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ORIGINAL ARTICLE

Quantitative analysis of the driving forces causing declines in marsh wetland landscapes in the Honghe region, northeast China, from 1975 to 2006

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Abstract The Sanjiang Plain has the most representative and largest concentration of inland freshwater wetlands in China, most of which have been degraded or have disappeared as a result of agricultural development and climatic change since the 1950s. To better understand the spatial and temporal variation and driving forces of marsh reduction, this study investigated variations of marsh reduction in the Honghe region of the Sanjiang Plain, Northeast China over a 30-year period, and analyzed the role of the different driving forces separately and their combined effect on marsh reduction and identified what driving forces have played key roles on the reduction in different periods. Nine natural and anthropogenic variables from remote sensing, GIS data and field surveys, such as precipitation, temperature, precipitation anomaly, population density, agricultural population density, per capita GDP, distance to road, distance to canal and distance to settlement, were evaluated on their impact on observed variations of marsh reduction between 1975 and 2006. The results show that all of these driving forces have significant influences on the decline of the marsh area, and the combination of driving forces that has crucial impacts on marsh reduction varied largely from 1975 to 2006. During 1975–1989, it was the construction of canal and road networks in farms and changes in average annual precipitation that led to marsh reduction. After 1989, the reduction was mainly related to increases in agricultural population, per capita GDP and settlements. These findings may help understand the declines or degradation of marsh areas and provide an empirical and theoretical base for managers, who design and implement wetland management and planning.

Keywords Driving forces · Marsh wetland · Multivariate logistic regression · Sanjiang Plain

Introduction

Wetlands cover less than 6 % of the global land area, but they provide many important ecosystem functions and services (Acreman et al. 2007; Costanza et al. 1997), including climate mediation (Michener et al. 1997), flood mitigation (Bullock and Acreman 2003), water supplies (Jeng and Hong 2005), carbon storage (Mitra et al. 2005), nutrient cycling (Bunn et al. 1999), provision of habitats for wildlife (Tiner 2005), etc. Unfortunately, throughout the world, wetlands are one of the most threatened natural ecosystems; and they are decreasing and degrading because of many driving forces, which have led to the ongoing reduction in wetland ecological functions and services (An et al. 2007; Mitsch and Gosselink 2000). The detection and analysis of changes in wetland patterns and their driving forces have been studied extensively in many countries, such as Canada (Seilheimer et al. 2009), the United States (Brazner et al. 2007; Nielsen et al. 2008), Sri Lanka (Rebelo et al. 2009), China (Liu et al. 2004; Wang et al. 2011), Greece (Dimitrious and Zacharias 2010), and South Africa (Tooth et al. 2009). Most of the

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previous studies focused mainly on analyzing seasonal or interannual variations of wetland landscape patterns and dynamics of kinds of the natural and anthropogenic factors related to wetland change via a review of historical literature (Liu et al. 2006; McHugh et al. 2007; Turner 1990; Xie et al. 2010), while researches on quantitative identification of the combined effect and the relative importance of kinds of driving forces to wetland change in typical regions with wetlands were relatively few.

The Sanjiang Plain in northeast China has the most representative and largest concentration of inland freshwater wetland in China. Wetlands in the Sanjiang Plain are also recognized as having "international importance" in the Directory of Asian Wetlands and Ramsar List (Zhou and Liu 2005). Since the 1950s, more than 100 state-owned farms have been established in the Sanjiang Plain. These state farms have converted Sanjiang Plain into one of the eight national bases for grain production in China, and over 73 % of wetland in this area was lost because of large-scale reclamation (Liu and Ma 2002). Since the 1980s, some wetland protection projects have been implemented to protect the remaining wetland ecosystem, such as the Honghe National Natural Reserve (HNNR) and the Sanjiang National Natural Reserve (Liu and Ma 2002). However, the remaining wetland ecosystem not only in farms, but also in the Natural Reserves is gradually decreasing in size and degenerating in quality under the combined impacts of climate change and agricultural activities. There are several distinctly types of wetlands (e.g., marshes, lakes, rivers and paddy fields) in the Sanjiang Plain. Previously, most studies relating to this region mainly focused on spatiotemporal patterns of all kinds of wetland types and the causes of that change based on the historical literature (Liu et al. 2004; Yan et al. 2002; Zhang et al. 2003; Zhang et al. 2010). This study focuses only on marshes because it is one of the important wetland types in the Sanjiang Plain and limited attention has been paid to it (Zhou et al. 2009). To better understanding of the mechanisms or driving forces that degrade the marsh, it was imperative to quantitatively analyze the role of the different driving forces separately and their combined effect, and identify the relative contribution of driving forces to the reduction of marsh area in the Sanjiang Plain in different historical periods.

