IDENTIFYING WETLAND CHANGE IN CHINA'S SANJIANG PLAIN USING REMOTE SENSING

Shuqing Zhang[1], Xiaodong Na[1,2], Bo Kong[1,2], Zongming Wang[1], Hongxing Jiang[3], Huan Yu[1,2], Zhichun Zhao[1], Xiaofeng Li[1,2], Chunyue Liu[1,2], and Patricia Dale[4]
[1]*Northeast Institute of Geography and Agroecology*
Chinese Academy of Sciences
Changchun, Jilin, P. R. China 130012
Email: Zhangshuqing@.neigae.ac.cn
[2]*Graduate University*
Chinese Academy of Sciences
Beijing, P. R. China 100049
[3]*Research Institute of Forest Ecology, Environment and Protection*
Chinese Academy of Forestry
Beijing, P. R. China 100091
[4]*Center for Innovative Conservation Strategies*
Griffith School of Environment
Griffith University
Brisbane, Nathan, Queensland, Australia 4111

Abstract: Maximum likelihood supervised classification and post-classification change detection techniques were applied to Landsat MSS/TM images acquired in 1976, 1986, 1995, 2000, and 2005 to map land cover changes in the Small Sanjiang Plain in northeast China. A hotspots study identified land use changes in two National Nature Reserves. These were the Honghe National Nature Reserve (HNNR) and the Sanjiang National Nature Reserve (SNNR). Landscape metrics were used in both reserves to identify marsh landscape pattern dynamics. The results showed that the Small Sanjiang plain had been subject to much change. This resulted from direct and indirect impacts of human activities. Direct impacts, resulting in marsh loss, were associated with widespread reclamation for agriculture. Indirect impacts (mainly in HNNR) resulted from alterations to the marsh hydrology and this degraded the marsh ecosystem. Marsh landscape patterns changed significantly due to direct impacts in SNNR between 1976 and 1986 and again between 2000 and 2005, and, in HNNR between1976 and1986. Indirect impacts in HNNR after 1986 appeared to cause little change. It was concluded that effective wetland protection measures are needed, informed by the change analysis.
Key words: change detection, human influence, Landsat

INTRODUCTION

Wetlands are integral parts of the global ecosystem as they can prevent or reduce the severity of floods, feed ground water, and provide unique habitats for flora and fauna (Mitsch and Gosselink 1993). Because of this, many wetlands around the world are protected and monitored by various agencies and recognized by international treaties such as the Ramsar Convention on Wetlands (Tőyrä and Pietroniro 2005). As such, it is important to inform management using accurate quantitative scientific data for wetland landscapes at meaningful spatial and temporal scales. However, traditional field investigation methods are often inadequate to achieve this goal

(Belluco et al. 2006).

Multi-temporal satellite imagery can be a cost and time effective tool to rapidly gather repeated observations over broad regions (Haddad and Harris 1985, Bartlett 1987, Klemas and Hardisky 1987, Ferguson et al. 1993). Satellite remote sensing detection techniques have been widely used to detect and monitor wetland landscape dynamics at various scales (Ackleson and Klemas 1987, Pietroniro et al. 1996, Ramsey et al. 1997, Shalaby and Tateishi, 2007). Such analyses help us understand wetland landscapes, the relationships between human activities and landscape changes, and perhaps predict change (Gulinck et al. 2001). This aids in decision-making to achieve sustainable development, and there is growing interest in the application of remote sensing and GIS methods for mapping and analyzing wetland landscapes (see Dale et al. 1986, Johnston and Barson 1993, Eastwood et al. 1997, Munyati 2000, Shuman and Ambrose 2003, Belluco et al. 2006).

The Chinese government has also realized the significance of wetlands, and has been taking measures to protect them. Numerous wetland nature reserves were established over the past 20 years, and China now has 473 wetland nature reserves, with up to 45% (17.2 million ha) of natural wetlands being protected (Jiang et al. 2006). However, rapid population growth and economic development is placing increasing pressure on wetland ecosystems. Wetlands are still being disturbed or destroyed, even within reserves (Cui and Liu 1999).

Our study area focused on two wetland reserves, the Honghe National Nature Reserve and the Sanjiang National Nature Reserve. Both were listed in 2002 as wetlands of international importance by the Ramsar Convention (Li et al. 2006). We assessed whether the large-scale agricultural development that has occurred over the past 50 years has resulted in the degradation of these wetland ecosystems, and whether recent wetland protections are effective in preserving the reserves. Specifically we 1) contrasted landscape structure between 1976 and 2005 in areas under heavy human influence and 2) analyzed the characteristics of marsh landscape change related to direct and indirect human impacts within each of the two NNRs to suggest strategies to better manage the wetland resources.

METHODS
Study Area

Our study area, the Small Sanjiang Plain is located at 46° 48′ 5.83″ ~ 48°29′16.43″N, 132° 26′ 25.52″ ~ 135° 7′ 24.4″E, and lies in the northeast of the Sanjiang Plain (Figure 1). Prior to the 1950s the Sanjiang Plain was pristine (Liu 1995). At the end of the 1950s, many retired soldiers moved into this region to reclaim wetlands, and by 2000 many large intensively cultivated farms had been created (Liu and Ma 2002). With a population of 7.8 million, of which 53.4% is engaged in farming, the Sanjiang Plain is an important commodity grain and bean supplier for China (Chen and Ma 1997).

