasons between 1973 and 2013 were selected (see Table 1), where the acquisition dates are in December of each year (except for 2001). Additional data in December were obtained here as compared to that in Han, Chen, and Feng (2015), which is a result of the recent Landsat Global Archive Consolidation effort. Similarly, 10 high-quality images between July and

Table 1
Remote sensing images used in this study. The column 'year' denotes hydrological year of Poyang Lake starting on April 1 of the current year and ending March 31 of the next year.

Dry seasons				Wet seasons			
Year	Date	Sensor	Resolution (m)	Year	Date	Sensor	Resolution (m)
1973	1973/12/24	MSS	60	1977	1977/7/3	MSS	60
1984	1984/12/8	MSS	60	1984	1984/8/2	MSS	60
1990	1990/12/9	TM	30	1989	1989/7/15	TM	30
1995	1995/12/7	TM	30	1996	1996/9/4	TM	30
1996	1996/12/9	TM	30	2002	2002/8/4	TM	30
1999	1999/12/10	ETM+	30	2003	2003/7/30	ETM+	30
2001	2002/1/8	TM	30	2007	2007/08/10	ETM+	30
2004	2004/12/15	TM	30	2010	2010/08/18	ETM+	30
2006	2006/12/21	TM	30	2012	2012/07/22	ETM+	30
2008	2008/12/10	TM	30	2014	2014/07/20	OLI	30
2013	2013/12/24	OLI	30				
2010	2010/12/31	HJ	30				
2011	2011/12/24	HJ	30				
2012	2012/12/08	HJ	30				

September of 1977–2014 were used to represent the wet season conditions of Poyang Lake (see Table 1), where the image selection was based on two rules: 1) the water level of Poyang Lake (Xingzi station) generally reached to its maxima during each year, and 2) the differences of the water level between the 10 image acquisition dates were small. Under similar phenological and hydrological conditions between different years, results based on the long-term data should be comparable. Note that the term "year" used here is the hydrological year starting on April 1 of the current year and ending on March 31 of the next year, as April is the dry–wet transition month in the Poyang Lake region.

In addition to the Landsat images, several images collected by the HJ-1A/1B charge-coupled devices (CCD) in December were also downloaded from the China Centre for Resources Satellite Data and Application (CCRSDA) (http://www.cresda.com/n16/index.html) (see Table 1). The HJ-1A/1B satellites were launched in 2008 by China, and each of the HJ-1A and HJ-1B satellites has two CCD cameras onboard. The CCD cameras have a spatial resolution of 30 m, and their four spectral bands (430–520, 520–600, 630–690, and 760–900 nm) are analogous to those of the Landsat instruments. The details of the HJ-1A/1B satellites and CCD instruments can be found in Li, Chen, Tian, and Feng (2015).

Four decades of water level data at Hukou station (located in the Yangtze River, Fig. 1) were collected by the Changjiang Water Resources Commission of the Ministry of Water Resources of China, and at Xingzi station (located in Poyang Lake, Fig. 1) were obtained from Jiangxi Provincial Institute of Water Sciences. Meteorological data (precipitation and air temperature) collected at the nearest station of Poyang Lake (Boyang station, see Fig. 1) were downloaded from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). These hydrological and meteorological data were used to understand the potential driving forces of the wetland changes in Poyang Lake.

Census of the winter migratory bird of the Poyang Lake wetlands were conducted by the Forestry Administration of Jiangxi Province for most of the years between 1999 and 2011 (Wu et al., 2014). The number of birds and species were recorded for each survey year. The data were used to understand weather grazing played a significant role in the wetland vegetation changes in Poyang Lake.

3. Methods

Landsat images were calibrated to top-of-atmosphere (TOA) radiance using the coefficients provided in the metadata file (Chander, Markham, & Helder, 2009); the data were then processed with the FLAASH module (MODTRAN4 radiation transfer code) embedded in ENVI 4.8 software to derive atmospherically corrected surface reflectance (Kaufman et al., 1997). A more detailed image processing can be found in Han et al. (2015).

The classification method for remote sensing data used in this study is the same as in Han et al. (2015). High resolution images (Quickbird) obtained from Google Earth™ (http://earth.google.com) were used to "train" the concurrently collected Landsat OLI image in 2013, resulting in a Support Vector Machine (SVM) classifier with the best performance (i.e., classification accuracy) over other typical classification methods (e.g., Minimum Distance, Mahalanobis Distance and Maximum Likelihood). Then, the land cover of the Poyang Lake wetland was classified into four major types, including vegetation, mudflat, sand, and water. Validation by Han et al. (2015) showed that the overall accuracy of the SVM classifier was >91% for any given class. Before Landsat surface reflectance images were used as the inputs of the classifier, an empirical line correction was used to adjust the differences between the four Landsat sensors (Smith & Milton, 1999), with the surface reflectance of all the Landsat images adjusted to the same level as the OLI data in 2013. These differences can result from spectral responses, band configurations, and illumination conditions. As such, the classification maps derived from the different Landsat instruments over the last four decades are deemed to be comparable.

The processing methods for the HJ-1A/1B CCD images were the same as for Landsat. After converting into TOA radiance, atmospheric correction was performed to obtain the surface reflectance. The data were then adjusted to the same reference of the Landsat OLI image in 2013 using an empirical line correction method. Finally, the adjusted reflectance of the CCD images was classified into four wetland cover types with the same SVM classifier as for Landsat data.

Most of the regions within the lake boundary were exposed during the dry seasons, forming a large wetland with various cover types, thus the wetland classification maps of the whole lake were used to study the land cover transitions during the last four decades. In contrast, these same regions tended to be inundated in high water-level months between July and September, when vegetation boosted in the NWNNR in certain years (see Fig. 2). In wet seasons, changes of the wetland cover type between different years primary occurred in the NWNNR, thus the inter-annual wetland changes in other regions of Poyang Lake can be interpreted as the long-term variability of this region. Two pairs of wetland classification maps were used to generate wetland transition maps of Poyang Lake under different hydrological conditions (2001–2013 for dry seasons, and 2003–2014 for wet seasons, respectively), where the wetland changes were color coded in Figs. 1 and 3. The year of 2001 and 2003 have been chosen because they are the closet years to the impoundment of the TGD for the two different seasons. The associated transition matrixes are presented in Tables 2 & 3.

After accounting for the sensor differences between the four Landsat instruments with an empirical line correction, the surface reflectance of the red and NIR bands were used to estimate the Normalized Difference Vegetation Index (NDVI) for the 21 Landsat images. Then, a three-band Red-Green-Blue composite was generated using NDVI of 1973 (B), 2001

