Environ Monit Assess (2011) 179:279–292
DOI 10.1007/s10661-010-1735-6

Characterizing wetland change at landscape scale in Jiangsu Province, China

Chi Xu · Sheng Sheng · Wen Zhou · Lijuan Cui · Maosong Liu

Received: 21 May 2010 / Accepted: 4 October 2010 / Published online: 16 October 2010

Abstract Human activities produced great impacts on wetlands worldwide. Taking Jiangsu Province, China, as a representative wetland region subject to extensive human activities, the aim of this study is to understand the conversion trajectory and spatial differentiation in wetland change from a multi-scale perspective. Based on multi-temporal Landsat images, it was found that the natural wetlands decreased by 11.2% from 1990 to 2006 in Jiangsu Province. Transition matrices showed that the conversion of natural wetlands to human-made wetlands (mostly aquaculture ponds) was the major form of natural wetland reduction, accounting for over 60% of the reduction. Percentage reduction and area reduction of natural wetlands were respectively quantified within different wetland cover zones using a moving window analysis. Average percentage reduction showed a decreasing tendency with increasing wetland cover. The high-cover and mid-cover zone presented the largest area reduction at the scales of 1–2 km and 4–8 km, respectively. Local hotspots of natural wetland reduction were mapped using the equal-interval and quantile classification schemes. The hotspots were mostly concentrated in the Lixiahe marshes and the coastal wetland areas. For the area reduction hotspots, the quantile classification presented larger area and more patches than the equal-interval classification; while an opposite result was shown for the percentage reduction hotspots. With respect to the discontinuous distribution of the natural wetlands, area reduction could be more appropriate to represent reduction hotspots than percentage reduction in the study area. These findings could have useful implications to wetland conservation.

Keywords Hotspot · Landsat · Moving window analysis · Remote sensing · Wetland reduction

Chi Xu and Sheng Sheng contributed equally to this paper.

C. Xu · S. Sheng · W. Zhou · M. Liu (✉)
School of Life Sciences, Nanjing University,
22 Hankou Road, Nanjing 210093, China
e-mail: msliu@nju.edu.cn

L. Cui
Wetland Research Center, State Forestry
Administration, Beijing 100091, China

L. Cui
Research Institute of Forestry, Chinese Academy
of Forestry, Beijing 100091, China

Introduction

Although wetlands comprise less than 3% of the Earth's surface, they are among the most important ecosystems in the world (Mitsch and Gosselink 2000). Wetlands are integral to a range of ecosystem processes (Daniels and Cumming 2008), and provide important habitats for wildlife (Gibbs 2000; Trebitz et al. 2005). Wetlands are also closely related to human well-being: they contribute up to 40% of the annual globe's ecosystem services (Costanza et al. 1997), including flood protection (Hey and Philippi 1995), water quality enhancement (Jeng and Hong 2005), carbon storage (Mitra et al. 2005), nutrient cycling (Bunn et al. 1999), etc. Unfortunately, wetlands are subject to adverse impacts, more than any other ecosystem type (Millennium Ecosystem Assessment 2005). Multiple threatening factors (e.g., climate change, biological invasion, human reclamation, hydrological modification, and water pollution) can separately or additively reduce ecological functions and services of wetlands (Brinson and Malvarez 2002; Mitsch and Gosselink 2000). Of those, human activities have been recognized as a major cause of these wetland problems (Zedler and Kercher 2005).

Natural wetlands are the most important component of wetlands. Being biologically productive, natural wetlands have undergone extensive exploitations worldwide. From a landscape perspective, human exploitations can convert natural wetlands to agricultural or built-up uses by draining water. This type of wetland change, accounting for a primary proportion of global wetland loss, has been well documented in various geographical regions (Foote et al. 1996; Moser et al. 1996; Ladhar 2002; An et al. 2007). Alternatively, with the persistence of wetland water, natural wetlands could be converted to aquaculture ponds, reservoirs, or other forms of human uses. Such conversion is usually associated with losses of wetland vegetations, modifications of hydrological processes (e.g., via bank constructions), and water eutrophication, all of which can substantially modify ecological processes and functions of natural wetlands. Consequently, the original natural wetlands are converted to human-dominated wetland ecosystems, representing a noteworthy form of natural wetland reduction. However, it received less attention relative to wetland drainage since wetland coverage is rarely reduced.

Human-induced reductions of natural wetlands could produce significant ecological consequences (Gibbs 2000). The importance of persistence and restoration of natural wetlands subject to human activities is increasingly recognized. Monitoring wetland change at landscape scale plays a fundamental role in wetland conservation. Based on remotely sensed data, a variety of approaches for wetland change detection have been developed to facilitate wetland monitoring and assessment (Dabrowska-Zielinska et al. 2009; MacAlister and Mahaxay 2009; Rebelo et al. 2009). With support of remote sensing technology, wetland change can be detected with precise spatial information, which can allow further exploration of patterns and drivers of the change.

Driven by various factors with spatial heterogeneity, landscape dynamics generally present spatial differentiation (Bürgi et al. 2004). In this context, some local areas representing significantly greater change magnitude than the other areas, which can be referred to as hotspots (Nelson and Boots 2008) of landscape change, could exist in a given landscape. Quantifying the spatial differentiation and detecting the hotspots of wetland change at landscape scale can help to understand the driving mechanisms of the change, and has useful implications to wetland conservation. Specifically, such questions as "Where do the wetlands change faster/slower?" or "Which wetlands are mostly prone to be reduced?" could be important concerns of wetland managers.

The complex spatiotemporal patterns of wetland change are far from being fully understood. Although wetland monitoring techniques have been well studied (Jones et al. 2009), dynamic wetland inventory at fine resolutions, which is the basis of wetland change studies, is still lacking in many regions in the world (Zedler and Kercher 2005). Furthermore, previous studies showed that the spatial differentiation of deforestation, in association with forest cover, could spatially present some hotspots (Etter et al. 2006). Similar questions may arise: Does wetland change also tend to occur in specific wetland cover zones? How to detect and interpret wetland change hotspots? Adequately addressing these specific questions can help to better understanding of wetland change. In addition, it has been increasingly recognized that landscape studies necessarily require multi-scale perspectives (Wu et al. 2006). However, to our knowledge, wetland change patterns have not been fully explored across spatial scales.

China's natural wetlands experienced tremendous changes over the past 50 years (An et al. 2007). Jiangsu Province, a representative wetland region in China, is rich in wetlands in terms of both coverage and diversity. It is also one of the most developed regions in China. Understanding wetland change in Jiangsu Province can provide supports to future decision making of wetland conservation in China in the context of rapid socioeconomic development. In this study, wetland change at landscape scale in Jiangsu Province during 1990–2006 is characterized using remotely sensed data. Here we focus on the reduction of the natural wetlands from a multi-scale perspective, and specifically aim to (1) investigate the conversion trajectory of the natural wetlands; (2) quantify the reduction magnitude of the natural wetlands within different wetland cover zones; and (3) map the hotspots of natural wetland reduction.