Due to the relatively cold weather, deep surface waters, large marsh patches, and sparse population, reclamation of Small Sanjiang Plain marshes started relatively late, and the Honghe National Nature Reserve (HNNR) and Sanjiang National Nature Reserve (SNNR) were created. HNNR is relatively small (about 24,738 ha) with no residential areas, and has limited water resources because it lies in the headwaters of the Nong River. SNNR is larger (about 185,231 ha), has scattered settlements, and more water as it is located in the lower reaches of the Nong River. These contrasts provide an opportunity to investigate and compare differing marsh landscape dynamics using remote sensing.

The regional climate is temperate humid to sub-humid continental monsoon. Average

temperatures range from -18°C in January to 21–22°C in July, with a frost-free period of 120–140 days. Annual precipitation is 500–650 mm, with 80% occurring in May-September. Most of the rivers in the area have riparian wetlands supporting meadow and marsh vegetation. Sedge (*Carex* spp.) is the dominant plants with *Phragmites* spp. scattered across some portions (Liu 1995).

Remote Sensing Data

Landsat MSS and TM remote sensing images were used to detect change in the Small Sanjiang Plain marsh study area. The well-integrated assemblage of Landsat's spectral, spatial, and temporal resolutions, combined with its extensive archive and relative low cost provide an invaluable data source for change detection research (Woodcock et al. 2001, Cohen and Goward 2004,Wulder et al. 2008,). Ten cloud-free scenes for 1976, 1986, 1995, 2000, and 2005 were used for change detection (see Table 1 for detailed description of the images). All the images were acquired from June to September, which is during the growing season and best for vegetation research. Weather conditions were near normal (neither very dry nor very wet) for the study years as determined from historical meteorological data (Heilongjiang Meteorological Bureau).

Ancillary GIS Data

Other ancillary GIS data used in this research were: 1) a digital district map and topographic maps at the scale of 1:100,000 in 1976 and 1999, 1: 50,000 in 1986, and 1:10,000 in 1995 from the Heilongjiang Mapping and Surveying Bureau; 2) a vegetation thematic map at the scale of 1:200,000 from the Geography Institution of Changchun, Chinese Academy of Sciences in 1985; 3) meteorological data from 1970 to 2005 from the Heilongjiang Meteorological Bureau; 4) social and economic statistics from the statistical yearbook for Jiansanjiang by the Heilongjiang Land Use Bureau (Editorial Department of Land Reclamation Statistical Yearbook, Jiansanjiang (2006)); and 5) ground water level data for 1996 to 2005 from the Long-Observation Well (#2) in Qianfeng ranch near HNNR (School of Conservancy & Civil Engineering, Northeast Agricultural University).

Geometric Rectification and Radiometric Normalization

Radiometric rectification plays a significant role in the process of multi-temporal change detection (Tang et al. 2005). Prior to analysis, digital values recorded at the top of the atmosphere were converted to total radiance values at the satellite level and corrected for atmospheric effects by the dark-pixel subtraction technique (Chavez 1988). It was necessary to geo-reference the images as the imagery contained geometric errors from sources that ranged from variations in the altitude, attitude, and velocity of the sensor platform, to factors such as panoramic distortion, earth curvature, earth rotation, relief displacement, and nonlinearities in the sweep of the sensor's instantaneous field of view (IFOV) (Lillesand and Kiefer 1994). All images were registered to the Gauss projection (identical to that of the digital district map) using ERDAS software. Between 55 and 66 Ground Control Points (GCPs) were used for each image. They were evenly distributed throughout the whole study area and most of them were laid on distinguishable objects, for example, the intersections of roads or fence lines. The images in 1976 were re-sampled to pixel size 30 x 30 m, so as to match the TM image's resolution for other years. The two scenes of images acquired in 2005 were used as reference images to correct the other eight scenes (for image to image registration) from 1976 to 2000. The registration procedure achieved an accuracy of less than 0.5 pixel root mean square error (RMSE) for images in 1976, 1986, 1995, and 2000.

Two scenes of TM imagery cover our study area, so a mosaic had to be made in the pre-

processing step. Due to the variation of sensor-target-illumination geometry (Mas 1999, Yang and Lo 2002, Wang et al. 2004, Tang et al. 2005), it was necessary to conduct image-to-image radiometric normalization between the adjacent images so that the distribution of brightness values within the two images were as close as possible in the resultant mosaic image (Richards and Jia 1993). To do this, we performed histogram matching between the adjacent scenes for the same year using the ERDAS Imagine 8.7 software as suggested by Tang et al. (2005).

Field Surveys

For training and testing of the supervised classification and investigating vegetation change and succession, field surveys were conducted in August 2005, collecting real time ground truth reference data, aided by a global positioning system (GPS). Vegetation cover was identified in the field. The two NNRs (HNNR and SNNR) were most intensively observed. Observations also included vegetation gradient distribution, shrub encroachment, reforestation, and tree plantation in HNNR. A large wetland reclamation in SNNR was also recorded.