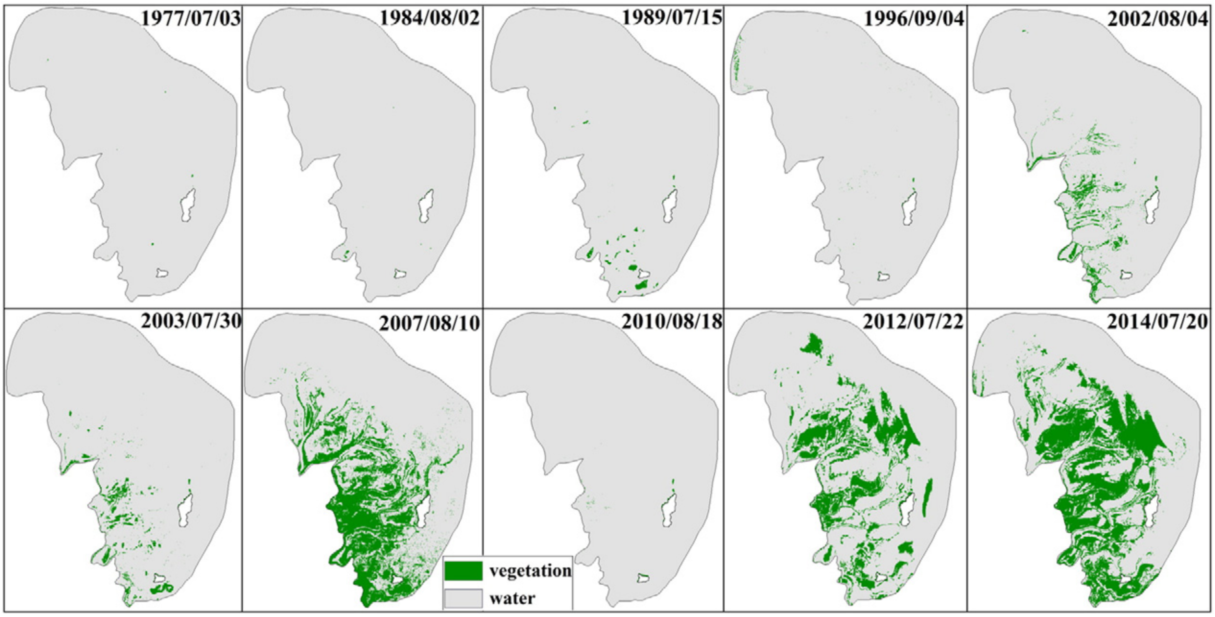


Fig. 2. Landsat-based binary classification maps (vegetation and water) of the Nanjishan Wetland National Nature Reserve (NWNNR) between 1977 and 2014 during the wet seasons.

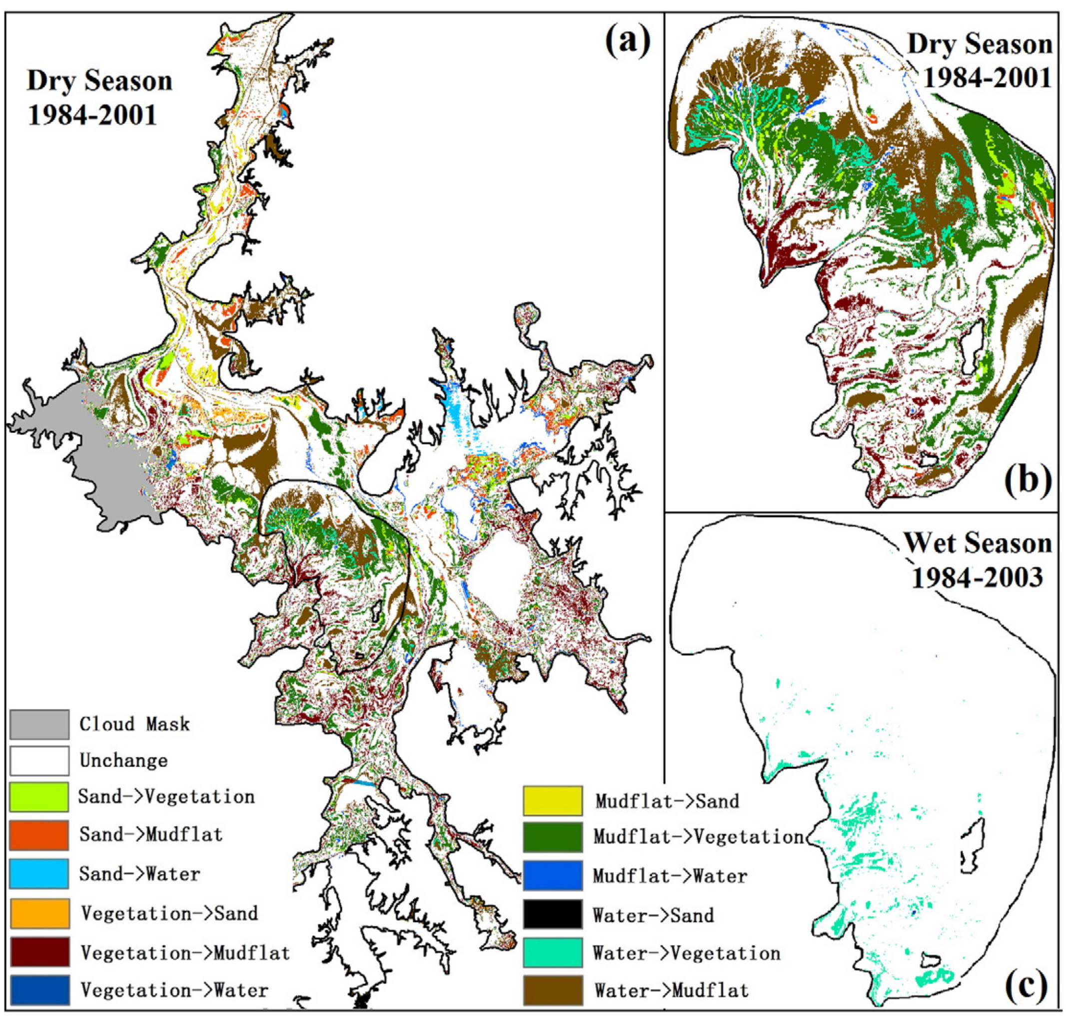


Fig. 3. (a) Transition map of Poyang Lake wetland between 1984 and 2001 during the dry seasons. The transitions of major wetland cover types were between mudflat and wetland vegetation. The details of the NWNNR are enlarged in (b). (c) Transition map of NWNNR between 1984 and 2003 during the wet seasons. Transition maps between different years of the pre-TGD period showed similar changing patterns.

Table 2
Landsat-based wetland transition matrix of Poyang Lake between 2001 and 2013 during the dry seasons (left) and between 2003 and 2014 during the wet seasons (right). The last row shows the cumulated changes of each class during this period, with positive numbers representing increases. Note that all changes in the last row add up to 0.0.

2001							2003				
		Sand	Vegetation	Mud flat	Water	Total			Vegetation	Water	Total
2013	Sand	37.5	3.2	18.7	0.5	59.9	2014	Vegetation	8.3	101.5	109.8
	Vegetation	29.4	978.5	691.6	50.2	1749.7		Water	2.3	264.1	266.4
	Mud flat	20.5	126.4	667.5	210.7	1025.2		Total	10.6	365.6	376.2
	Water	12.9	20.7	147.2	726.5	907.4		2014–2003	99.2	−99.2	
	Total	100.3	1128.8	1525.0	988.0	3742.2					
	2013–2001	−40.3	620.8	−499.9	−80.6						

(G), and 2013 (R) to demonstrate the changing trend of the wetland vegetation in dry seasons of the past four decades. Similarly, NDVI RGB composite of NWNNR in 1977 (B), 2003 (G), and 2014 (R) was used to study the changes during wet season. To further study the vegetation growth in the past four decades, NDVI changing rate was estimated. The changing rate was calculated as follows. For any location within the Poyang Lake boundary, linear regressions were conducted between NDVI of the selected images and their collection times, and such regressions were performed separately for the two different seasons. The regression slopes was considered as the NDVI changing rate if the linear relationship was statistically significant (i.e., $p < 0.05$). Note that the inundated areas with negative NDVIs were not included in these calculations. Although the HJ-1A/1B CCD data could also be used to derive the NDVI images, the images were not used in the trend analysis for otherwise the post-TGD period would have many more images to create a weighting bias.