Materials and methods

Study area

Jiangsu Province (116°21′–121°56′ E, 30°45′–35°07′ N) is located in Eastern China, covering an area of 1,030 million hectares (Fig. 1). The mean annual temperature is about 15°C; the mean annual precipitation is about 1,000 mm. Plains and low hills (with a maximum elevation of 625 m) account for approximately 85% and 15% of the province area, respectively. Wetlands (excluding rice paddies) comprise about 25% of the terrestrial area of Jiangsu Province (Jiangsu Forestry Bureau 2000), including considerable wetlands of global or national significance. Specifically,

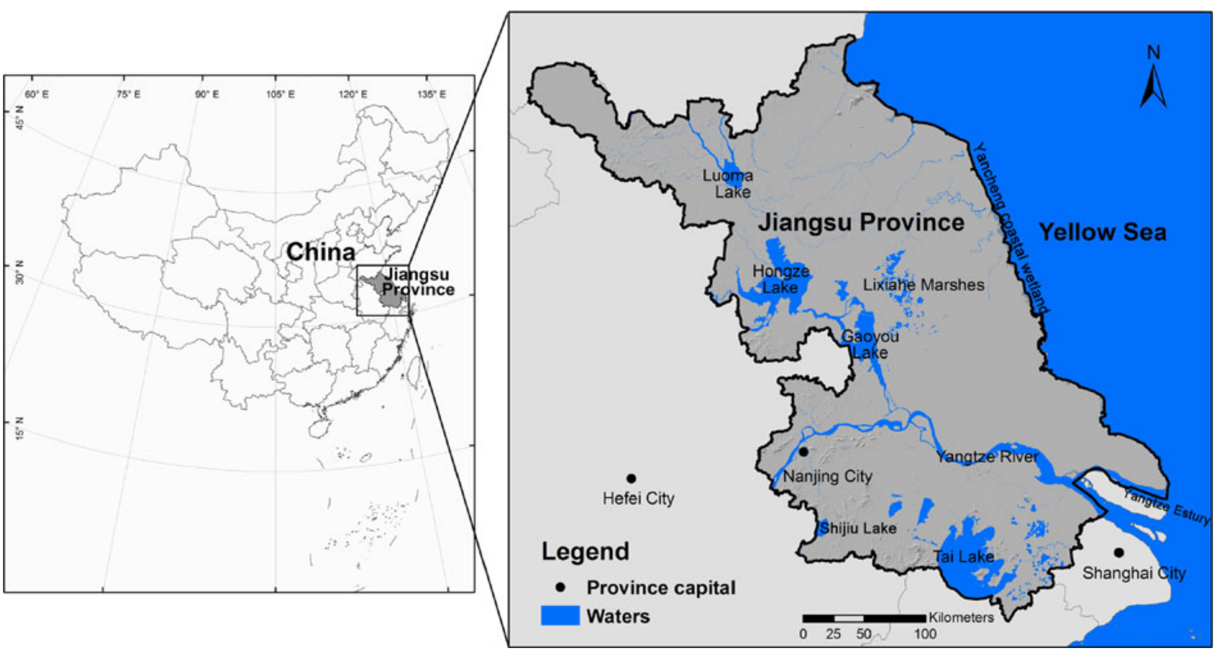

Fig. 1 The location of Jiangsu Province, China

Yancheng coastal wetland (YCW) is the largest tidal flat in China, and two Ramsar sites (known as wetlands of international importance) (Ramsar 1987) together covering 0.53 million hectares, are located within the YCW. Five wetlands have been designated as wetlands of national importance, including Tai lake, Hongze Lake, Gaoyou Lake, Shijiu Lake, and YCW. Of those, Tai Lake is the third largest and Hongze Lake is the fourth largest freshwater lake in China. These important wetlands cover 37% of the total wetland area (9% of the terrestrial area of Jiangsu Province). In addition, Yangtze River, the third longest river in the world, runs through the south part of Jiangsu Province into the sea; Yangtze Estuary, the largest estuary in the world, has its north branch located in Jiangsu Province. At present, there are 26 wetland nature reserves and 14 wetland parks in Jiangsu Province, protecting 347,000 ha of natural wetlands, accounting for 12% of the total wetland area (Jiangsu Forestry Bureau 2010). Thanks to effective protection measures, these protected wetlands remain relatively stable status during the past two decades (Jiangsu Forestry Bureau 2010).

Jiangsu Province is one of the most important agricultural and industrial regions in China. It experienced rapid socioeconomic growth during the past two decades. At present, Jiangsu Province is among the most developed regions of China. In 2008, the total population was about 76 million at a density of 748 individuals per square kilometer (the highest density among China's provinces); and the gross domestic production was over 440 billion US dollars (the second highest among China's provinces) (Jiangsu Statistical Bureau 2009).

In Jiangsu Province, the coastal wetlands are increasing with the expansion of the coastal tidal flats (at a mean annual rate of 50–200 m towards the Yellow Sea) caused by sedimentary deposition (Zhang et al. 2006). These newly generated wetlands are mostly covered by marine waters, and have rarely undergone human-induced transformation during the study period, thus they were not taken into account in this study. To facilitate spatially explicit change detection, the specific study area was restricted within the outer boundary of the tidal flats mapped by the Wetland Inventory of Jiangsu in 2000 (Jiangsu Forestry Bureau 2000).

Data source and wetland mapping

Landsat TM images were used to map wetland distribution at a spatial resolution of 30 m in this study (rice paddies were excluded). The Landsat data were downloaded from the website of Center for Earth Resources Observation and Science of US Geological Survey (http://earthexplorer.usgs.gov). We aim to map wetland distribution in the three time phases of 1990, 2000, and 2006. For the purpose of wetland mapping, the source images need to be cloud-free; meanwhile, they should not be acquired during dry seasons, with respect to seasonal variation of water cover. Such qualified images were not available in each year, so we selected 10 scenes of imagery acquired from the closest dates of the tree target years (Table 1). The raw images were geometrically corrected (map projection UTM zone 50N, WGS84 datum) with an accuracy of less than 0.5 pixel root mean square error. The digital numbers of the images were converted into radiance using

Table 1 The acquisition dates of the Landsat TM images used to map wetland distribution

Path/row	Acquisition date		
	Around 1990	Around 2000	Around 2006
118/038	11 August 1989	14 June 2000	15 August 2005
119/037	2 July 1990	16 February 2001	27 May 2006
119/038	23 July 1991	26 July 2001	7 March 2005
119/039	23 July 1991	11 October 2000	17 October 2005
120/036	21 September 1988	16 September 2000	27 October 2006
120/037	25 October 1988	16 September 2000	20 May 2006
120/038	5 July 1988	28 April 1998	20 May 2006
121/036	13 February 1989	3 April 2001	14 May 2007
121/037	11 August 1988	21 July 2000	24 May 2005
122/036	15 June 1988	14 September 2000	9 October 2006

These cloud-free images can present the largest water cover of the intermittent wetlands around 1990, 2000, and 2006, respectively the gain and offset coefficients from the header files. A second simulation of the satellite signal in the solar spectrum (the 6S model) (Vermote et al. 1997) was then employed to make the atmospheric correction.