Land Cover Classification

The vegetation mapping component focused on evaluating the use of TM multispectral scenes for mapping general vegetation types in the Small Sanjiang Plain. A previous study by Terrain Resources Ltd. (1995) demonstrated that Landsat TM imagery did not satisfactorily separate different meadow types. May et al. (1997) found that Landsat TM and SPOT-1 imagery could discriminate shrub vegetation from meadows, but could not distinguish meadow sub-types. A major concern for the HNNR has been whether or not the potential reduction in flood frequency and water depth due to the reclamation of the surrounding area would allow encroaching willow (*Salix* sp.) shrubs to invade more productive areas covered by graminoid vegetation (including sedges). The land cover classification system was designed to consider three factors: 1) the spatial resolution of MSS and TM imagery and the spectral difference among diverse land use/cover categories; 2) the characteristics of vegetation distribution and the process of vegetation change and succession in the study area; and 3) the previous national standard land cover classification system used in China.

Six land use/cover categories (Table 2) were chosen for the land use/cover classification, and a nine-pixel minimal patch size was used so as to avoid the 'salt and pepper' phenomena without losing too much detail. The land use/cover categories were: Cultivated land, Forestland, Meadow, Marsh, Residential area, and Open water. The spectral characteristics of each land use/cover types on false color composite images (bands 4, 3, and 2) were also studied. A traditional supervised classification method, Maximum Likelihood Classification (MLC), was used to classify the images into land use/cover classes using all the reflective bands (MSS bands 1, 2, 3, 4; TM bands 1, 2, 3, 4, 5, 7) with ERDAS Imagine 8.7 software. Considering the requirement of MLC and size of the study area, a separate set of training and test samples of around 600 pixels were chosen for the images. The number of training and testing plots could be adjusted based on the relative importance of the categories in terms of the objectives of the mapping or by the inherent variability within each of the categories or classes. The accuracy of the resultant landscape maps was assessed with an independent set of test samples in the study area. An error matrix was generated. The producer's accuracy, user's accuracy, overall accuracy, and Kappa coefficients were derived for accuracy assessment.

Analysis of Land Use/Cover Change

A post-classification change detection technique was used to detect change. Post-classification comparison proved to be an effective technique because data from different dates were separately classified, thereby minimizing the problem of normalizing for atmospheric and

sensor differences among dates (Shalaby and Tateishi 2007). Cross-tabulation analysis was carried out to analyze the spatial distribution of different land cover classes and land cover changes between the beginning (1976) and the end (2005) of the study period.

Land use/cover analysis was performed at two levels: the regional level and a more detailed NNR level. At the regional level of the Small Sanjiang Plain the temporal and spatial dynamics of diverse land use/cover categories were calculated and visualized in maps. At the NNR level, land use/cover dynamics of HNNR and SNNR were analyzed in detail.

Analysis of Landscape Pattern Change

As land use/cover change and the related driving forces in the two NNRs varied both spatially and temporally, how the marsh landscape pattern changed in each NNR was a central concern. Landscape indices were used to analyze landscape pattern over time at class level for both NNRs. Five landscape indices commonly used in landscape ecology studies were employed including: mean of fractal dimension index (FRAC_MN), mean of the contiguity index (CONTIG_MN), number of patches (NP), patch cohesion index (COHESION), and largest patch index (LPI) (McGarigal et al. 2002). Table 3 provides more detail for each. FRAC_MN and CONTIG_MN defined the patch shape complexity and patch boundaries connectedness respectively. NP was an indicator of the degree of fragmentation. COHESION and LPI reflected the connectivity and dominance of marsh landscape, respectively (McGarigal et al. 2002).

RESULTS AND DISCUSSION

Land Use/Cover Dynamics of Small Sanjiang Plain

After classifying the remote sensing imagery and assessing its accuracy, land use/cover classification maps of the Small Sanjiang Plain study area were made for 1976, 1986, 1995, 2000, and 2005. The classification accuracy assessment results of the maximum likelihood method are shown in Table 4. Over the five periods, the % accuracy and Kappa coefficient ranged from a low of 77.3% and 0.7279 respectively in 1986, to a high of 81.8% and 0.7776 in 2000. The accuracy for the six land use/cover categories is similar at each time period. The classification accuracy is highest for forestland and this is related to its distinct spectral characteristics. In contrast the accuracy for marsh land and meadow is relatively low. This is due to their similar spectral characteristics leading to some lack of discrimination.

Figure 2 shows the classification maps for marsh and cultivated land. The land use/cover of the Small Sanjiang Plain has experienced significant changes related to human influences during the past 30 years (see Table 5). In brief, the area of cultivated land has increased and the area of marsh, meadow, and forest has greatly decreased. Specifically, the area of cultivated land within the study area increased continuously over the 30 years, from 459,300 ha in 1976 (28.6% of the total area) to 1,068,370 ha in 2005 (66.5% of the total area) (see Table 5 for details for each year). It showed a particularly rapid increase between 2000 and 2005, increasing from 46.6 to 66.5% of the total area. The reason for the rapid increase in cultivated land was the policy to subsidize agriculture in the period.