4. Results

4.1. Wetland transitions during the pre- and post-TGD periods

The prominent change during the dry seasons between the two years of 2001 and 2013 was that a large area (691.6 km^2) of the mudflat has been transited into vegetation, representing 18.5% area of the entire lake and 52.0% of the changed area in this period. Similar observations can also be made between any two years with one before the TGD and one after the TGD. Most of this transition occurred in the north lake and the lake center (see Fig. 1a and Table 2). The overall decreased mudflat area was ~500 km^2. Vegetation was the only increased wetland cover type within this period, with an increased area of 620.8 km^2 (16.6% of lake area). Some of the ponds in the lake center were transformed into mudflat (brown), indicating changes in the inundation conditions of these regions. For clarity, the details of the NWNNR are illustrated in Fig. 1b, where the major wetland transitions appeared very similar to those of the entire Poyang Lake. For the wet seasons between the two years of 2003 and 2014, the dominant change was from water to vegetation (Fig. 1c), which occurred along the near-shore regions of the NWNNR. The vegetation area increased by 99.2 km^2, accounting for 26.3% of the entire NWNNR (Table 2). On the other hand, transition from vegetation to water was negligible during this period.

In contrast to changes in the post-TGD period, significantly different wetland transitions were identified during the pre-TGD period. For the dry seasons between 1984 and 2001 (see Fig. 3a and Table 3), the coverage of both vegetation and mudflat increased by 124.8 km^2 and 322.6 km^2 between the two years, respectively, where rapid inter-conversions between mudflat and vegetation also occurred between 1984 and 2002. Indeed, transition maps produced using different years during the pre-TGD period showed similar changing patterns, with comparable transitioned areas between different cover types. In addition, during the wet seasons the transitions in the NWNNR during the pre-TGD period also appeared different from the post-TGD period. While small or negligible vegetation coverage could be observed for the pre-TGD period, vegetation bloomed in a large area of the NWNNR during the post-TGD period (except for 2010) (Figs. 2 & 3c). These observations clearly indicate different driving forces of the wetland changes between the pre- and post- TGD periods in both dry and wet seasons.

4.2. Long-term NDVI changes

The NDVI RGB composites are shown in Fig. 4, where the reddish color indicates higher NDVI and better wetland vegetation growth in recent years than in earlier years, while the opposite is true for the bluish color. Note that such a composite figure can help visualize changes at synoptic scale, while the digital data of changing rates for each pixel are presented in Fig. 5.

For the dry seasons, the dominated color in the lake center is red, indicating that wetland vegetation spread to near-shore regions from 2001 to 2013. In contrast, in the offshore regions the vegetation showed better growth in 1973 than in 2001–2013, as shown by the bluish color and higher NDVI values in 1973. From the lake boundary to the water/land interface (gray in Fig. 4a) of Poyang Lake, the NDVI RGB composite color generally changed from bluish to reddish, suggesting a potential role of the lake's inundation in regulating the spatial distribution of the wetland vegetation. Likewise, the NWNNR also showed high NDVI values in 2013 (red) in the near-water regions, while high NDVI values in 1973 (blue) were distributed along the lake boundary (Fig. 4b).

For the wet seasons, red is the primary color in the along-shore regions of the NWNNR, indicating that the coverage of vegetation was dramatically expanded in recent years. Note that the gray color shows the lake's common inundation area during all three years used in making the RGB composite.

Table 3
Landsat based wetland transition matrix in Poyang Lake between 1984 and 2001 during the dry seasons (left) and between 1984 and 2003 during the wet seasons (right). The last row shows the cumulated change of each class during this period, with positive numbers representing increases. Note that all these changes in the last row add up to 0.0.

1984							1984				
		Sand	Vegetation	Mud flat	Water	Total			Vegetation	Water	Total
2001	Sand	38.8	14.6	38.0	11.7	103.0	2003	Vegetation	0.2	11.6	11.8
	Vegetation	58.1	608.9	311.1	36.6	1014.7		Water	0.2	364.4	364.6
	Mud flat	84.8	255.0	722.6	379.8	1442.3		Total	0.4	376.0	376.4
	Water	17.9	11.3	48.0	858.0	935.2		2003–1984	−11.4	11.4	
	Total	199.5	889.9	1119.7	1286.1	3495.2					
	2001–1984	−96.5	124.8	322.6	−350.9						

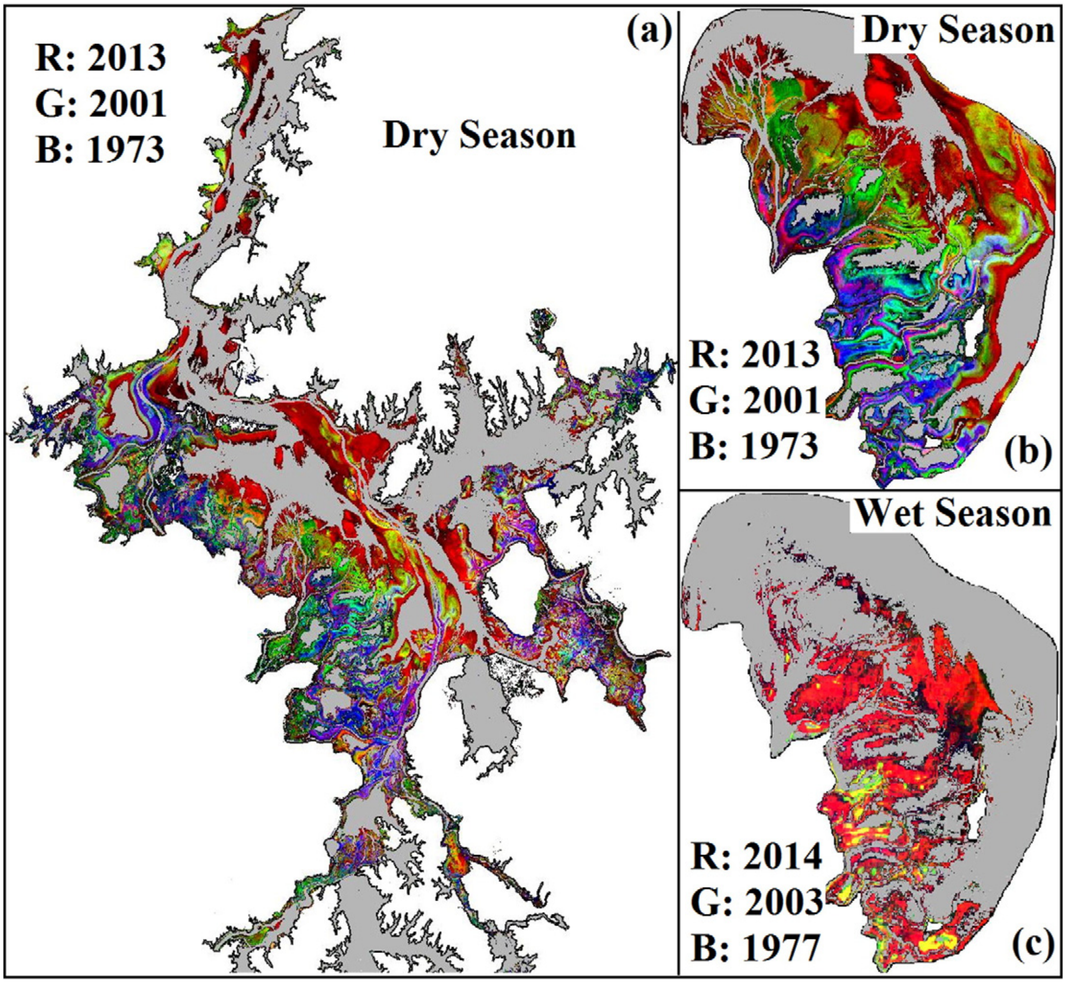


Fig. 4. (a) RGB composite of Poyang Lake using NDVI from three years during the dry season (Red: 2013, Green: 2001, Blue: 1973). The enlarged parts in (b) illustrate the details of the NWNNR. (c) RGB composite of NWNNR using NDVI from three years during the wet season (Red: 2014, Green: 2003, Blue: 1977). Gray color indicates the common inundation area during all three years. Note that such a composite figure can help visualize changes at synoptic scale, while the digital data of changing rates for each pixel are presented in Fig. 5.