Multivariate logistic regression (MLOR) has been proven to be efficient in analyzing the combined effect and identifying the predominant driving forces for land cover/land use changes (Serra et al. 2008), and it has recently been applied to wetland studies. For example, MLOR has been used in the simulation and prediction of the spatial distribution of red-crown cranes (*Grus japonensis*) in wetland ecosystems (Li et al. 1997), prediction of the spatial distribution probability of various wetland types (Koneff and Royle 2004; Van Horssen et al. 2002), analysis of the relationship between the spatial distribution of wetland plants and environmental factors (Peters et al. 2008), and identification of the impact of human accessibility to wetland vegetation reduction at multiple scales (Sheng et al. 2012). In this article, MLOR, incorporating spatial analysis of marsh in a 30-year period (1975–2006) from Remote Sensing and GIS data, was applied to quantitatively explore the time-specific combination effect of driving forces influencing the decrease in the extent of marshland in the Honghe region of Sanjiang Plain, northeast China in different time periods, and to reveal to what degree each driving force can explain this decline.

Materials and methods

Description of the study area

The area selected for this study is the Honghe region (133°18′–134°5′E and 47°25′–48°1′N), which is located in northeast Sanjiang Plain in Heilongjiang Province, and includes four portions: the Honghe National Nature Reserve (HNNR) and three farms, the Honghe, Qianfeng and Yalvhe farms (Fig. 1). The area covers 2,491.4 km^2 and is a typical alluvial floodplain between three rivers: the Hong, Xi and Bielahong rivers. This area is an example of a temperate humid continental monsoon climate, with an annual average temperature of 1.78 °C, total evaporation of about 1,300 mm, and average annual precipitation of about 585 mm, most of which falls between June and September. This area has a low population density, with an average of 29 people per km^2 in 2006 (http://www.hljnktj.com/index.aspx) as compared with 110 per km^2 in the province and 177 per km^2 nationwide (National Bureau of Statistics of China 2006); this region is composed mainly by state-owned farms and its main industry is agriculture. In the Honghe region, the HNNR was established to protect the marsh ecosystem and its biodiversity in 1984 and it gained international recognition under the Ramsar Convention in 2002 (http://www.ramsar.org/pdf/sitelist.pdf). However, the remaining marsh ecosystem in the HNNR is gradually degrading in quality and decreasing in size and the remaining marshes are becoming vulnerable to impact from agricultural activities on farms and climate change. Thus, quantitative analysis related to the driving forces to the marsh wetland landscape in the Honghe region may provide a scientific basis for managers to design wetland protection laws, rules or guidelines for management of this fragile and valuable wetland ecosystem.

Wetland classification and mapping

Three remote sensing images were used to examine wetland landscape change. A full scene Landsat TM recorded

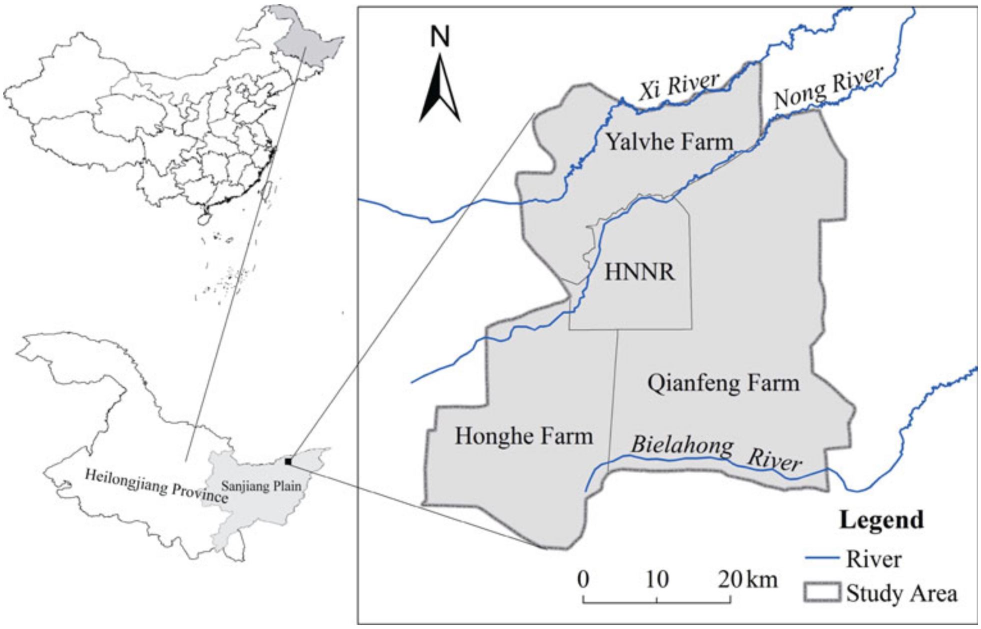

Fig. 1 Location map of study area

on August 3, 2006, was purchased from the China Remote Sensing Satellite Ground Station (http://www.rsgs.ac.cn). A Landsat TM image of June 6, 1989 and a Landsat MSS image of July 25, 1975 were obtained from the University of Maryland (http://www.glcf.umiacs.umd.edu). Landsat TM images have six bands and 30 m spatial resolution and the Landsat MSS image has four bands with a resolution of 80 m; these images were predominantly cloud free. Auxiliary data included 1:100,000 scale topographic maps.