By 1995, the meadow had mostly been converted to cultivated land and meadow percentage was reduced to only 0.8% of the area. Meadow is generally the top-priority for land development. The marsh area in the study area continued to decrease over the entire 30 years of the study period. The rate of decrease was extremely high between 1976 and 1986, declining from 41% of the total area to only 22.5% (see Table 5). The loss of marsh has been constrained to a certain degree since the 1980s, when a national program to revert cropland to wetlands started. Compared to the loss of marsh area prior to 1986, the rate of loss during the 1986–1995

period was clearly slower than previously (decreasing from 22.5% to 20.2%) and this was related to the measures for wetland protection. However, between 2000 and 2005 the marsh % dropped from 19 to 12.5, which reflects the fact that there was very little meadow left to be developed and so attention turned to converting marsh.

Forestlands increased at first and then began to decrease. A national program for shifting cropland to forest was implemented during 1976–1995, after massive deforestation from the late 1950s to early 1970s. The forestlands area percentage thus increased from 6.7% to 26.6% between 1976 and 1995. However, since the late 1990s forestlands decreased, with a high rate of decrease when there was virtually no meadow left to be developed (see above). The areas of residential land and open water were relatively unchanged between 1986 and 2005 (see Table 5).

Land Use/Cover Dynamics of Honghe NNR

Table 6A shows that the area of meadow and marsh taken together was over 23,000 ha at each time, but the amounts of each varied inversely. The reason for the variation of the two land covers may be partly because of different annual hydrological conditions and partly because of their similar spectral properties. For example, flooding or drier periods when the imagery was taken may appear to increase marsh or meadow, respectively. This made it difficult to discriminate the particular change tendency of the two land cover types. However the trend appears to be for marsh loss between 2000 and 2005. The lost marshes were primarily converted into forestland and meadow.

Cultivated land increased from mid 1976 to late 2000 (from 225 ha to 891 ha), then decreased to 136 ha by 2005 (Table 6A). Measures of wetland protection taken by the Chinese government from 2002, such as the "Turning cultivated land into forestland and wetland" program, played an important role in constraining the increase of cultivated land within the Honghe NNR.

The area of forestland decreased from 1,112 ha in 1976 to 205 ha in 1986. The great decline in forestlands was due to the massive deforestation since the early 1980s and between 1976 and 1986, 923 ha of forestland changed to meadow, and 67 ha of forestlands changed to marsh. Subsequently, forestlands within the study area increased from the 205 ha in 1986 to 895 ha in 2005 (Table 6A). Field surveys of the Honghe NNR and analysis of the historical records indicated that increases were from revegetated forestland growing on formerly deforested areas, a small amount of forestland being planted on the formerly cultivated land, and forestlands being extended into former meadow or marsh land.

Land Use/Cover Dynamics of Sanjiang NNR (SNNR)

The area of marsh land decreased greatly during the first 10 years. The percentage of marsh land declined from 48% in 1976 to 19.2% in 1986 (Table 6B). Then it remained relatively steady during 1986–2000 when wetlands were protected. However, between 2000 and 2005, the percentage of marsh land decreased from 22.4% to 19.3%, and the percentage of cultivated land increased from 14.3% to 43%. Although it was difficult to distinguish meadow from marsh due to their similar spectral characteristics and different annual hydrological conditions, the two land cover types decreased significantly under heavy human influence. Cross tabulation analysis between 2000 and 2005 demonstrated that up to 80.5% of the total area of lost marsh land in the Sanjiang NNR had been replaced by cultivated land. There was practically no more meadow available to be converted to cultivation. Meadow had been reduced from 19,236 ha in 1976 to only 101 ha in 2005.

The area of forestlands in Sanjiang NNR increased from 38,142 ha in 1976 to 78,344 ha in 2000 (Table 6B), as a result of forest revegetation after massive deforestation and a sylvicultural

project initiated by the government during the period. Between 2000 and 2005 forestland was greatly reduced, decreasing from 42.3% of the total area in 2000 to 20.7% in 2005, a loss of 39,950 ha.

Landscape Pattern Change in HNNR and SNNR

Landscape indices (see Table 3) at class level and the marsh area in both NNRs between 1976 and 2005 is shown in Figure 3. The dynamics of the number of patches (NP) related to marsh area in HNNR and SNNR, respectively (Figure 3A). In both areas, the NP increased between 1976 and 1986. The NP in SNNR then declined continuously after 1986 accompanied by a decline in marsh area. In HNNR, however, the NP generally changed less than the area of marsh. Figure 3B shows the change tendency of the means of the fractal dimension index (FRAC_MN) and of the contiguity index (CONTIG_MN) of the two NNRs. In HNNR both the FRAC_MN and CONTIG_MN fluctuated very little, except for the early period between 1976 and 1986, in which CONTIG_MN declined. In contrast, in SNNR, FRAC_MN tended to increase, although it was stable between 1986 and 2000, and CONTIG_MN fluctuated at a high level, with an increase between 1986 and 2000. Figure 3C demonstrates the patch cohesion index (COHESION) and the largest patch index (LPI) of the two NNRs. The COHESION and LPI in HNNR changed irregularly from time to time without a distinct trend. In SNNR, however, these two indices decreased continuously throughout the study period. In summary, all indices in HNNR fluctuated within a small range at most time periods except from 1976–1986 when there was a massive reduction in marsh land. In SNNR, however, all indices changed linearly (either increasing or decreasing more or less continuously).