Similar to those shown in the NDVI RGB composite, the NDVI changing rate during the dry seasons showed that wetland vegetation flourished in the center areas of Poyang Lake during the four-decade period (outlined in red in Fig. 5a), as indicated by the positive changing rate in these regions. Negative changing rates were observed along the boundary far away from the lake center, suggesting that the vegetation growth was stressed in these areas. Similar trend was also revealed in the enlarged figures of the NWNNR (Fig. 5b), with NDVI decreased with increasing distance from the water. During the wet seasons, vegetation boosted in the last four decades in the NWNNR, as indicated by the highly positive NDVI changing rate in this region (Fig. 5c).

4.3. Influence of the TGD

Correlation analyses between the wetland vegetation area and hydrological and meteorological factors were conducted to see if there were any significant changes after the impoundment of the TGD in 2003. The classified vegetation areas using HJ 1 A/1B CCD images were combined with Landsat data in these analyses.

Fig. 6a plots the classified vegetation area of Poyang Lake against the Julian day when the water level of Poyang Lake (Xingzi station) started to fall below 14 m. The reason to select the critical water level of 14 m is that the coefficient of determination (R^2) reached the maximum at this water level, and ~50% of the lake bottom started to expose at this water level (Zhang, 1988). A small Julian day suggests an early-started dry season and a longer exposure period of the lake bottom in that year, and vice versa. Although the vegetation area was negatively correlated to the Julian day in the period of 1973–2001, it remained high in the post-TGD period of 2004–2013 given the rapid variations in Julian day. Correlation analysis revealed a statistically significant relationship ($R^2 = 0.69$, $p < 0.05$) between the vegetation area and the Julian day for the pre-TGD period of 1973–2001 (Fig. 6a). In other words, changes in water level could explain ~70% of the variability in the wetland vegetation during the pre-TGD period, but this mechanism appeared to have diminished during the post-TGD period.

For the wet seasons, different relationships for the pre-TGD (1977–2003) and post-TGD (2007–2014) periods were also revealed between water level and vegetation area (Fig. 6b). When the mean water level of 30 days before the image acquisition date was used, the correlation between the vegetation area and the mean water level reached the highest, with a determination coefficient (R^2) of 0.98 ($p < 0.05$). In contrast, a consistently low vegetation coverage from 1977 to 2003 was observed, regardless of the water level changes. Note that the water level of Poyang Lake has dropped significantly after 2003 (TGD impoundment year) (Fig. 6 d & e). This is no data was found after 2003 in the wet seasons with previous 30-day mean level >18 m (except for a flooding year of 2010).

For both the dry and wet seasons, the different relationships between the water level and vegetation area for the pre- and post-TGD periods clearly demonstrated a noticeable change of the Poyang

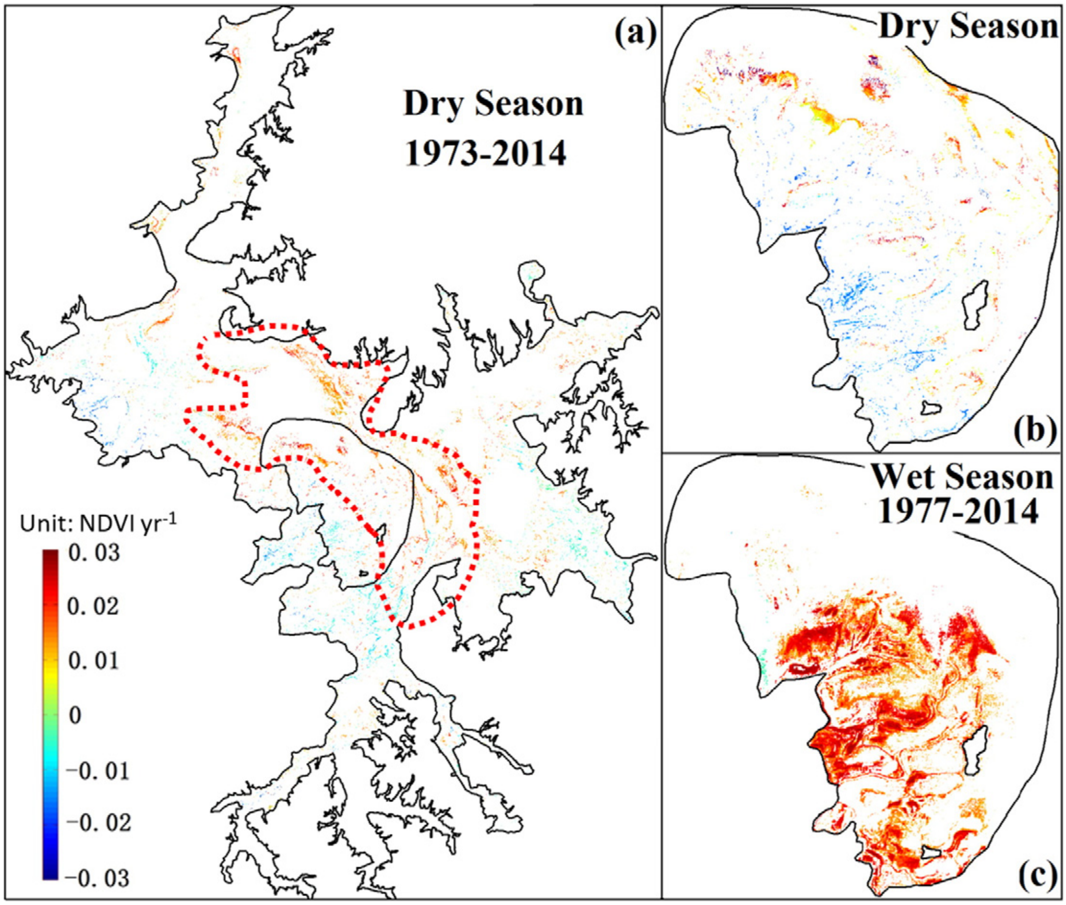


Fig. 5. (a) NDVI changing rate in the Poyang Lake wetland between 1973 and 2013 during the dry season. While NDVI of the lake center areas (close-water, red circled) showed a rapid increasing rate, the vegetation growth of the off-water regions was stressed during the overall period. The enlarge parts in (b) illustrate the details of the NWNNR (outlined in black in (a)). (c) NDVI changing rate in the NWNNR between 1977 and 2014 during the wet season.

wetland after 2003. Whether such a change and post-TGD increases in the vegetation coverage can be linked to the TGD is not trivial, however.

Fig. 6e shows the climatological monthly mean water levels of Poyang Lake (Xingzi station) and Yangtze River (Hukou station) during the pre- and post- TGD periods. The water level at both stations in any single month was lower in the post-TGD period than in the pre-TGD period. Specifically, the decreases between the two periods ranged from 0.6 m in August to 2.3 m in October (Table 4), with the most significant decreases occurred in the low water level months. Similarly, the mean water level of Yangtze River also decreased from the pre-TGD period to the post-TGD period, with more pronounced decreases between July and November than between December and March. Such water-level decreases for both Poyang Lake and Yangtze River after 2003 (particularly in 2006, 2007 and 2009) could also be revealed in the multi-year time-series plot in Fig. 7a. In addition to the post-TGD water-level changes, the water-level difference between Poyang Lake and Yangtze River also showed a significant change. Before 2003, the water level difference between Poyang Lake and Yangtze River fluctuated between 0 m and 2.6 m; after 2003, the difference reached a stable level of 0.4 ± 0.1 m.