Images were rectified and registered based on 1:100,000 scale topographic maps with RMS of less than 0.5 pixels. They were then transformed into an Albers Equal Area Conic projection. Three bands of the images (bands 4, 3, and 2 for Landsat MSS and bands 7, 4, and 3 for Landsat TM) were combined as the optimal setting for wetland mapping. Other bands were used for references. Spectral signatures for different landscape types were then established in ArcGIS 9.2 software, based on their hues and textures on Landsat images, followed by manual interpretation. Finally, the classes in each image were grouped into six landscape types: marsh, river, forest, meadow, dry lands and paddy fields (Fig. 2). The total accuracy of the landscape classification for 1975, 1989 and 2006 were 92.33, 92.60 and 90.14 %, respectively. Additional details of data processing and accuracy assessment can be found in Zhang et al. (2009). In this research, we only analyzed the driving forces impacting marshes. Thus, marshes were extracted from the vector data of landscape classification from 1975, 1989 and 2006 data.

The mechanism of MLOR

Multivariate logistic regression is a statistical approach used to describe and model the relationship of several independent variables with a dichotomous dependent variable (Kleinbaum 1994). MLOR presents certain significant differences when compared with multivariate linear regression (MLIR) used in analysis of wetland changes and their driving forces: dependent variables can be dichotomous (presence or absence of a specific phenomenon). For example, wetland presence versus absence and wetland increase versus decrease, independent variables can be continuous or categorical and the linearity of relationships between independent variables and the dependent variable is not assumed. In this article, MLOR was applied to identify the time-specific combination effect of driving forces and the key driving forces behind the decline of marsh area. The formula of MLOR is presented as Eqs. (1) and (2):

$$\log\mathrm{it}(p) = ln\left(\frac{P}{1-P}\right) = \alpha + \sum_{i=1}^{n} \beta_i \chi_i \tag{1}$$

$$P = \frac{1}{1 + e^{-(\alpha + \beta_1 \chi_1 + \beta_2 \chi_2 + \cdots + \beta_i \chi_i)}} \tag{2}$$

where P is the present probability of marsh which range from 0 to 1, with 0 indicating no or minimal probability of presence and 1 maximum probability of presence. α is the constant. χ_i is the original values of independent variables. In this article P indicates driving forces of marsh decrease. β_i is the partial regression coefficient indicating the contribution of driving force χ_i to P.

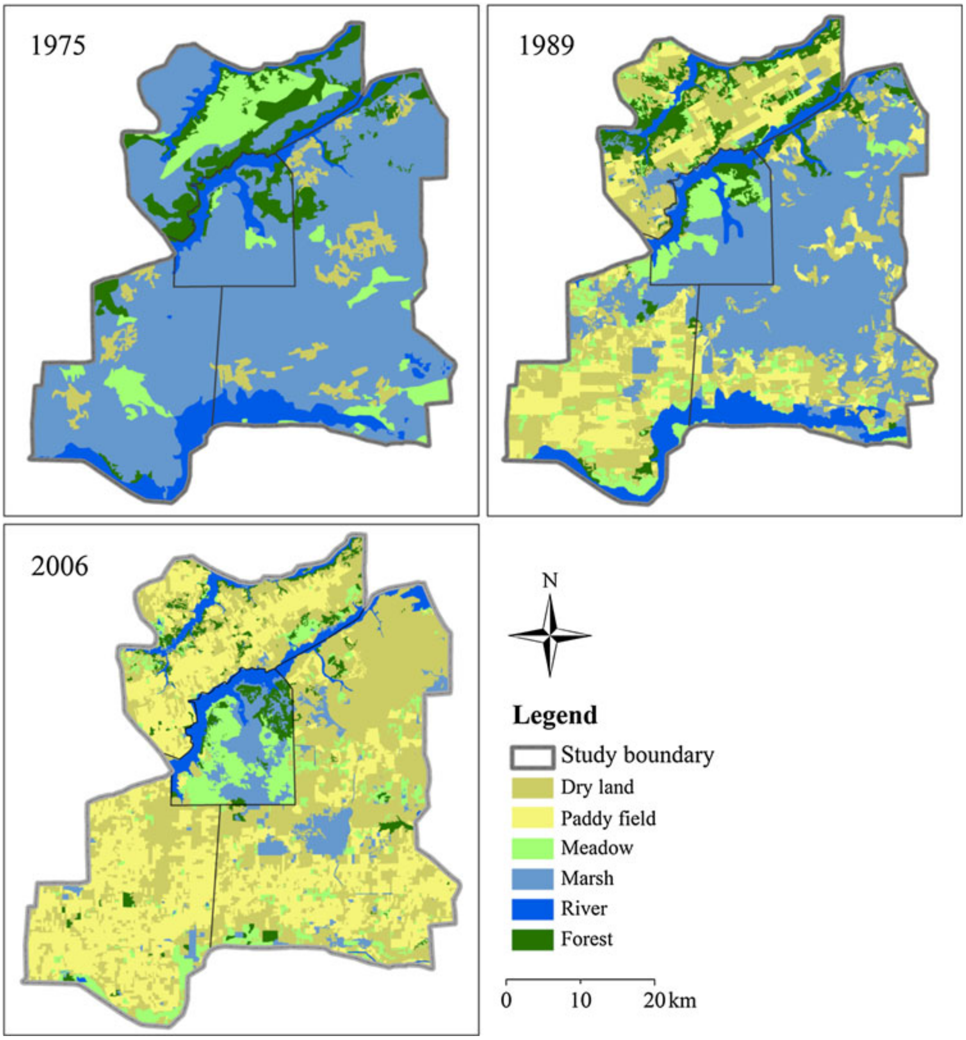

Fig. 2 Classification maps of landscape types in the study area in 1975, 1989 and 2006