MANAGEMENT IMPLICATIONS

Our study used remote sensing and GIS to identify the ecological problems in the two national nature reserves that are under heavy human influence, and results demonstrate that Landsat classifications can produce relatively accurate landscape change maps and statistics. In addition to the generation of information tied to geographic coordinates (i.e., maps), statistics quantifying the magnitude of change and ''from-to'' information can be readily derived from the classifications (Khorram et al. 1999). These results can help us understand the characteristics of landscape change more generally in the Sanjiang Plain marsh land, also subject to under human impacts.

The Small Sanjiang Plain has undergone a very large land cover change as a result of agricultural development projects. Massive pristine marsh land has decreased considerably during the last 30 years, particularly during the first period (1976−1986) and the last period (2000−2005). The lost marsh land has been largely transformed into cultivated land. Therefore, the marsh landscape change in the study area has primarily resulted from direct human impact. Wetlands are very fragile ecosystems (Wang and He 2003) and human activities may also affect the wetland ecosystems indirectly. There might be several reasons for the rapid degradation of the HNNR marsh land: 1) the area of Honghe NNR is too small (about 24,738 ha, and is surrounded by a large area of cultivated land and hence disturbed by human activities outside the reserve; 2) the cultivated lands (mainly paddy fields) around HNNR are irrigated with pumped underground water, resulting in a lowering of groundwater level from 45.8 m to 44.1 m from 1997 to 2007; and 3) recharge of surface water from outside the NNR has been disconnected by a man-made ditch around the reserve. Alterations of hydrological conditions have led to degradation of the marsh landscape, changing plant species composition from aquatic vegetation to graminoids and shrubs. After 1980, distinct changes of the marsh landscape are not evident, or

the change is so small that it cannot be detected with Landsat imagery.

We agree with Liu (2000) that economics and policies are the major driving forces for land use/cover change. Pursuing economic profit plays a major role in transforming wetland to cultivated land, and that explains the inverse landscape dynamics between agriculture and wetland change (see Figure 2). During the late 1970s to the early 1980s, the introduction of the family contracted responsibility system with renumeration linked to output and the lower price of agricultural production materials such as fertilizer, pesticide, and seeds, both led to massive wetland reclamation for agriculture. During the 1986−2000 period, the speed of agricultural development and wetland reclamation slowed due to the higher cost of fertilizer, pesticide, and seeds and the lower crop prices. From 2000−2005, however, agricultural development and wetlands reclamation was promoted by government subsidies for agriculture. Therefore, wetland loss in the Sanjiang Plain can be primarily attributed to direct human activity, mainly agricultural development.

The Sanjiang NNR was approved in 2000 and listed as a Ramsar wetland in 2002. However, instead of reinforcing wetland protection in the NNR, wetlands reclamation was intensified, probably driven by the economic profit to be gained from reclamation for other purposes. This means that wetland management and protection actions may not completely fulfill protection objectives even within wetland nature reserves. Management must address complex direct and indirect impacts of humans on wetland ecology, and an adaptive management approach, informed by continued monitoring efforts, might best achieve long-term conservation goals. .

LITERATURE CITED

Ackleson, S. G. and V. Klemas. 1987. Remote sensing of submerged aquatic vegetation in Lower Chesapeake Bay: a comparison of Landsat MSS to TM imagery. Remote Sensing of Environment 22:235–248.

Bartlett, D. S. 1987. Remote sensing of tidal wetlands. p. 145–156. *In* V. V. Klemas, J. P. Thomas, and J. B. Zaitzeff (eds.) Remote Sensing of Estuaries, Proceedings of a Workshop, Department of Commerce, NOAA, Washington, D. C., USA.

Belluco, E., M. Camuffo, and S. Ferrari. 2006. Mapping salt-marsh vegetation by multispectral and hyperspectral remote sensing. Remote Sensing of Environment 105:54−67.

Chavez, P. S. Jr. 1988. An improved dark-object substraction technique for atmospheric scattering correction of multispectral data. Remote Sensing of Environment 24:459–479.

Chen, G. Q. and X. H. Ma. 1997. A study on the underground and its water balance change after development in the Sanjiang Plain. Scientia Geographica Sinica (supplement) 16:427–433.

Cohen, W. C. and S. N. Goward. 2004. Landsat's role in ecological applications of remote

sensing. BioScience 54:535–546.

Cui, B. S. and X. T. Liu. 1999. Ecological character changes and sustainability management of wetland in the Sanjiang Plain. Area Research and Development 18:45−48.

Dale, P. E. R., K. Hulsman, and A. L. Chandica. 1986. Classification of reflectance on colour aerial photograph and sub-tropical salt-marsh vegetation types. International Journal of Remote Sensing 7:1783−1788.