Wetland mapping was conducted with two steps. Firstly, a supervised classification approach using maximum likelihood method was employed to extract the wetlands from the pre-processed images with the TM bands 1–5 and 7 (the thermal band 6 was excluded). However, we found this spectral-based classification alone was not able to effectively distinguish between (1) land vegetations and high-cover wetland vegetations (mostly represented as emerged plants) and (2) non-wetlands and intermittent wetlands at dry conditions (see Fig. 2 as an example), thus the area of the wetlands could be substantially underestimated. The first type of misclassification was carefully revised by visual interpretation (using a pseudo-color combination of TM bands 5, 4, and 3) (Niu et al. 2009) based on published maps, high-resolution remotely sensed images, as well as ground truth survey. The high-resolution images including aerial photographs in 1990 and SPOT, IKONOS, and Quickbird images in 2000 and 2006, serve as a part of reference data of ground truth as they only cover partial wetland areas in Jiangsu Province. By comparing images in different dates, it was found that seasonal variation of wetland was significant, and selection of images in dry seasons/years could lead to extraction failure of most intermittent wetlands. To reduce the second type of misclassification, we compared all available cloud-free TM images (four images in average for each path/row) acquired within 2 years from each target year, and selected those representing the highest water cover (as listed in Table 1). Further, the misclassified intermittent wetlands were carefully detected and revised visually based on the abovementioned ground truth data.

The second step is to distinguish the wetland types. Here we adopted the Ramsar wetland classification system (Ramsar 1987), which presents three wetland types, i.e., coastal wetland, inland wetland, and human-made wetland. In Jiangsu Province, the dikes covering the complete coastline were built in the 1970s, which can separate the inlands from the influence of tides. Thus the coastal wetlands can be identified with reference to their locations relative to the dikes, i.e., the natural wetlands outside the banks were identified as coastal wetlands. Human-made wetlands in the study area are mostly represented as the four types: aquaculture pond, saltern, reservoir, and channel (Fig. 3). As they are usually separated by artificial banks and have linear boundaries, they can be identified by visual interpretation of such distinct textures with the support of ground truth data (Niu et al. 2009). It should be noted

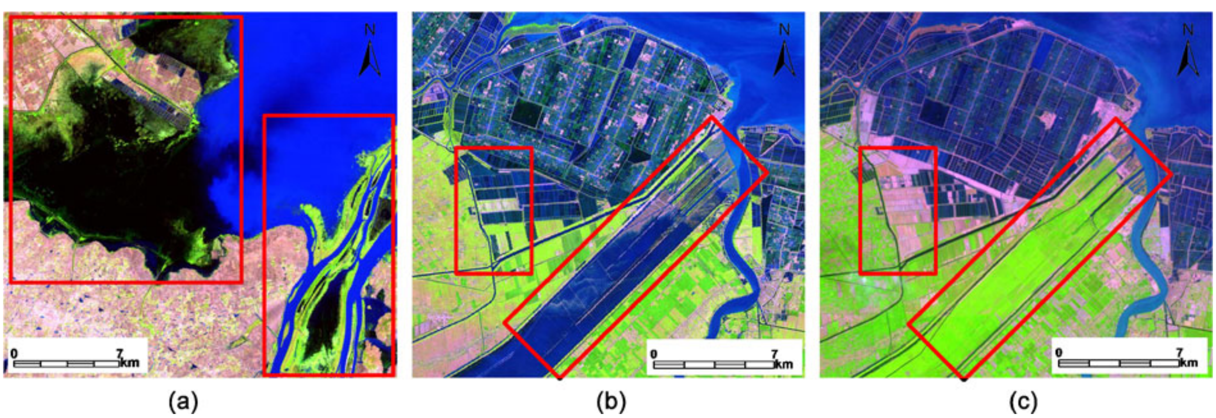

Fig. 2 Illustration of two types of wetlands which can have classification errors using supervised classification alone (using a pseudo-color combination of TM bands 5, 4, and 3). **a** Represents the wetlands with high aquatic vegetation cover; **b** and **c** represent intermittent wetlands with/without water cover

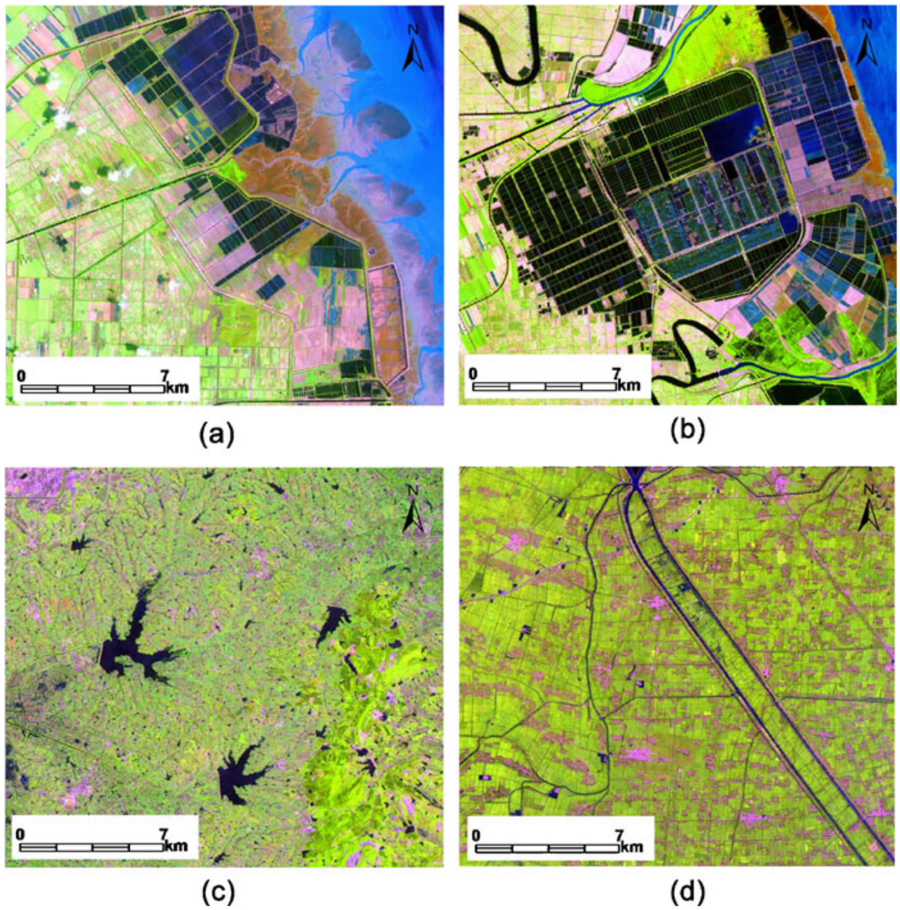

Fig. 3 Illustration of four types of human-made wetlands in the study area (using a pseudo-color combination of TM bands 5, 4, and 3). **a** Aquaculture ponds, **b** salterns, **c** reservoirs, and **d** channels

that a considerable proportion of the aquaculture ponds were converted from natural wetlands. Despite the fact that they were originated from natural wetlands, they were identified as human-made wetlands in this study because the natural hydrological and ecological processes have been substantially modified and they have presented human-dominated features.