Selections of variables for MLOR

In general, marsh change was closely related to certain natural factors (e.g., geology, geomorphology, climate, hydrology and soil). In this paper, geology, geomorphology and soil remained relatively stable compared with climate and hydrology because of the short study period, 1975–2006. Climate and hydrology experienced large changes and had a large influence on marsh change. Therefore, precipitation, temperature and precipitation anomaly were selected as variables for MLOR in two time periods 1975–1989 and 1989–2006 (see Table 1).

Aside from natural factors, human activities have also affected marsh greatly (de Jong and de Jong 2002; Zhou et al. 2009). Thus, population density, agricultural population density and per capita GDP were used to analyze the influence of population mobility and social-economic growth on marsh change (see Table 1). In addition, the proximity to roads, canals and settlements were three factors that help to determine the impact of human accessibility on marsh change. Hence, three variables (e.g., distance to roads, distance to canals and distance to settlements) were also selected to analyze their impact on marsh change (see Table 1).

Acquisitions of variables for MLOR

As noted above, in this case, the independent variables, temperature, precipitation and precipitation anomaly, are natural driving forces influencing marshes. The detailed extraction process of natural driving forces is shown as follows. The annual temperature, precipitation and precipitation anomaly for 1975–2006 at the HNNR and the Honghe, Qianfeng and Yalvhe farms were obtained from the climate station supported by the Field Station of Wetland Ecology of the Chinese Academy of Sciences and the statistical yearbooks of the three farms, respectively. The mean temperature, precipitation and precipitation anomaly at the four areas (HNNR and Honghe, Qianfeng and Yalvhe farms) in the two periods (1975–1989, 1989–2006)

Table 1 Evaluation on the driving forces of the wetland landscape changes in Honghe region

Variable	Definition and ecological meaning
Precipitation	Average annual precipitation; it is one of the important water supplies for wetland ecosystem in Honghe region; plenty of water is an important index that can keep wetland habitat healthy
Temperature	Average annual temperature; it can affect evapotranspiration which have an influences on the spatial distribution of wetland vegetation. A local warming temperature speeds up the evaporation process, which shrinks wetland area by reducing its water capacity
Precipitation anomaly	The deviation of precipitation over a period in a given region. It shows the interannual variation of precipitation in Honghe region over 30 years
Population density	The number of people living within a specified area (person/km^2). The greater the population density, the greater the pressure of local people on demand of wetland reclamation
Agricultural population density	The number of agricultural population living within a specified area (person/km^2). The greater the agricultural population, the larger the ability of local people on wetland reclamation
Per capita GDP	The gross domestic product of a country/region divided by the number of people living there (RMB/person). It indicates the benefits of local people from the crop production which has direct influences on crop plantation area. Thus, the more the Per capita GDP, the greater the effects of human activities on wetland reclamation
Distance to settlement	The Euclidean distance from each cell to the nearest settlement (km) within the study region. It shows the proximity of residential area. The larger the area and number of settlements, the easier accessibility for people to wetland. The less distance to settlements, the greater effects of human activities on wetland ecosystem
Distance to road	The Euclidean distance from each cell to the nearest road (km) within the study region. It can help to determine the population mobility that is associated with accessibility to wetland. The larger road density can cause the easier accessibility for people to wetland. The less the distance to road network, the greater effects of human activities on wetland ecosystem
Distance to canal	The Euclidean distance from each cell to the nearest canal (km) within the study region. It can help to determine the drainage ability of canal network. With the development of canal network, the surface water in wetland habitat can be drained off easily. The less the distance from wetland distribution region to nearest canal, the greater effects of canal system on wetland habitat

were first calculated, and then all of these were correspondingly related to vector maps of the four partitions as attribute data in ArcGIS 9.2.

Statistical data for the total population, the agricultural population and per capita GDP, at the local farm scale from 1975–2006, came from the statistical yearbooks of the three farms surrounding the HNNR. First, the growth rates of the three human variables mentioned above in the two periods were obtained. Second, all of the three variables were correspondingly attached to map data of the three farms using the ArcGIS 9.2. There were no permanently residences and agricultural activity in the HNNR. Therefore, the value of the three variables in the HNNR was zero.

The vector information of the settlements in 1989 and 2006 was obtained from Landsat images. The vector information of roads in 1989 and 2006 was obtained from the local farms road maps with the scale of 1:250,000. Maps of local canal networks in the three farms surrounding HNNR in the 2 years, 1989 and 2006, were provided by the local farm administration. All these vector data related to settlements, roads and canals in 1989 and 2006 were first converted into grid data with a resolution of 30 m × 30 m, and then the three variables (distance to settlements, distance to roads and distance to canals) were calculated by a GIS spatial analysis method.