Eastwood, J. A., M. G. Yates, A. G. Thomson, and R. M. Fuller. 1997. The reliability of vegetation indices for monitoring saltmarsh vegetation cover. International Journal of Remote Sensing 18:3901−3907.

Editorial Department of Land reclamation Statistical Yearbook in Jiansanjiang. 2006. Land reclamation statistical yearbook in Jiansanjiang—2005, China Statistics Press, Beijing, China.

Ferguson, R. L., L. L. Wood, and D. B. Graham. 1993. Monitoring spatial change in seagrass habitat with aerial photography. Photogrammetric Engineering and Remote Sensing 59:1033–1038.

Gulinck, H., M. Múgica, J. V. Delucio, and J. A. Atauri. 2001. A framework for comparative landscape analysis and evaluation based on land cover data, with an application in the Madrid region (Spain). Landscape and Urban Planning 55:257–270.

Haddad, K. D. and B. A. Harris. 1985. Assessment and trends of Florida's marine fisheries habitat: an integration of aerial photography and thematic mapper imagery. p. 130–138. *In* anonymous (ed.) Machine Processing of Remotely Sensed Data with Special Emphasis on Quantifying Global Process: Models, Sensor Systems, and Analytical Methods. Laboratory for Application of Remote Sensing, Purdue University, West Lafayette, IN, USA.

Jiang, M. K., Z. Wang, and W. H. Qin. 2006. Effectiveness of national priority wildlife protection in Nature Reserves. Journal of Ecology and Rural Environment 22:35−38.

Johnston, R. M. and M. M. Barson. 1993. Remote-sensing of Australian wetlands- an evaluation of Landsat TM data for inventory and classification. Australian Journal of Marine and Freshwater Research 44:235−252.

Khorram, S., G. S. Biging, N. R. Chrisman, D. R. Colby, R. G. Congalton, J. E. Dobson, R. L. Ferguson, M. F. Goodchild, J. R. Jensen, and T. R. Mace. 1999. Accuracy Assessment of Remote Sensing-derived Change Detection. American Society for Photogrammetry and Remote Sensing (ASPRS), Monograph, Bethesda, MD, USA.

Klemas, V. and M. A. Hardisky. 1987. Remote sensing of estuaries: an overview. p. 91–120. *In* V. Klemas, J. P. Thomas, and J. B. Zaitzeff (eds.) Remote Sensing of Estuaries: Proceedings of a Workshop. Washington, DC, USA.

Li, W. H., Q. W. Min, and Y. H. Sun. 2006. Discussion on the scientific research of natural and cultural heritage. Geographical Research 25:561–569.

Lillesand, T. M. and R. W. Kiefer. 1994. Remote Sensing and Photo Interpretation, third edition. John Wiley and Sons, Inc., New York, NY, USA.

Liu, X. T. 1995. Wetland and its rational utilization and conservation in the Sanjiang Plain. p. 108–117. *In* Y. Y. Chen (ed.) Study of Wetlands in China., Science Press, Beijing, China.

Liu, X. T. 1997. Marsh resource and its sustainable utility in the Songnen-Sanjiang Plain. Scientia Geographica Sinica (supplement) 16:451–460.

Liu, X. T. 2000. Influence of large-scale reclamation on natural environment and regional environmental protection in the Sanjiang Plain. Scientia Geographica Sinica 20:14–19.

Liu, X. T. and X. H. Ma. (ed.). 2002. Natural Environmental Changes and Ecological Protection in the Sanjiang Plain. Science Press, Beijing, China.

Liu, H. Y., S. K. Zhang, and X. G. Lu. 2004. Wetland landscape structure and the spatial-temporal changes in 50 years in the Sanjiang Plain. Acta Geographica Sinica 59:391−400.

McGarigal, K., S. A. Cushman, M. C. Neel, and E. Ene. 2002. FRAGSTATS: Spatial Pattern Analysis Programme for Categorical Maps. Computer software programme produced by the authors at the University of Massachusetts, Amherst. Available online at: http://www.umass.edu/landeco/research/fragstats/fragstats. html (accessed August 28 2008).

May, A. M. B., J. E. Pinder III, and G. C. Kroh. 1997. A comparison of Landsat Thematic Mapper and SPOT multi-spectral imagery for the classification of shrub and meadow vegetation in northern California, U.S.A. International Journal of Remote Sensing 18:3719–3728.

Mas, J. F. 1999. Monitoring land-cover changes: a comparison of change detection techniques. International Journal of Remote Sensing 20:139–152.

Mitsch, W. J. and J. G. Gosselink. 1993. Wetlands, 2nd edition. Van Nostrand Reinhold, New York, NY, USA.

Munyati, C. 2000. Wetland change detection on the Kafue Flats, Zambia, by classification of a multitemporal remote sensing image dataset. International Journal of Remote Sensing 21:1787−1806.

Pietroniro, A., T. Prowse, L. Hamlin, N. Kouwen, and R. Soulis. 1996. Application of a grouped response unit hydrological model to a northern wetland region. Hydrological Processes 10:1245–1261.