The accuracy of wetland mapping in 2006 can be assessed using our ground truth survey data covering the whole province obtained during 2005–2007. However, precise observation of historical wetland distribution is impossible as the study period stretches nearly across two decades. Instead, the abovementioned historical maps and high-resolution images were used to derive ground truth data for the 1990 and 2000 wetland maps. In each time phase, 300 sample points were generated randomly for each wetland type, and the confusion matrix and the kappa coefficient (Liu and Mason 2009) were used to calculate the overall accuracy of wetland mapping. It should be noted that using the images from different years for one exact date could bring some errors to accuracy assessment. However, according to our observation, wetland change during such short periods could be relatively minor, thus the errors in accuracy assessment could be small. We compared the accuracies of wetland extraction before (i.e., only using the supervised classification approach) and after the revision of misclassification, and found such revision can substantially enhance the accuracy of wetland extraction by over 8% for each time phase. Ultimately, the overall accuracy of each wetland map achieved over 87% (87.8%, 87.5%, and 89.3%

for 1990, 2000, and 2006, respectively). All image processing tasks were accomplished in ENVI 4.3 and ArcGIS 9.2 software.

Quantifying the spatial differentiation of natural wetland reduction

Based on the time-series wetland maps, transition matrices were calculated to examine the trajectory of wetland change between the types of natural wetlands (including coastal and inland wetlands), human-made wetlands and non-wetlands in 1990–2000 and 2000–2006. Reduced natural wetlands (being converted to human-made wetlands or non-wetlands) in each period were detected pixel by pixel by overlaying the wetland maps. A moving window analysis (McGarigal et al. 2002) (referred to as neighborhood statistics in the ArcGIS software) was conducted on these reduction maps to quantify the spatial differentiation in local reduction magnitude. Four window sizes of 1 × 1, 2 × 2, 4 × 4, and 8 × 8 km were adopted in this analysis. Such selection of window sizes was based on the scales of human activities from the rural settlements (i.e., village/township), with regard to that most wetland uses by human occurred in the rural areas. Specifically, the lower limit scale of 1 km was in accordance with the average scale of land modification from a single village (Shi et al. 2008); while the upper limit scale of 8 km approximately corresponded to that from a single town in the study area; and 2 and 4 km were selected as mid scales.

In the procedure of the analysis, the center of the square windows moved pixel by pixel on the maps. The edge areas which cannot cover the full window sizes were removed. Within each moving window, percentage covers of the natural wetlands were quantified, thereby the center pixels were classified into 10 cover zones with an equal interval of 10% in each date. Based on the reduction maps of the natural wetlands, area reduction and percentage reduction were respectively quantified within the moving windows. For each period (1990–2000 and 2000–2006), average percentage reduction and the summed area reduction were calculated within each cover zone in the initial date. Moreover, the hotspots of natural wetland reduction were detected as the center pixels of the windows representing relatively high area or percentage reduction. Thus, two kinds of hotspots were represented, which can be termed as "area reduction hotspot" (ARH) and "percentage reduction hotspot" (PRH). The 95% threshold is commonly adopted as the criterion of hotspot identification (Nelson and Boots 2008). Here we applied this threshold in two different data classification schemes, which were referred to as *equal-interval* and *quantile* in the ArcGIS software. Using the equal-interval classification scheme, the areas represented over 95% of the maximum value of area reduction or percentage reduction were identified as the hotspots; while the quantile classification scheme presented classes with an equal area, and the top-rank class with the highest area reduction or percentage reduction was identified as hotspots. Ultimately, we have four types of hotspot: area reduction hotspot based on equal-interval classification (ARHE), area reduction hotspot based on quantile classification (ARHQ), percentage reduction hotspot based on equal-interval classification (PRHE), and percentage reduction hotspot based on quantile classification (PRHQ). Three landscape indices, i.e., total area (TA), number of patches (NP), and mean patch area (MPA), were used to quantify the patterns of natural wetland reduction hotspots (McGarigal et al. 2002).

Results

Conversion of the natural wetlands

The distribution of the wetlands in Jiangsu Province during 1990–2006 is illustrated in Fig. 4. The results show that the coastal wetlands continuously decrease by 8.6% (0.08 million hectares), the inland wetlands continuously decrease by 13.8% (0.13 million hectares), and the overall natural wetlands decreased by 11.2%. In contrast, the human-made wetlands continuously increase by 54.0% (0.31 million hectares). As a net result, the total wetlands increase by 4.4% (0.10 million hectares) in the study area during 1990–2006 (Fig. 5).

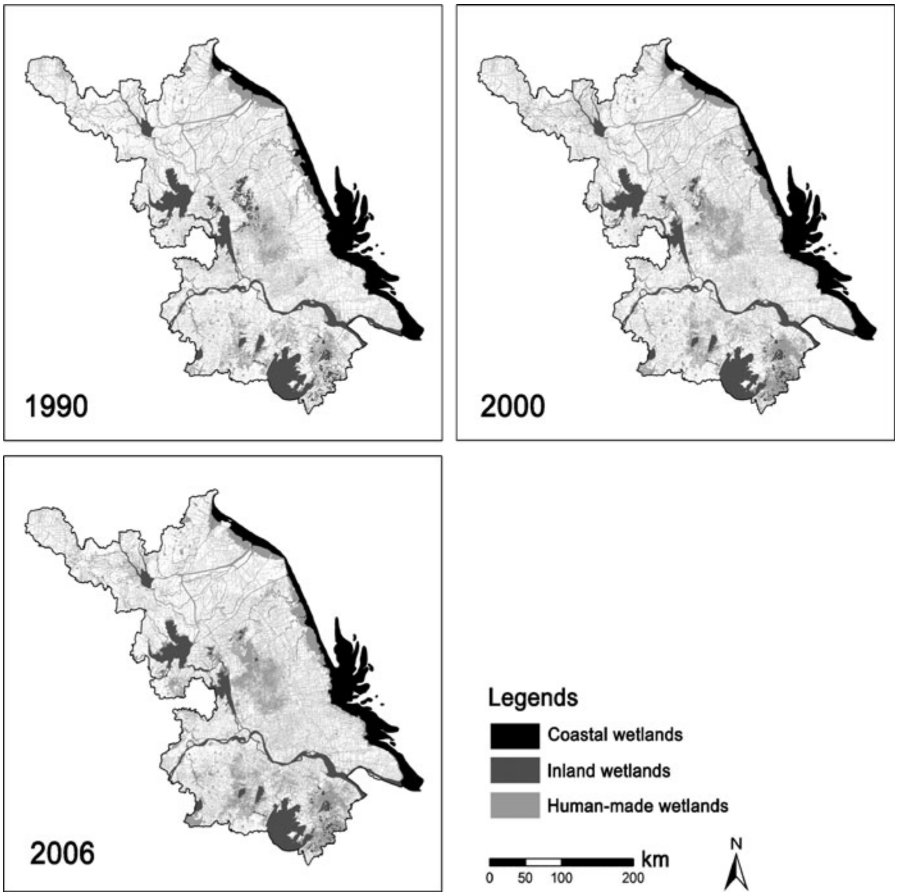

Fig. 4 Wetland distribution in the study area in *1990*, *2000*, and *2006*

The transition matrices demonstrate similar conversion trajectory of the natural wetlands in 1990–2000 and 2000–2006 (Table 2). The conversion from natural to human-made wetlands (over 65% of which are aquaculture ponds across the study period) is the primary form of natural wetland reduction, accounting for over 60% of the reduction in each period; while the drained natural wetlands (i.e., being converted to non-wetlands) account for less than 40% of the reduction. Also, there are some newly generated natural wetlands (being converted from non-wetlands and human-made wetlands), which offset 10% and 28% of the reduction in 1990–2000 and 2000–2006, respectively.