The operation time of the TGD during each year appeared to coincide with the water-level decreasing months of Poyang Lake, thus might be a major reason for the vegetation expansion in dry seasons during the post-TGD period. The reservoir begins to increase water storage in autumn and then starts to release water for power generation in the next spring (Shankman, Keim, & Song, 2006), lowering the water level in the downstream river channel and increasing the water outflow from Poyang Lake to compensate for the water loss due to the impounded dam. Consequently, the exposure time of the lake bottom (especially in the lake center regions) has been significantly extended during these months due to the rapidly dropped water level, boosting the growth of the wetland vegetation and resulting in rapidly expanded vegetation coverage in recent years. On the other hand, longer dry seasons, as indicated by the early-dropped water level, could result in lower soil moisture due to increased evaporation in the none-water regions, restricting the growth of the local wetland vegetation. Also, the vegetation of *Carex spp.* species has been gradually replaced by the species of *Triarrhena lutarioriparia* and *Polygonum criopolitanum*, and the former contains more biomass in winter than the latter species (Hu, Ge, Liu, Chen, & Li, 2010), leading to decreased NDVI in these regions.

The recently increased vegetation coverage in the wet seasons might also be linked to the TGD. Other than the water level decrease in summer months, the duration days of high water levels significantly decreased after 2003. The duration days are defined as the number of days during which the water level is higher than a pre-defined threshold. For example, if there were 100 days when the water level of Poyang Lake was above 14 m in 2000, the number of duration days for the 14 m threshold was 100 in 2000. Fig. 6d illustrates the climatological duration days for different water-level thresholds during the pre- and post-TGD periods. The duration days for all water-level thresholds dropped in the latter period, with the most significant changes occurred for the high water levels of 17–19 m. Specifically, the duration days decreased from 69.6 ± 40.5 to 32.1 ± 39.7 for 17 m, from 39.6 ± 29.3 to 11.2 ± 20.1 for 18 m, and from 21.2 ± 24.0 to 7.2 ± 16.3 for 19 m between the two periods (see Table 5). The differences were even larger when

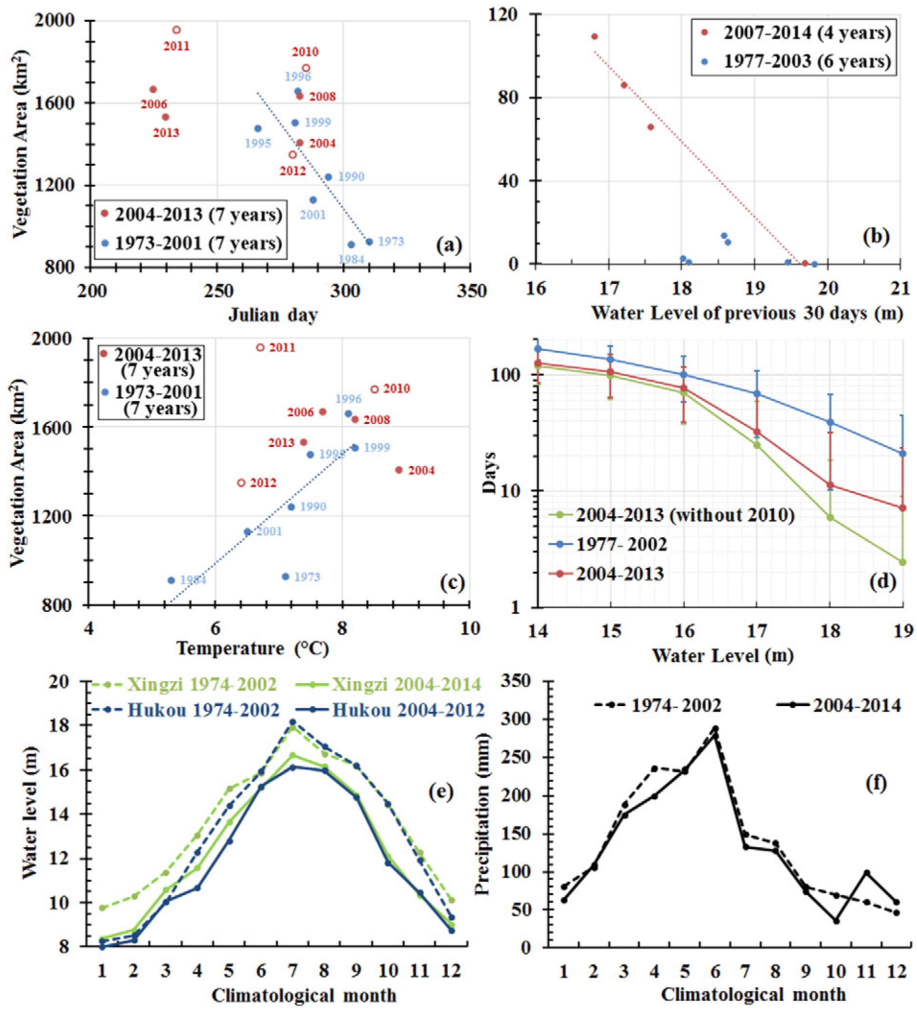


Fig. 6. (a) Relationship between the wetland vegetation area in the entire Poyang Lake and the Julian day when the water level of Poyang Lake (Xingzi station) started to fall below 14 m. The fitting line applies to the pre-TGD points only; (b) Relationship between the classified vegetation area in the NWNNR and the mean water level of 30 days before the image acquisition dates. The fitting line applies to the post-TGD points only; (c) Relationship between the wetland vegetation area of Poyang Lake and local mean air temperature in December of each year. The fitting line applies to the pre-TGD points only; (d) Climatological duration days for different water levels of Poyang Lake during the pre- and post-TGD periods. The post-TGD period with the year of 2010 excluded is also presented. (e) Climatological monthly mean water level of Poyang Lake (Xingzi station) and Yangtze River (Hukou station) during the pre- and post-TGD periods. (f) Climatological monthly mean precipitation, measured at the nearest meteorological station of Poyang Lake, between pre- and post-TGD periods. The red empty circles in (a) and (c) represent the results from HJ-1A/1B CCD.

the year of 2010 was excluded from the analysis. In other words, the high water-level inundation period for Poyang Lake has decreased in recent years.

Associated with the shorter high water-level inundation period is the increased light penetration to the bottom of the lake, stimulating underwater photosynthesis and growth of wetland vegetation species. The expanded vegetation in the NWNNR during the wet seasons is likely due to this reason. According to our field surveys and communications with local natural conservation agency, the vegetation species in the NWNNR during summer months was *Zizania latifolia*, which is a newly

Table 4
Climatological monthly mean and standard deviations (in parenthesis) of precipitation and water level (Xingzi and Hukou) during the pre- and post-TGD periods.