The MLOR model establishment

In this case, MLOR was used as an explanatory model to quantitatively analyze the relationship of the decline in marshes and natural and human driving forces in each of the grid cells, using climate, population, GDP and distances to roads, canals and settlements as explanatory variables. The dichotomous dependent variable was the marsh change as a result of map overlays in the two periods (1975–1989, 1989–2006). The maps of marsh change in two periods were transformed into grid data with a pixel size of 30 × 30 m. Then, the dichotomous layers of marsh change in the Honghe region were produced in ArcGIS 9.2 software package (1 corresponds to presence of marsh spatial decrease and 0 equals to absence of marsh spatial decrease). MLOR modeling procedure was performed as follows.

To apply MLOR, nine variables in each studied period (1975–1989, 1989–2006) were converted into raster data with a resolution of 30 × 30 m. To reduce the possible effects of spatial auto-correlation, thousands of grids of the binary marsh change maps and the score maps of the nine variables were randomly sampled for estimating the coefficients. All of the independent variables were normalized to identify the relative contribution of the driving forces to the decrease of marsh area.

The best logistic regression model was obtained from the stepwise backward selection algorithm, reducing the number of independent variables to the most explanatory. To assess the fit of the obtained models, we used the area under the relative operating characteristic (ROC) curve. This curve plots the probability of detecting sensitivity, which measures the proportion of correct positives, and specificity, which measures the proportion of negatives correctly identified. Values of ROC near 0.5 indicate a random model, whereas a value of 1 is equivalent to a perfectly fitted model (Swets 1998). This method has been used successfully to evaluate how well a model was calibrated in some studies (Badia et al. 2011; Serra et al. 2008).

Results

Marsh dynamics in 1975–2006

The spatial change in marsh in the study area is presented in Fig. 2. Marsh in the study area suffered large losses during the overall time period 1975–2006. Marsh dominated the study area, covering 1,811.67 km^2 (approximately 72.72 % of the region) in 1975. It was reduced to 759.87 km^2 (30.50 % of the region) in 1989 and 292.73 km^2 (11.75 % of the region) in 2006; 1,518.94 km^2 or 83.84 % of its initial extent was replaced by other land covers/uses (e.g., dry lands and paddy fields).

The general trends of the marsh landscape change in four partitions of the study area in 1975–2006 showed an obvious decline. Especially since 1989, the downward trends have accelerated (Fig. 3). The largest reduction and loss rate of marsh area occurred in the Qianfeng Farm during the entire time period of 1975–2006. During the period 1975–1989, the largest reduction in marsh area appeared in the Honghe Farm and the largest loss rate of marsh area occurred in the Yalvhe Farm. During the period 1989–2006, the loss rate of marsh in the three farms (Honghe, Qianfeng, and Yalvhe) was >80 %, and the loss rates of marsh in the three farms were 80.58, 85.68 and 84.61 %, respectively. The reduction of marsh area in the HNNR was smaller as compared with that in the three farms. Nonetheless, there was still a decreasing trend in marsh area in the HNNR in 1975–2006, though the HNNR was established to protect the marsh ecosystem in 1984.

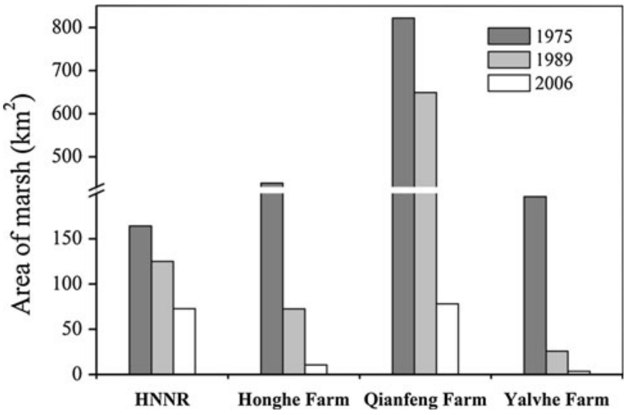

Fig. 3 Changes of marsh area in four sections of the study area in 1975, 1989 and 2006

Analysis of individual driving forces to the loss of marsh

Climate change

Figure 4 indicates the annual precipitation has generally decreased at a rate of 4.22 mm per year in the Honghe region from 1975 to 2006. At the same time, the annual temperature has gradually increased with a rate of 0.02 °C per year. The climatic trend in the Honghe region during the past 31 years was therefore clearly toward a warmer and drier climate. Precipitation was one of the main sources of water to the marsh ecosystem and the decrease of precipitation in this area led directly to water shortages for marsh. Temperature can affect evaporation on the water surface by which the water storage capacity of wetland ecosystem was altered. Thus, warming temperature also led to reduction in the marsh area.