Natural wetland reduction by percentage cover zone

The percentage cover zones of the natural wetlands show similar area distribution across the four investigated scales (Fig. 6a). The 10–90% zones took small proportions below 10% with a relatively even distribution, while the 0–10% and 90–100% zones are predominant in area propor-

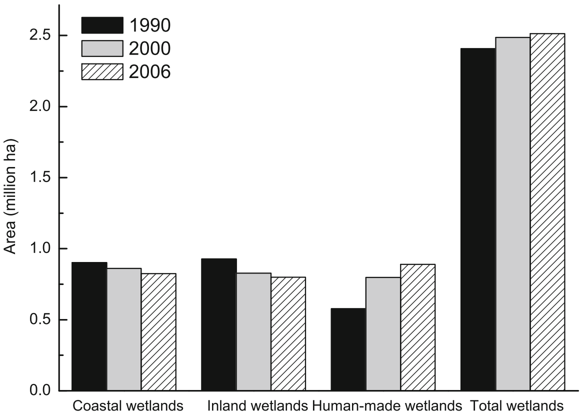

Fig. 5 Areas of the wetlands in the study area in *1990*, *2000*, and *2006*

Table 2 Transition matrices of wetland types in the study area during 1990–2000 and 2000–2006

		Natural wetlands		Human-made wetlands		Non-wetlands	
		Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)
		1990					
2000	Natural wetlands	1,671,710	91.3	5,429	0.9	10,797	0.1
	Human-made wetlands	108,162	5.9	415,709	72.0	273,605	1.1
	Non-wetland	50,197	2.8	156,191	27.1	23,912,944	98.8
		2000					
2006	Natural wetlands	1,600,005	94.8	10,657	1.3	13,978	0.1
	Human-made wetlands	54,947	3.3	586,306	73.5	247,547	1.0
	Non-wetlands	32,979	1.9	200,513	25.2	23,857,809	98.9

tion. Also, these two zones (0–10% and 90–100%) present considerable proportions of area reduction, especially for the 90–100% zone at the scale of 1 and 2 km (Fig. 6b). In the zones of 10–90%, a consistent unimodal distribution of area reduction is shown, with the largest value falling into the 50–

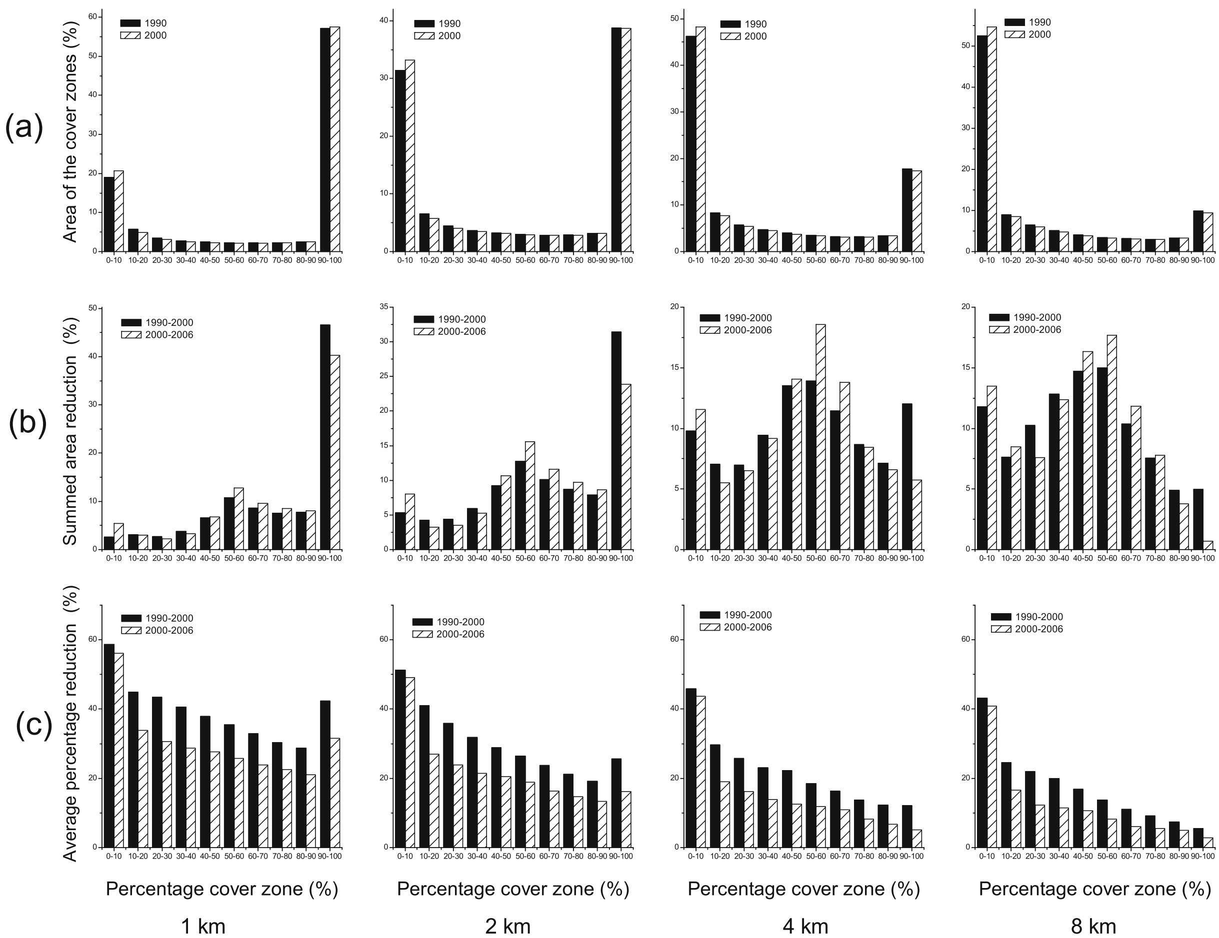

Fig. 6 Area distribution of the 10 wetland cover zones from 0–100% (**a**), summed area reduction (**b**), and average percentage reduction (**c**) in the wetland cover zones at the four investigated scales