	Precipitation (mm)			Xingzi water level (m)			Hukou water level (m)		
	1974–2002	2004–2014	Diff	1974–2002	2004–2014	Diff	1974–2002	2004–2012	Diff
Jan	81 (44)	63.5 (33.1)	17.6	9.8 (1.1)	8.4 (0.9)	1.4	8.3 (1.1)	8 (0.6)	0.3
Feb	106.1 (53)	109 (44.8)	−2.9	10.3 (1.3)	8.8 (1.3)	1.5	8.5 (1.3)	8.3 (1.1)	0.2
Mar	188.5 (79.6)	174.5 (91.8)	14.0	11.4 (1.6)	10.6 (1.5)	0.8	10 (1.8)	10 (1.4)	0.0
Apr	236.1 (121.7)	199.8 (64.6)	36.3	13.1 (1.4)	11.6 (1.6)	1.5	12.3 (1.5)	10.7 (1)	1.6
May	231.7 (75.3)	234.1 (127.3)	−2.3	15.2 (1.8)	13.7 (2.2)	1.5	14.4 (1.6)	12.8 (2.1)	1.6
Jun	288.6 (152.2)	278.8 (170.6)	9.8	15.9 (1.8)	15.2 (2.8)	0.7	15.9 (1.3)	15.3 (1.3)	0.7
Jul	149 (111.6)	133.1 (104.7)	15.9	17.9 (1.7)	16.7 (1.4)	1.3	18.2 (1.6)	16.1 (0.9)	2.1
Aug	137.7 (108)	127.7 (51.9)	9.9	16.7 (2.1)	16.2 (2)	0.6	17.1 (1.9)	16 (1.9)	1.1
Sep	80.4 (59)	74.3 (41.5)	6.1	16.2 (1.9)	14.9 (2.4)	1.3	16.2 (2)	14.8 (2.5)	1.4
Oct	69.5 (40.9)	35.8 (38.1)	33.7	14.4 (1.8)	12.1 (2.1)	2.3	14.5 (1.6)	11.8 (1.8)	2.7
Nov	60.2 (58.6)	99.4 (54.6)	−39.1	12.3 (1.7)	10.4 (1.9)	1.9	11.9 (1.5)	10.5 (1.7)	1.5
Dec	46.7 (46.1)	60 (41.8)	−13.4	10.1 (1.2)	9 (1.2)	1.1	9.3 (1.2)	8.7 (0.9)	0.6
Mean			7.1 (19.5)			1.3 (0.5)			1.1 (0.8)

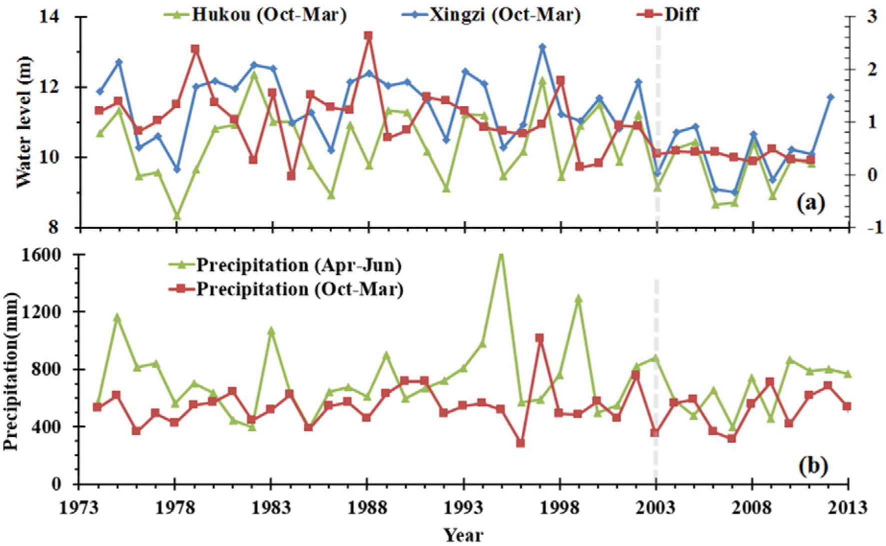


Fig. 7. (a) Long-term mean water level of Poyang Lake (Xingzi station) and the Yangtze River (Hukou station) from 1973 to 2013. Also plotted is the difference between the two stations. (b) Long-term precipitation measured at the nearest meteorological station of Poyang Lake from 1973 to 2013. The gray dashed lines indicate the year of 2003 when the TGD was impounded.

emerged plant in the local region that rapidly bloomed in recent years. In contrast, during the pre-TGD period when the lake was inundated with high water levels, growth of the submerged vegetation species was restricted (Yamasaki & Tange, 1981), leading to smaller vegetation area. This is further confirmed by the small vegetation coverage in 2010 (0.5 km^2). High precipitation in the growing seasons of *Z. latifolia* (April to June) (Asaeda & Siong, 2008) resulted in severe floods in the local area during this year (http://www.chinanews.com/gn/2010/07-26/2423960.shtml), leading to long duration days of high water levels (Table 5) (even longer than the mean level of the pre-TGD period). Thus, the long inundated period posed a stress to the growth of *Z. latifolia*, leading to a minimum coverage during this year.

5. Discussion

5.1. Potential effects of other factors

As documented in Han et al. (2015), the vegetation area in dry seasons was highly correlated to local temperature (mean of December) (Fig. 6c). Thus, one may argue that the flourished wetland vegetation in the NWNNR region and the central lake in recent years may be attributed to the increased air temperature rather than the TGD, as temperature in the latter period was significantly higher than in previous years (7.12 ± 0.99 °C and 8.05 ± 0.65 °C respectively) (Fig. 6c). However, temperature cannot be the sole causal factor for two reasons. First, the decreased NDVI in the off-water regions (in contrast to the NWNNR region and the central lake) in dry seasons could not be explained by the local temperature changes. In fact, the NDVI variations in these regions may be due to the low-water level induced changes of vegetation species (Hu et al., 2010). Secondly, high temperature not only occurred in the post-TGD period but also occurred in the pre-TGD period (Fig. 6a & c). Although for the past four decades the relationship between temperature and vegetation cover is obvious (fitting line in Fig. 6c), such a relationship only holds for low air temperature only. Above ~7.4 °C, there is no relationship between temperature and vegetation color (Fig. 6c). In contrast, the high-vegetation years before and after the TGD can be well separated by the starting Julian day of low-water level (Fig. 6a) and by the water level (Fig. 6b). Thus, temperature alone could not explain the observed two regimes before and after the TGD. Indeed, the air relative humidity has decreased significantly after the impoundment of the TGD in 2003 (Feng et al., 2013). The elevated local temperature may be closely related to the decreased relative humidity, as the two meteorological factors appear to negatively correlate with each other (Lawrence, 2005; Sun & Oort, 1995). Thus, the changes in local temperature might also be partially associated to the TGD. However, the exact reason needs to be further investigated with additional meteorological data and numerical modeling to quantify the roles of other possible factors such as global warming.

Other than the water level decrease of the Yangtze River, changes in local precipitation may also modulate the inundation conditions of Poyang Lake (Feng et al., 2012) and thus impacting the spatial patterns of the wetland cover types. However, after partitioning the monthly climatological precipitation data into pre- and post-TGD periods (see Fig. 6f and Table 4), no significant changes could be observed. As shown in a long-term perspective in Fig. 7b, although low precipitation was observed in certain years after 2003 with associated droughts in the Poyang Lake regions (Feng, Hu, & Chen, 2012), no significant decreasing trend could be identified when data for the four decades was considered together. Thus, the low water level of Poyang Lake in recent years is unlikely due to changes in local precipitation.

Other meteorological factors (such as wind speed, pressure, data not shown here) were also analyzed to understand whether there was any potential linkage between these factors and the classified wetland vegetation. Results showed insignificant relationships, and no obvious changes could be observed when the data were split into pre- and post-TGD periods, suggesting that the impact of these factors on the changes of the vegetation growth in Poyang Lake (especially the rapid expansion after the impoundment of the TGD in 2003) should be much smaller.