Population and GDP

Since 1975, the total population, the agricultural population and per capita GDP in the three state-owned farms around the HNNR has shown a general increasing trend, and after 1990 they all experienced accelerated growth (Fig. 5). With the rapid increase of population in the Honghe region, the demand for food, housing and other infrastructure has increased significantly, which has forced local people to

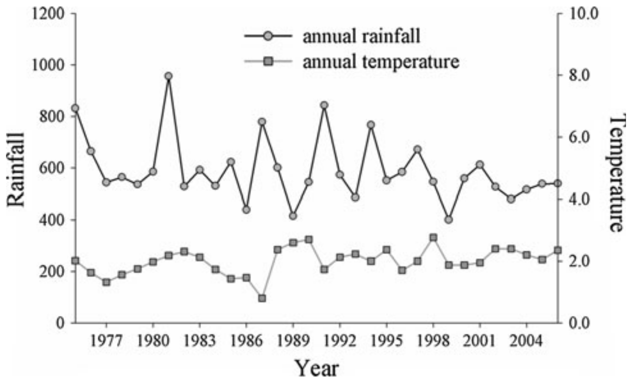

Fig. 4 Changes of precipitation and temperature in the Honghe region 1975–2006

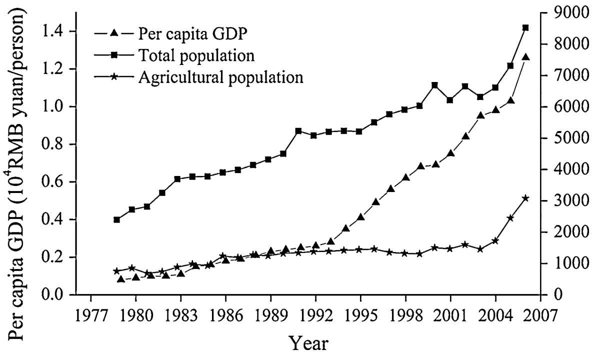

Fig. 5 Changes of some socioeconomic indicators in the Honghe region 1975–2006

reclaim marshland to meet these demands. Also, the growth rate of per capita GDP in the Honghe region was 3.9×10^3 RMB yuan/year after 1990. The enormous benefits from agriculture also motivated the local people reclaim marsh to expand the area under cultivation.

Distance to canals

Pixels of marsh decrease were significantly correlated with distance to canals in the two periods of 1975–1989 and 1989–2006 (Fig. 6). For areas within 4 km of canals, the level of reduction in the marsh area decreased sharply with distance to canals. At distance >6 km, the reduction rate of the marsh area was stable with increasing distance. When the two periods were compared, the distance from pixels of the center of the marsh to the nearest canal has shortened largely. This means the development of irrigation and drainage systems in the Honghe region and marsh suffered greater anthropogenic pressure in 1989–2006 as compared to that in 1975–1989.

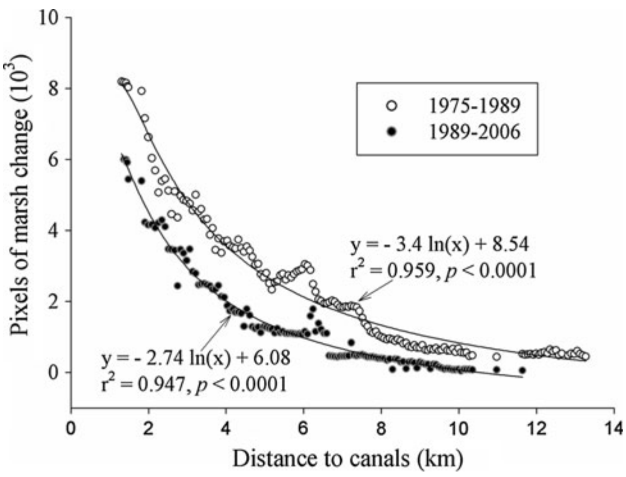

Fig. 6 Relationship between the loss of marsh and the distance to canals in 1975–1989 and 1989–2006

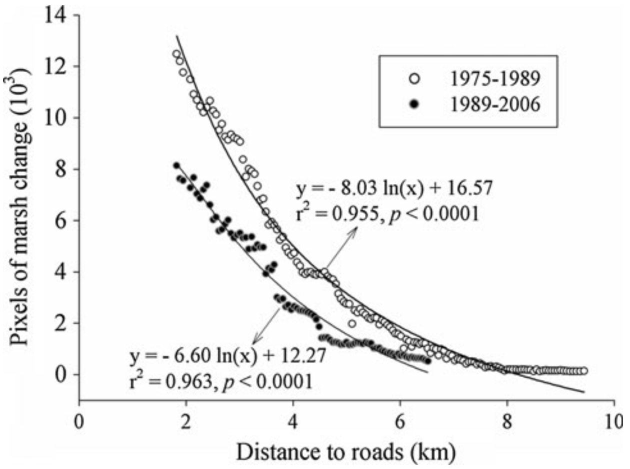

Fig. 7 Relationship between the loss of marsh and the distance to roads in 1975–1989 and 1989–2006

Distance to roads

The relation between pixels of marsh decrease and distance to roads can also be seen in Fig. 7. For marshland in the Honghe region, the level of reduction in the marsh area decreased sharply with distance to roads. This means that marshland reduction near roads was more serious than that further from roads. Figure 7 also showed that the reduction rate of the marsh area gradually decreased with increasing distance and the reduction rate rapidly decreased at distances larger than 4 km from roads. Similar to distance to canals, the distance from pixels of the center of the marsh to the nearest road has also shortened largely from 1975 to 2006 because of the rapid development of the road traffic system in the Honghe region.