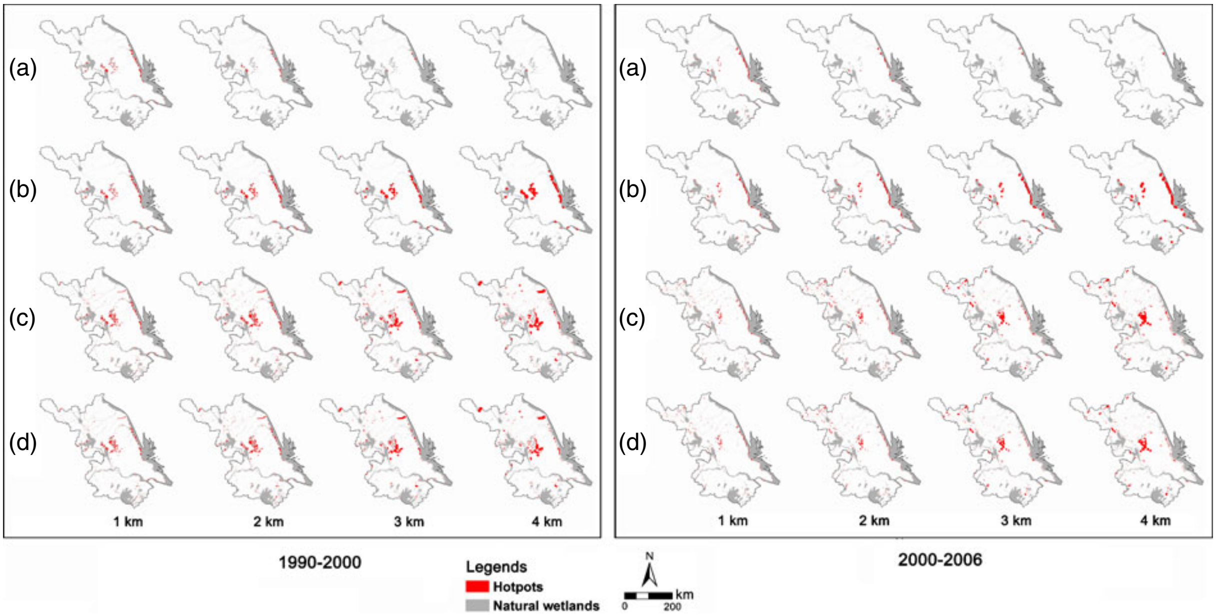

Fig. 7 Hotspots of natural wetland reduction in the study area during 1990–2000 and 2000–2006. **a** Area reduction hotspot based on equal-interval classification, **b** area reduction hotspot based on quantile classification, **c** percentage reduction hotspot based on equal-interval classification, and **d** percentage reduction hotspot based on quantile classification

60% zone at the scales of 4 and 8 km. The average percentage reduction show a declining tendency with increasing percentage cover, except the 90–100% zone at the scale of 1 and 2 km where a relatively high value is shown (Fig. 6c).

Hotspots of natural wetland reduction

In the two study periods, the hotspots of natural wetland reduction are mostly concentrated in the coastal wetland area and the Lixiahe area, central Jiangsu (Fig. 7). However, the patterns of the four types of hotspots are quite different (Figs. 7 and 8). Generally, the ARHs show less patch number (NP) and total patch area (TA), but greater mean patch area (MPA) than the PRHs at all four scales. Moreover, classification scheme can substantially influence hotspot patterns. For the ARHs, the quantile classification present higher NP, TA, and MPA than the equal-interval classification; while for the PRHs, an opposite result is shown. The landscape indices of the hotspots show monotonic tendency in response to spatial scale. NP of all four types of hotspots declines, while both TA and MPA increase (except for the ARHEs) along with increasing observation scale from 1 to 8 km.

Discussion

In China, natural wetlands occupy 3.8% of the terrestrial area, and provide 54.9% of the annual ecosystem services for the country (An et al. 2007). As a heavy cost of rapid socioeconomic growth, China has suffered serious environmental problems, a remarkable one of which is natural wetland reduction (An et al. 2007). Fortunately, along with increasing awareness of the critical importance of natural wetlands, China has carried out a series of actions, including monitoring wetland change, implementing wetland conservation and restoration projects, and designating “Wetland of National Importance” (State Forestry Administration of China 2000; An et al. 2007). Fine-scale national/regional wetland datasets can play an important role as a basis of these comprehensive actions. However, such datasets are limited yet (Niu et al. 2009). Jiangsu Province is recognized as one of the most important wetland

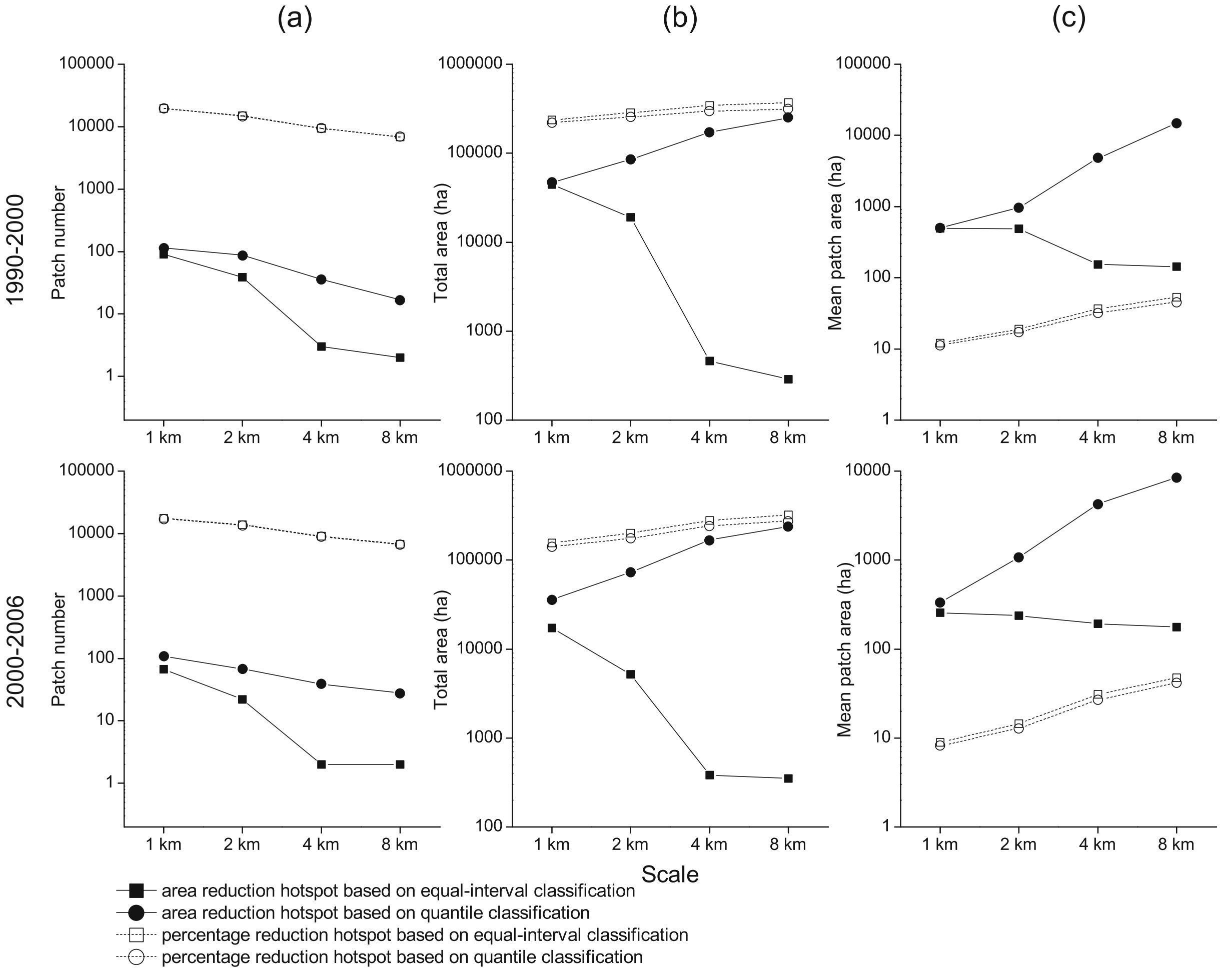

Fig. 8 Landscape indices of the hotspots of natural wetland reduction at the four investigated scales, **a** patch number, **b** total area, and **c** mean patch area, note that the *y*-axes are in geometric proportion

region in China, not only because it holds an extensive area of wetlands but also because these wetlands are supporting the highest population density and fastest socioeconomic development in China. To date, multi-temporal datasets of Jiangsu's wetland distribution at fine resolutions are still lacking. The present study can provide a useful knowledge of wetland change in this wetland-rich province since the 1990s when the economic booming was accelerated.