The local water control structures and levees over individual smaller lakes and channels within the wetland may also affect the hydrological properties of Poyang Lake (Qi et al., 2009). In particular, the hydrological conditions in these small areas may not be well characterized by the data collected at the gauge stations. However, previous studies using either observational or hydrological modeling methods have demonstrated the significant influence of the TGD on the Poyang-Yangtze water interactions in both wet and dry seasons after 2003 (Guo et al., 2012; Zhang et al., 2012), which are in agreement with the water level analysis in the current study. Indeed, to mitigate the effects of TGD on the water level of Poyang Lake, a dam at the lake mouth has been proposed by the local government to regulate the river–lake water exchange (Li, 2009). Thus, local water controls appeared to play a limited role in decreasing the water level of Poyang Lake in recent years.

Table 5
Duration days for different water levels of Poyang Lake for each year between 1973 and 2013. The long-term climatology means and standard deviations (in parenthesis) of the pre- and post- TGD periods are presented in the last rows.

Year	14 m	15 m	16 m	17 m	18 m	19 m
1973	212	203	192	122	72	33
1974	163	130	113	62	27	13
1975	225	200	155	99	57	2
1976	151	103	66	58	28	18
1977	172	150	125	100	52	21
1978	83	51	39	3	0	0
1979	131	115	66	26	5	0
1980	199	185	151	95	69	38
1981	188	151	81	39	51	0
1982	187	143	124	116	33	13
1983	220	212	188	160	74	50
1984	206	163	123	80	37	0
1985	127	102	45	12	0	0
1986	86	56	49	30	0	0
1987	179	125	93	69	14	0
1988	160	100	63	35	27	19
1989	221	176	140	98	35	21
1990	186	104	70	49	20	10
1991	197	142	89	66	41	17
1992	156	147	102	52	35	23
1993	175	152	114	104	86	64
1994	189	124	52	26	18	12
1995	168	138	107	74	58	37
1996	128	118	103	71	60	45
1997	114	89	51	43	30	17
1998	179	153	119	111	104	94
1999	188	151	140	120	94	73
2000	164	154	108	41	5	0
2001	130	63	34	0	0	0
2002	158	150	139	126	57	16
2003	173	136	63	46	23	11
2004	149	116	74	10	0	0
2005	158	138	109	53	4	2
2006	94	61	32	0	0	0
2007	115	106	95	30	11	0
2008	136	120	59	19	0	0
2009	114	71	60	1	0	0
2010	181	174	144	96	59	50
2011	47	39	20	7	0	0
2012	170	152	116	105	38	20
2013	94	85	67	0	0	0
1977–2002	168.1 (37.0)	135.0 (40.6)	101.4 (42.6)	69.6 (40.5)	39.6 (29.3)	21.2 (24.0)
2004–2013	125.8 (41.1)	106.2 (42.5)	77.6 (38.5)	32.1 (39.7)	11.2 (20.1)	7.2 (16.3)
2004–2013[a]	119.7 (38.4)	98.7 (37.3)	70.2 (32.5)	25.0 (24.7)	5.9 (12.6)	2.4 (6.6)

[a] Calculations without the year of 2010.

Sand dredging could have also altered aquatic vegetation both directly (via sediment deposition and changes in the bottom elevation) and indirectly (through changes in water clarity). Due to the intensive sand dredging activities starting from 2002, water turbidity of Poyang Lake has increased remarkably. However, the vegetation expansion observed in this study cannot be explained by sand dredging for two reasons: 1) turbidity increase due to sand dredging mainly occurred in the north lake (Feng, Hu, Chen, Tian, & Chen, 2012; Leeuw et al., 2010) as opposed to the south lake and the NWNNR region; 2) turbidity increase would limit light reaching the bottom, causing decreased vegetation rather than vegetation expansion observed in this study.

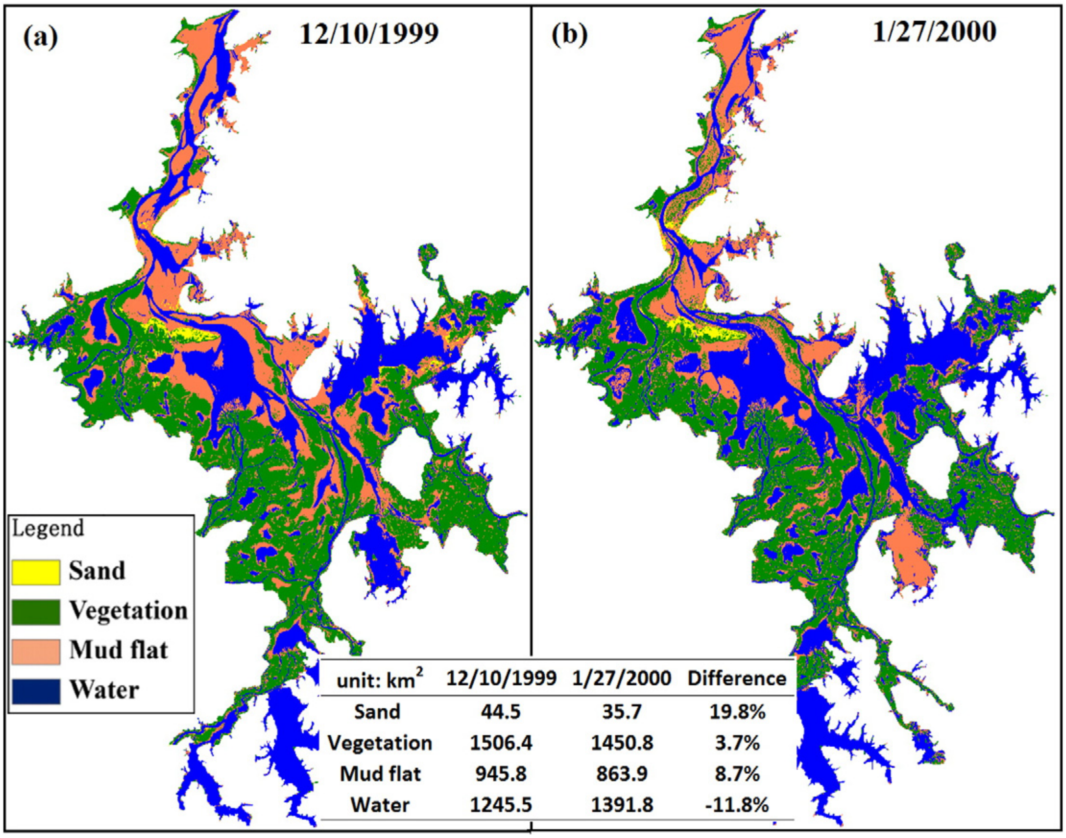
Other regional human activities, such as crab farming, may also regulate the distribution of local aquatic vegetation through consumption of important local aquatic macrophytes, thus affecting distribution of bird grazers, water clarity, and nutrient cycling (Fox et al., 2011). However, aquaculture is rarely found in the NWNNR regions where the vegetation expansion is significant. While land use and land cover changes of the central Yangtze region may change the composition of aquatic plant communities (Fang et al., 2006), the effects tend to be slow and gradual, thus not likely to cause an abrupt change of the vegetation area of Poyang Lake in two different periods. Yet all these arguments are based on educated speculations, and a more comprehensive and carefully designed study to combine field and remote sensing measurements is required to exclude all these possible local factors before a causal relationship between the construction of the TGD and the wetland vegetation expansion can be verified firmly.

Poyang Lake serves as an important habitat for numerous migratory winter birds (Finlayson et al., 2010) that may pose some grazing pressure on the vegetation, and changes in grazing pressure may have some effects on the green vegetation extent (NDVI). However, this possibility can be easily ruled out. Firstly, according to numerous field surveys, the winter birds are more active in limited areas of the national and provincial nature reserves in the southern and western Poyang Lake, which is outside of main vegetation bloom region (the central lake). Secondly, the number of bird and species slightly increased in recent years (Fig. 9), and therefore the grazing pressure could only increase and the vegetation area could only decrease, which is contradict to the remotely sensed results here.