Distance to settlements

From the correlation analysis between pixels of marsh reduction and distance to settlements, it can be seen that distance to settlements has a significant and negative relation with pixels of marsh decrease (Fig. 8). Between 2 and 8 km, the level of reduction in marsh area was stable. The reduction rate of the marsh area rapidly increased at distances larger than 8 km from settlements. When comparing the two time periods of 1975–1989 to 1989–2006, the distance between pixels of marsh change and the nearest settlement has shortened (Fig. 8) because of the increase in area and number of the settlements in the three farms around the HNNR.

Multivariate analysis of driving forces to the loss of marsh

The ROC curves of MLOR in the Honghe region in the period 1975–1989 and 1989–2006 were 0.71 and 0.75,

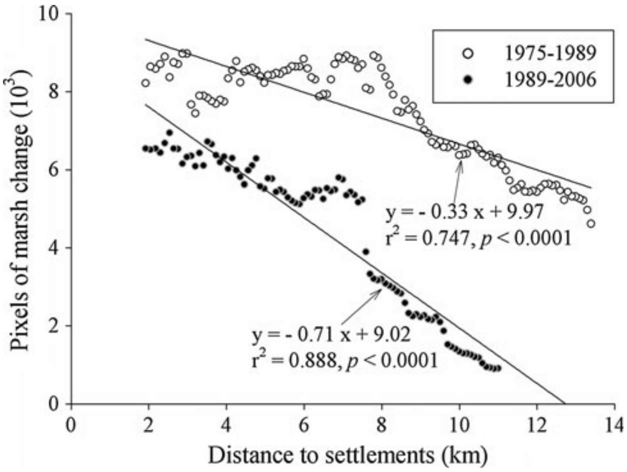

Fig. 8 Relationship between the loss of marsh and the distance to settlements in 1975–1989 and 1989–2006

respectively, which indicates the goodness of fit of MLOR in the two periods were good, so it can be used to analyze the driving forces behind the loss of marsh (Table 2). As Table 2 showed, three variables (distance to canals, annual precipitation (1975–1989) and distance to roads) have a significant, negative influence in explaining the losses of the marsh area. Low values of these variables are related to the occurrence of the decrease of the marsh area during 1975–1989. Table 2 also shows the five explanatory variables in explaining the occurrence of reduction in the marsh area from 1989 to 2006 were the agricultural population density, the distances to settlements and to canals, the per capita GDP and the annual precipitation. Of these five explanatory variables, the first three explanatory variables showed a positive relation with the decrease of the marsh area, while the other variables have a negative effect on the probability for marsh decrease.

Discussion

The interaction of different driving forces to marsh reduction

The Honghe region, with its continuous warmer and drier climate and increasing anthropogenic pressures, has undergone strong reduction of the marsh area over the past decades, and these decreases of the marsh area are exemplary for many other regions in the Sanjiang plain and the world (Hawbaker and Radeloff 2004; Liu and Ma 2002; Zhou et al. 2009). The results of the analysis of possible explanatory driving forces illustrate that there was no simple, single factor, causation in marshland reduction and that the spatio-temporal process of reduction was the result of a combined effect of natural and anthropogenic driving forces. These results indicate that annual precipitation, agricultural population density, Per capita GDP, distance to canals, distance to roads and distance to settlements all have a significant value in explaining the processes of marshland reduction. The result was consistent with other studies, supporting the conclusion that reduction was attributed to the interaction of kinds of driving forces (Zhou et al. 2009; Zhang et al. 2010). The exact combination of driving forces influencing marshland reduction was time-specific and differences in the driving forces across the study period caused spatio-temporal variations in reduction of the marsh area.

For natural driving forces, decreased precipitation, severe interannual precipitation variation and warming temperature not only have separate influences but also have superimposed effects on the marsh ecosystem, and all of which would degrade marsh slowly over a long-term period. For example, warming climate would lead to decreased precipitation and/or increased precipitation variation and then marsh may began to degrade because of reduction in supply water. Meanwhile, these degraded

Table 2 Model estimation of the driving forces impacting the loss of marsh in the Honghe region

Period	Independent variables	MLOR coefficients*	Standard variance	Wald	Odds ratio	ROC
1975–1989	Distance to canals	−1.451	0.470	9.540	0.234	0.71
	Annual precipitation	−1.314	0.267	24.292	0.269	
	Distance to roads	−0.969	0.542	3.194	0.380	
1989–2006	Agricultural population density	3.643	0.610	35.716	28.206	0.75
	Distance to settlements	3.021	0.646	21.882	20.505	
	Per capita GDP	2.576	0.465	30.646	13.150	
	Distance to canals	−1.340	1.248	1.529	0.262	
	Annual precipitation	−1.308	0.608	4.625	0.270	

* $p < 0.05$

marshlands may be preferentially reclaimed to cropland by local people. However, the annual precipitation was the single-selected variable in explaining decrease of marsh area among the three natural driving forces in the Honghe region (Table 2). That the two natural driving forces of temperature and precipitation anomaly were eliminated from the MLOR may be explained by the fact that there were multicollinearity among these three natural factors and the influence of interannual precipitation variation and annual temperature on wetland habitat was less important when compared with that of annual precipitation on reduction of marsh area.