Despite of the proven advantages, remotely sensed monitoring of wetlands could have, more or less, some uncertainties resulted from classification error (Lunetta and Lyon 2005; MacAlister and Mahaxay 2009). Particularly, intermittent wetlands under dry conditions (mostly represented as flooded areas in the study area) and wetlands with high-cover aquatic plants (e.g., reed marshes) are hard to detect only using optical remotely sensed data (radar imaging can differentiate open water and aquatic vegetation, Bartsch et al. 2009), since they often present similar spectral and texture features with non-wetlands. Hence, some studies did not take intermittent wetlands into account (e.g., Daniels and Cumming 2008). Our study demonstrated that visual interpretation of Landsat data based on expert knowledge and ground truth data can be a feasible approach reducing theses classification errors, and using multi-temporal instead of single-date images, can effectively reduce the uncertainties caused by temporal variation of wetlands. Nonetheless, this integrated approach could be data and labor intensive, which could limit its application.

It was estimated that half of global wetlands have been lost as a result of human activities (Zedler and Kercher 2005). Drainage for agriculture was recognized as the primary cause of global wetland loss (Zedler and Kercher 2005). Although the total wetland area showed an increasing tendency, the natural wetlands experienced remarkable reduction in Jiangsu Province, China. The conversion of natural wetlands to human-made wetlands, mostly aquaculture ponds, was found to be the major form of natural wetland reduction. Aquaculture has a long history and large production amount (accounting for about 20% of the primary industry in 2008) (Jiangsu Statistical Bureau 2009) in Jiangsu Province. The natural wetlands, especially those with shallow waters, are prone to be constructed into aquaculture ponds due to relatively low time and economic costs and high production output. For example, in Jiangsu Province, the large-scale reclamation transformed 75% of the Yancheng coastal wetland during the past three decades (Zhai et al. 2009); Lixiahe Marshes, once the largest freshwater marsh in Eastern China, has experienced a conversion of 70% to aquaculture ponds during the past two decades (Sheng et al. 2008). Fortunately, increasing wetland restoration has offset a proportion of natural wetland reduction. At present, more and more initiated wetland restoration projects are expected to enhance the protection of the natural wetlands in Jiangsu Province (Jiangsu Forestry Bureau 2010). But fully restoring the natural wetlands might be difficult since some changes of wetland ecosystems could not be reversible (Zedler and Kercher 2005).

Detecting the spatial differentiation of natural wetland reduction from the multi-scale perspective can have some useful implications to wetland conservation, particularly for identification of conservation priority. Our results showed that both area reduction and percentage reduction varied in different wetland cover zones. The low wetland cover zone (0–10%) showed the largest average percentage reduction, suggesting that discrete small wetlands and the edge areas of large wetlands (both can present low wetland cover) were relatively susceptible to human influences. For the high-occurrence wetland cover zone of summed area reduction, the distinct shift from the scale of 2 to 4 km could suggest that most reduction occurred in the wetlands with sizes (average diameter) between these two scales. Overall, conservation measures should be taken with respect to the reduction trend by wetland cover zone at corresponding spatial scales.

Most studies of hotspot mapping adopted the kernel estimation method (as adopted in the present study) (Etter et al. 2006; Alessa et al. 2008; Nelson and Boots 2008). However, hotspot patterns are rarely compared across different hotspot identification schemes. In the present case, the hotspots reflecting absolute area (i.e., ARHs) and relative rate (i.e., PRHs) of natural wetland reduction showed greatly different patterns. It should be noted that the natural wetlands had a discontinuous distribution in the study area, and considerable reduction occurred at the edge areas of the natural wetlands (e.g., lake/river beaches since the shallow waters can facilitate human constructions). Thus the moving windows containing such edge areas could present PRHs, as a result, the center pixels (identified as hotspots) of these windows could apparently depart from the wetland areas, particularly at large observation scales (Fig. 7); and a great number of hotspot patches was produced (Fig. 8). Therefore, ARHs could be more suitable than PRHs in the study area. In addition, classification scheme can substantially influence hotspot pattern as the values of local reduction magnitude were unevenly distributed. Since only a very small proportion of the lost wetland areas presented high values of local magnitude of area reduction, the equal-interval classification showed less and smaller hotspot patches than the quantile classification. Adoption of identification scheme could be context dependent. Despite of the abovementioned differences, the marsh wetlands in the Lixiahe region and coastal wetlands were consistently detected in all schemes of hotspot mapping across the four scales. Both regions present unique wetlands which provide important habitats for regional biodiversity. Nonetheless, as these wetlands could have high productivity and developing suitability (e.g., the water is very shallow and the topography is very flat), they are prone to be utilized. Such natural wetland reduction occurring at regional scale could produce significant threats to biodiversity conservation and water security (Zhai et al. 2009). These wetlands should be the priority of wetland conservation and restoration.

Conclusions

Monitoring natural wetland reduction plays an important role in wetland conservation. Landsat images can provide useful data source for mapping regional wetland distribution with a fine resolution. With respect to diverse wetland types, wetland monitoring using Landsat data could have some uncertainties, especially for intermittent wetlands and wetlands with high-cover aquatic vegetation. Visual interpretation based on ground truth data can be a feasible approach reducing these uncertainties, and using multi-temporal instead of single-date images, can effectively improve the accuracy of extraction of intermittent wetlands.

Jiangsu Province is one of the most important wetland regions in China. During 1990–2006, it suffered natural wetland reduction by 11.2% (0.2 million hectares). The conversion of natural wetlands to human-made wetlands (mostly aquaculture ponds) was found to be the major form of natural wetland reduction, accounting for over 60% of the reduction in each period. From a multi-scale perspective, the spatial differentiation of natural wetland reduction was quantified within different wetland cover zones. The largest area reduction occurred in the high-cover zone (90–100%) at the scales of 1 and 2 km, while in the mid-cover zone (50–60%) at the scale of four and 8 km; percentage reduction showed a decreasing tendency with increasing wetland cover across all investigated scales. The hotspots of area reduction and percentage reduction were mapped using the equal-interval and quantile classification schemes. The reduction hotspots were mostly concentrated in the Lixiahe marshes and coastal wetland areas. Hotspot patterns could substantially vary by classification scheme and spatial scale. As the discontinuous distribution of the natural wetlands can bring significant edge effect when mapping the percentage reduction hotspots, area reduction could be more appropriate to represent reduction hotspots in the study area. Ultimately, these findings could have useful implications to wetland conservation.

Acknowledgements This study was supported by the Special Forestry Project of Public Interests (200904001), the Key Project of Control and Treatment of Water Pollution of China (2008ZX07526-002-03), and the National Natural Science Foundation of China (30870433 and 40801068).

References

Alessa, L., Kliskey, A., & Brown, G. (2008). Social–ecological hotspots mapping: A spatial approach for identifying coupled social–ecological space. *Landscape and Urban Planning, 85*(1), 27–39.

An, S., Li, H., Guan, B., Zhou, C., Wang, Z., Deng, Z., et al. (2007). China's natural wetlands: Past problems, current status, and future challenges. *AMBIO, 36*(4), 335–342.