5.2. Validity of the observations

Could the significant wetland changes be an artifact of the miss-interpretation of the classification results from long-term Landsat images? The spectral features of the major types of wetland cover in Poyang Lake are highly distinguishable, thus the classified maps using multi-spectral remote sensing images should be valid (Han et al., 2015). A sophisticated atmospheric correction was applied to remove the interference of the path radiance to the Landsat imagery, and an empirical line correction (Smith & Milton, 1999) was used to adjust the sensor-specific differences between the four Landsat missions. Given the close acquisition dates and therefore similar phenological and hydrological conditions of the selected images, the classification results between different years were regarded as consistent and comparable. Indeed, classified vegetation areas from two Landsat TM images in 1999 with 48 days apart only showed a difference of 3.7% (Fig. 8), indicating that the coverage of winter wetland vegetation was relatively stable within a short period (1–2 months). Similar results were observed from another pair of images (not shown here) within a short period although that image pair contained substantial cloud cover. Because the images used during the dry seasons were collected in the same month (except for 2001), the uncertainties in the observed inter-annual changes due to intra-annual changes should be small when compared with the >50% vegetation area expansion from 2001 to 2013 (except for the abnormal year of 2010, which can be well explained using meteorological and hydrological data). Therefore, the small uncertainties in the classified Landsat maps would play a very minor role in explaining the rapid vegetation expansion after 2003.

The current study is based on four decades of Landsat measurements between 1973 and 2014. The data of the post-TGD period only covered 8 ~ 10 years (2004–2013 for dry seasons and 2007–2014 for wet seasons), while the pre-TGD period spans more than three decades. Ideally, more images should be used after 2003 to eliminate the potential possibility of inter-annual changes instead of a rapid change caused by the TGD. Indeed, data collected in spring (rather than in winter) are preferable to study the changes in dry seasons, as these “plateau months” can represent the maximum biomass of Poyang Lake's vegetation (Hu et al., 2010) during which short-term changes (e.g., within a month) are minimal, thus more suitable for studies of inter-annual changes. However, the objective of this study is not to document the maximum biomass during these plateau months, but to show long-term inter-annual changes during the same season (month). As long as NDVI and vegetation area are relatively stable within these non-plateau months (compared with long-term changes), the use of these data should be appropriate. For example, in both 1999 and 2006 short-term changes within 48 days are only a few % (Fig. 8), as compared to >50% vegetation area expansion after the TGD impoundment.



unit: km^2	12/10/1999	1/27/2000	Difference
Sand	44.5	35.7	19.8%
Vegetation	1506.4	1450.8	3.7%
Mud flat	945.8	863.9	8.7%
Water	1245.5	1391.8	-11.8%

Fig. 8. Classification maps derived using two consecutive cloud-free Landsat TM images in hydrological year of 1999. The inset table illustrates the areal coverage of different cover types, where a small difference of 3.7% was observed between the classified vegetation areas of two images 48 days apart.

Indeed, there is too much cloud-cover during the plateau months, and the use of the non-plateau months is to avoid this problem. Given the limited data availability in this study due to the relatively long revisiting period (16 days) of Landsat and frequent cloud cover, and the current dataset appears to be the best data available to study the long-term wetland changes of Poyang Lake.

The use of HJ 1 A/1B CCD images with similar spatial resolution and spectral bands to Landsat, after the empirical line correction to assure-cross sensor consistency, complemented the Landsat-based observations of vegetation cover in the post-TGD period. Indeed, comparison between the classified vegetation areas from the Landsat OLI image on 24 December 2013 and HJ 1A/1B CCD image on 22 December 2013 showed a difference of 4.3%, suggesting that the HJ 1A/1B CCD data can be used to increase the temporal coverage of Landsat observations.

The conclusion of the linkage between the wetland changes and the TGD is not solely based on the temporal coincidence between the abrupt vegetation change and the impoundment of the TGD, but also based on other evidence from long-term hydrological and meteorological measurements as well as published literature. Thus, although only 8 ~ 10 years of data were available and used for the post-TGD period, the vegetation expansions during both dry and wet seasons of Poyang Lake are indeed likely to be linked to the impoundment of the TGD in 2003 even though other potential causes cannot be completely ruled out.

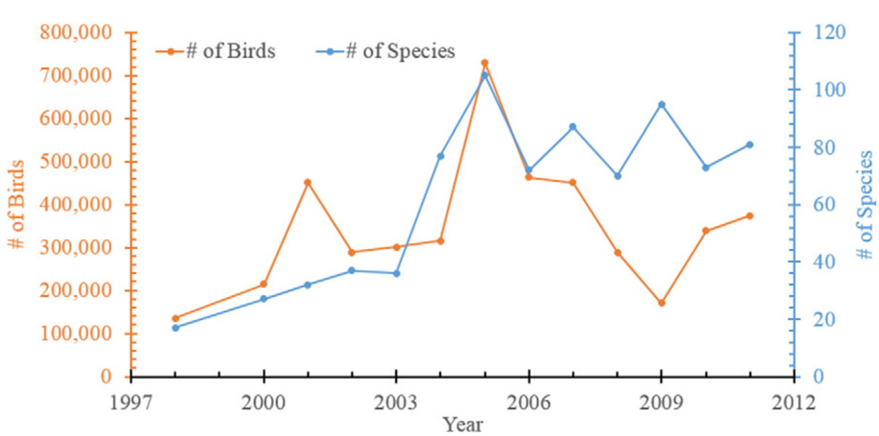


Fig. 9. The number of birds and specifies during different years from field surveys. Slight increasing trends can be observed for both numbers.

6. Conclusions

Based on four decades of Landsat observations and recent HJ-1A/1B CCD observations, the long-term changes of Poyang Lake wetland showed distinct periods for both dry and wet seasons. Before the impoundment of the TGD, the transitions of major types of wetland cover were inter-conversions between mudflat and wetland vegetation in dry seasons, which appeared to be driven by both of the lake's water level and the local temperature. For this period, low or negligible vegetation coverage was observed in wet seasons. After the TGD was impounded, wetland vegetation was boosted in both dry and wet seasons. In dry seasons, in addition to the rapid vegetation expansion in the lake center, the growth of the off-water regions was stressed, which is likely due to the decreased water level and increased exposure period of the lake bottom after the construction of the TGD. In wet seasons, the coverage of emerged plant in the NWNNR has increased considerably, which can be linked to the evidently decreased water level in wet seasons after 2003. All these vegetation changes in recent years after 2003 could be well explained by long-term hydrological and meteorological data. For example, although extreme weather events may also be able to modulate the growth of the wetland vegetation (e.g., the high precipitation-induced minimum vegetation area in wet season of 2010), such events are unlikely to cause long-term changes.

Thus, although wetlands are complex systems under the influence of many environmental factors and the eventual confirmation of the preliminary findings here require more comprehensive and integrated analysis with remote sensing as well as metrological and hydrological modeling, the significant spatial and temporal changes of the wetland vegetation in Poyang Lake in recent years appear to be linked to the impoundment of the TGD. This observation is not based on remote sensing data alone but also based on thorough analyses of other environmental variables. The results presented here are also consistent with previous findings on the lake's inundation area and local climate conditions. The results here may provide critical information and scientific support to help government agencies to make management decisions for conservations of the lake's environment in the future, for example through providing reference to guide the construction and operation of the proposed dam at the lake mouth.

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