Ramsey, E. W., D. K. Chappell, and D. G. Baldwin. 1997. AVHRR imagery used to identify hurricane damage in a forested wetland of Louisiana. Photogrammetric Engineering and Remote Sensing 63:293–297.

Richards, J. A. and X. P. Jia. 1993. Remote Sensing Digital Image Analysis: An Introduction, first edition, Berlin: Springer-Verlag, Berlin, Germany.

Shalaby, A. and R. Tateishi. 2007. Remote sensing and GIS for mapping and monitoring land cover and land-use changes in the Northwestern coastal zone of Egypt. Applied Geography 27:28–41.

Shao, G. F. and J. G. Wu. 2008. On the accuracy of landscape pattern analysis using remote sensing data. Landscape Ecology 23:505−511.

Shuman, C. S. and R. F. Ambrose. 2003. A comparison of remote sensing and ground-based methods for monitoring wetland restoration success. Restoration Ecology 11:325−333.

Tang, J. M., L. Wang, and S. W. Zhang. 2005. Investigating landscape pattern and its dynamics in 1990-2000 of Daqing, China using remote sensing and GIS. International Journal of Remote Sensing 26:2259−2280.

Terrain Resources Ltd. 1995. Digital vegetation map of the Peace Athabasca Delta. Wood Buffalo National Park. Fort Smith, NT, Canada.

Töyrä, J. and A. Pietroniro. 2005. Towards operational monitoring of a northern wetland using geomatics- based techniques. Remote Sensing of Environment 97:174–191.

Wang, B. Z. and P. He. 2003. Landscape ecological assessment and eco-tourism development in the South Dongting Lake Wetland, China. Journal of Environmental Sciences 15:271–278.

Wang, L., W. P. Sousa, P. Gong, and G. S. Biging. 2004. Comparison of IKONOS and QuickBird images for mapping mangrove species on the Caribbean coast of Panama. Remote Sensing of Environment 91:432–440.

Wang, Y. Y. 2001. The basic scientific problem of wetland agriculture in the Sanjiang Plain. Chinese Journal of Eco-Agriculture 9:58−60.

Woodcock, C. E., S. A. Macomber, M. Pax-Lenney, and W. B. Cohen. 2001. Monitoring large

areas for forest change using Landsat: generalization across space, time and Landsat Sensors, Remote Sensing of Environment 78:194–203.

Wulder, M. A., C. R. Butson, and J. C. White. 2008. Cross-sensor change detection over a forested landscape: options to enable continuity of medium spatial resolution measures. Remote Sensing of Environment 112:796–809.

Yang, X. and C. P. Lo. 2002. Using a time series of satellite imagery to detect land use and land cover changes in the Atlanta, Georgia metropolitan area. International Journal of Remote Sensing 23:1775–1798.

Zhao, K. Y. (ed.). 1999. Chinese Mire Records. Science Press, Beijing, China

Table 1. Characteristics of Landsat imagery for the study area.

Sensor	Date	Band No.	Resolution(m)	Orbit
Landsat MSS	30/06/1976	1, 2, 3, 4	79	113/27
Landsat MSS	23/06/1976	1, 2, 3, 4	79	114/27
Landsat-5 TM	07/07/1986	1, 2, 3, 4, 5, 7	30	113/27
Landsat-5 TM	12/06/1986	1, 2, 3, 4, 5, 7	30	114/27
Landsat-5 TM	06/06/1995	1, 2, 3, 4, 5, 7	30	113/27
Landsat-5 TM	13/06/1995	1, 2, 3, 4, 5, 7	30	114/27
Landsat-5 TM	10/09/2000	1, 2, 3, 4, 5, 7	30	113/27
Landsat-5 TM	17/09/2000	1, 2, 3, 4, 5, 7	30	114/27
Landsat-5 TM	01/08/2005	1, 2, 3, 4, 5, 7	30	113/27
Landsat-5 TM	24/08/2005	1, 2, 3, 4, 5, 7	30	114/27

Table 2. The land cover classification scheme.

Class name	Description
Cultivated land	Dryland and paddy
Forestland	Broad leaf trees (*Populus davidiana*, *Betula platyphylla*, and *Quercus mongolica*) and shrubs (*Salix rosmarinifolia* var. *brachypoda*, *Salix myrtilloides, Alnus sibirica, Betula fruticosa*, and *Spiraea salicifolia*)
Meadow	*Deyeuxia angustifolia*, *Salix brachypoda*, and *Polygonum orientale* etc. (may contain scattered low shrubs)
Marsh	Wet sedges (*Carex lasiocarpa*, *C. schmidtii*, *C. meyeriana*, and *C. pseudo-curaica*); aquatic macrophytes (*Glyceria spiculosa*, *Phragmites communis*, and *Typha angustifolia*)
Residential area	Urban and rural residential area
Open water	Rivers, lakes, and alluvial land (land along a lake or river subject to flooding)

Table 3. Landscape metrics selected for use in this study.