Bartsch, A., Wagner, W., Scipal, K., Pathe, C., Sabel, D., & Wolski, P. (2009). Global monitoring of wetlands—The value of ENVISAT ASAR Global mode. *Journal of Environmental Management, 90*(7), 2226–2233.

Brinson, M. M., & Malvarez, A. I. (2002). Temperate freshwater wetlands: Types, status, and threats. *Environmental Conservation, 29*(2), 115–33.

Bunn, S. E., Davies, P. M., & Mosisch, T. D. (1999). Ecosystem measures of river health and their response to riparian and catchment degradation. *Freshwater Biology, 41*(2), 333–345.

Bürgi, M., Hersperger, A. M., & Schneeberger, N. (2004). Driving forces of landscape change—Current and new directions. *Landscape Ecology, 19*(8), 857–868.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature, 387*, 253–59.

Dabrowska-Zielinska, K., Gruszczynska, M., Lewinski, S., Hoscilo, A., & Bojanowski, J. (2009). Application of remote and in situ information to the management of wetlands in Poland. *Journal of Environmental Management, 90*(7), 2261–2269.

Daniels, A. E., & Cumming, G. S. (2008). Conversion or conservation? Understanding wetland change in Northwest Costa Rica. *Ecological Applications, 18*(1), 49–63.

Etter, A., McAlpine, C., Phinn, S., Pullar, D., & Possingham, H. (2006). Characterizing a tropical deforestation wave: A dynamic spatial analysis of a deforestation hotspot in the Colombian Amazon. *Global Change Biology, 12*(8), 1409–1420.

Foote, A. L., Pandey, S., & Krogman, N. T. (1996). Process of wetland loss in India. *Environmental Conservation, 23*(1), 45–54.

Gibbs, J. P. (2000). Wetland loss and biodiversity conservation. *Conservation Biology, 14*(1), 314–317.

Hey, D. L., & Philippi, N. S. (1995). Flood reduction through wetland restoration: The Upper Mississippi River Basin as a case history. *Restoration Ecology, 3*(1), 4–17.

Jeng, H., & Hong, Y. (2005). Assessment of a natural wetland for use in wastewater remediation. *Environmental Monitoring and Assessment, 111*(1–3), 113–131.

Jiangsu Forestry Bureau (2000). *Report of wetland inventory of Jiangsu Province.* Jiangsu Forestry Bureau.

Jiangsu Forestry Bureau (2010). *Report of wetland inventory of Jiangsu Province for the second nationwide wetland inventory.* Jiangsu Forestry Bureau.

Jiangsu Statistical Bureau (2009). *Statistical yearbook of Jiangsu 2008*. Beijing: China Statistics Press.

Jones, K., Lanthier, Y., van der Voet, P., van Valkengoed, E., Taylor, D., & Fernandez-Prieto, D. (2009). Monitoring and assessment of wetlands using Earth observation: The GlobWetland project. *Journal of Environmental Management, 90*(7), 2154–2169.

Ladhar, S. S. (2002). Status of ecological health of wetlands in Punjab, India. *Aquatic Ecosystem Health & Management, 5*(4), 457–465.

Liu, J. G., & Mason, P. J. (2009). *Essential image processing and GIS for remote sensing.* West Sussex: Wiley.

Lunetta, R. S., & Lyon, J. G. (2005). *Remote sensing and GIS accuracy assessment.* Boca Raton: CRC press.

MacAlister, C., & Mahaxay, M. (2009). Mapping wetlands in the Lower Mekong Basin for wetland resource and conservation management using Landsat ETM images and field survey data. *Journal of Environmental Management, 90*(7), 2130–2137.

McGarigal, K., Cushman, S. A., Neel, M. C., Ene, E. (2002). *FRAGSTATS: Spatial pattern analysis program for categorical maps.* Amherst: University of Massachusetts.

Millennium Ecosystem Assessment (2005). *Ecosystems and human well-being: Wetlands and water synthesis.* Washington, DC: World Resources Institute.

Mitsch, W. J., & Gosselink, J. G. (2000). *Wetlands* (3rd ed.). New York: Wiley.

Mitra, S., Wassman, R., & Vlek, P. L. (2005). An appraisal of global wetland area and its organic carbon stock. *Current Science, 88*(1), 25–35.

Moser, M., Prentice, C., & Frazier, S. (1996). *A global overview of wetland loss and degradation.* http://www.ramsar.org/cda/en/ramsar-news-archives-2002–a-global-overview-of/main/ramsar/1-26-45-87%5E16905_4000_0__. Accessed 29 September 2010.

Nelson, T. A., & Boots, B. (2008). Detecting spatial hot spots in landscape ecology. *Ecography, 31*(5), 556–566.

Niu, Z. G., Gong, P., Cheng, X., Guo, J. H., Wang, L., Huang, H. B., et al. (2009). Geographical analysis of China's wetlands preliminarily derived from remotely sensed data. *Science in China Series D: Earth Sciences, 39*(2), 188–203.

Ramsar (1987). The Convention on Wetlands text, as amended in 1982 and 1987. http://www.ramsar.org. Accessed 20 May 2010.

Rebelo, L. M., Finlayson, C. M., & Nagabhatla, N. (2009). Remote sensing and GIS for wetland inventory, mapping and change analysis. *Journal of Environmental Management, 90*(7), 2144–2153.

Sheng, S., Xu, M., Zhang, A., Liu, M., & Zhai, K. (2008). *Dynamics of the natural marsh vegetation in the Lixiahe region, Jiangsu Province.* Proceedings of the Eighth Biennial Meeting of Chinese Youth on Forest Science.

Shi, Q., Liu, M., Song, J., Xu, C., & Chen, H. (2008). Dynamic analysis on settlement percentage coverage in urbanization. *Chinese Journal of Ecology, 27*(11), 1979–1984.

State Forestry Administration of China (2000). *China's national wetland conservation action plan.* Beijing: China Forestry Publishing House.

Trebitz, A. S., Morrice, J. A., Taylor, D. L., Anderson, R. L., West, C. W., & Kelly, J. R. (2005). Hydromorphic determinants of aquatic habitat variability in Lake Superior coastal wetlands. *Wetlands, 25*(3), 505–519.

Vermote, E., Tanre, D., Deuze, J. L., Herman, M., & Morcrette, J. J. (1997). Second simulation of the satellite signal in the solar spectrum: An overview. *IEEE Transactions on Geoscience and Remote Sensing, 35*(3), 675–686.

Wu, J., Jones, K. B., Li, H., & Loucks, O. L. (2006). *Scaling and uncertainty analysis in ecology: Methods and applications.* Dordrecht: Springer

Zedler, J. B., & Kercher, S. (2005). Wetland resources: Status, trends, ecosystem services and restorability. *Annual Review of Environmental Resources, 30*, 39–74.

Zhai, K., Liu, M., Xu, C., Cui, L., & Xu, H. (2009). Land use/cover change in Yancheng coastal wetland. *Chinese Journal of Ecology, 28*(6), 1081–1086.

Zhang, X., Wang, G., Wang, Y., & Wang, Z. (2006). The changes of erosion or progradation of tidal flat and retreat or extension of wetland vegetation of the Yancheng coast, Jiangsu. *Marine Science, 30*(6), 35–39.