Acronym	Name	Algorithm	Parameter Description	Value Range	Range
NP	Number of Patches	$NP = N_i$	N_i: total number of patches in the landscape.	$NP \geqslant 1$, without limit	NP = only 1 patch consis
FRAC_ MN	Mean of Fractal Dimension Index	$FRAC = \dfrac{2\ln(0.25 P_{ij})}{\ln a_{ij}}$	P_{ij}: perimeter (m) of patch ij. a_{ij}: area (m^2) of patch ij.	$2 \geqslant FRAC \geqslant 1$	A frac for a 2 depar FRAC very s square with h

CONTIG_MN	Mean of Contiguity Index	$$CONTIG = \frac{\left[\sum_{r=1}^{z} c_{ijr} \Big/ a_{ij}\right] - 1}{v - 1}$$	C_{ijr} : contiguity value for pixel r in patch ij. v : sum of the values in a 3-by-3 cell template (13 in this case). a_{ij} : area of patch ij	$1 \geqslant CONTIG \geqslant 0$	CONT... patch... patch... increa...
COHESION	Patch Cohesion Index	$$COHESION = \left[1 - \frac{\sum_{j=1}^{m} p_{ij}}{\sum_{j=1}^{m} p_{ij}\sqrt{a_{ij}}}\right]\left[1 - \frac{1}{\sqrt{A}}\right]^{-1}\cdot(100)$$	P_{ij} : perimeter of patch ij in terms of number of cell surfaces. a_{ij} : area of patch ij A: total number of cells in the landscape.	$100 > COHE SION \geqslant 0$	COHE... propor... compri... and is... increas... propor... compri... increas...
LPI	Largest Patch Index	$$LPI = \frac{\max(a_{ij})}{A}\cdot(100)$$	a_{ij} : area of patch ij A: total landscape area	$100 \geqslant LPI > 0$	LPI ap... patch ... is incre... the ent... single ... patch t...

Table 4. The accuracy assessment of the maximum likelihood classification of the 1976, 1986, 1995, 2000, and 2005 Landsat images of the Small Sanjiang Plain. Mar = Marsh, Mea = Meadow, Cul = Cultivated land, For = Forestland, Ope = Open Water, Res = Residential Area.

	User's accuracy (%)						Producer's accuracy (%)						
Year	Mar	Mea	Cul	For	Ope	Res	Mar	Mea	Cul	For	Ope	Res	a
1976	78.2	71.7	63.2	81.6	74.7	81.3	67.5	81.4	80.6	91.2	80.1	69.1	
1986	81.7	73.2	66.8	83.2	77.7	79.7	92.1	71.1	64.2	90.1	75.3	71.5	
1995	77.8	70.4	70.1	80.1	76.5	70.2	66.2	74.2	94.2	96.3	68.6	83.7	
2000	76.4	77.7	67.5	79.7	73.6	72.8	84.1	76.5	75.6	91.2	81.2	82.1	
2005	70.1	76.4	68.8	84.1	71.3	83.2	70.1	80.2	71.4	94.2	74.6	79.2	

Table 5. Area and percentage of different land cover classes of classified images between 1976 and 2005 in Small Sanjiang Plain (area in ha).

Class name	1976		1986		1995		2000		2005	
	Area	%	Area	%	Area	%	Area	%	Area	%
Marsh	658,366	41.0	362,099	22.5	323,887	20.2	305,457	19.0	201,291	12.5
Meadow	331,374	20.6	127,892	8.0	12,782	0.8	17,392	1.1	4,863	0.3
Cultivated land	459,300	28.6	607,960	37.9	696,111	43.3	749,071	46.6	1,068,370	66.5
Forestland	106,947	6.7	356,207	22.2	427,398	26.6	386,748	24.1	193,030	12.0
Open water	43,035	2.7	143,674	8.9	137,588	8.6	139,094	8.7	127,649	8.0
Residential area	6,986	0.4	8,176	0.5	8,242	0.5	8,246	0.5	10,805	0.7

Table 6. Area and percentage of change of different land cover classes of classified images between 1976 and 2005 in A) HNNR and B) SNNR (area in ha).

Class name	1976		1986		1995		2000		2005	
	Area	%	Area	%	Area	%	Area	%	Area	%
A) HNNR										
Marsh	13,105	53.0	10,201	41.3	9,397	38.0	13,931	56.3	12,066	48.8
Meadow	10,296	41.6	13,734	55.5	13,837	55.9	9,151	37.0	11,641	47.0
Cultivated land	225	0.9	598	2.4	874	3.5	891	3.6	136	0.6
Forestland	1,112	4.5	205	0.8	630	2.6	765	3.1	895	3.6
B) SNNR										
Marsh	88,895	48.0	35,504	19.2	36,997	19.9	41,503	22.4	35,852	19.3
Meadow	19,236	10.4	21,913	11.8	5,127	2.8	880	0.5	101	0.1
Cultivated land	14,727	7.9	7,150	3.9	22,839	12.3	26,484	14.3	79,652	43.0
Forestland	38,142	20.6	72,670	39.2	75,918	41.0	78,344	42.3	38,394	20.7
Open water	24,117	13.0	47,834	25.8	44,229	23.9	37,859	20.4	30,854	16.7
Residential land	114	0.1	160	0.1	121	0.1	161	0.1	378	0.2