The Sanjiang Plain is one of the largest national bases for grain production in China. All of the cropland have been reclaimed from marshland. Most of the local people make a living by farming and the GDP growth depends mainly on crop production. This process may lead to a positive feedback: the increasing of population will directly improve the ability to convert marshland into cropland. The expansion of cultivated land derived from marshland will improve the income of local people which was indicated by per capita GDP. The increasing income will subsequently stimulate local people to reclaim marshland. During 1975–1989, growth in these three socioeconomic indicators in the Honghe region increased slightly and they had little effect on marsh, which may be the reason why they were not selected in MLOR in this period. Since the late 1980s, these three socioeconomic indicators experienced cumulative growth and their negative impact on marsh increased gradually (Fig. 5). Therefore, the agricultural population and per capita GDP were selected as explanatory variable in explaining decrease of marsh area from 1989 to 2006.

That canals can impose large hydrologic disturbances on a wide range of ecological processes for natural wetland ecosystems have been reported in the Sanjiang Plain and the world (Aznar et al. 2003; Evers et al. 1992; Zhou et al. 2009). These results showed that the higher reduction rate of the marsh area was found near the canal, while with increasing distance from the canal, the marshland became less reduced. The drainage of the surface water in marshland near the canal was more convenient than that further from the canal. Consequently, these places near the canal were preferentially reclaimed by the local people because of the suitable crop-growth environment. As reported in Zhou et al. (2009), seven large drainage channels have been constructed in the upstream areas of the Nong River since 1988 and the density of the original canal network has increased substantially from 1996 to 2002. The irrigation network has been established systematically until the late 1990s and since then the influence of canal networks on the marsh ecosystem remained relatively stable (with similar partial regression coefficient of -1.451 and -1.340 in 1975–1989 and 1989–2006, respectively) in the Honghe region (Table 2). Meanwhile, the impact of other anthropogenic driving forces to the local marsh ecosystem increased gradually. It may be the reason why the contribution of distance to canals to the reduction of the marsh area was less important in 1989–2006 as compared with other anthropogenic driving forces.

Roads are corridors of human activities that can connect settlements and by which human activities can spread into the nearby marsh ecosystem. Roads can also impact the major processes controlling natural wetland ecological dynamics and strongly influence wetland landscape patterns (Aznar et al. 2003; Hawbaker and Radeloff 2004). As reduction in the marsh area was more likely to occur within high proximity of roads, which provided higher accessibility and reduced transportation costs. That could explain that marsh reduction near the road was more serious than that further from the road. Since the 1990s, there was little increasing in roads networks in the Honghe region and the significance of roads to the reduction of marsh area became less important as compared with other driving forces during 1989–2006. That may also be the reason why it was selected in MLOR during 1975–1989, but was eliminated from MLOR after 1989.

With the distance from settlements, the reduction of marsh area firstly remained stable and then decreased sharply. This fluctuation of reduction with distance can be explained by the distribution of the road network. Nearby the settlements, the local people can easily access to and reclaim marshland because of the convenient traffic system. In addition, as indicated by the average slope of fitting lines in Figs. 6, 7, and 8, the influence of distance to settlements on reduction of the marsh area was largely different than that of distance to canals and distance to roads. This may be explained by that the influence of distance to settlements expanded in all directions, while the other two driving forces only expanded in two directions. Figure 8 shows there was a roughly negative relationship between losses of marsh and the distance to settlements. However, in the period 1989–2006 for MLOR, there was a positive correlation between the loss of marsh and the distance to settlements. Since 1989, most of the marsh in the Honghe region has become surrounded by settlements, and now both marsh and settlements are interspersed with agricultural land. Thus, during the period 1989–2006, the farther the distance to settlements in the Honghe region, the more marsh was distributed in the area. Consequently, greater marsh reclamation occurred in places that were further from settlements mainly because those were the only marsh regions left to reclaim.

Assessment of MLOR analysis

Much of the research on driving forces of wetland change in the Sanjiang Plain focused on qualitatively analyzing either the role of the different factors separately or the physical mechanism of wetland degradation (Liu et al. 2004; Yan et al. 2002; Zhang et al. 2003; Zhang et al. 2010; Zhou and Liu 2005; Zhou et al. 2007). On the contrast, the interaction of driving forces was quantitatively analyzed and the relative significance of driving forces to the decline of the marsh area in different historical periods were identified, based on a multivariate statistical model. The authors believe that greater success in understanding the causes of the spatio-temporal variations in marsh reduction will be achieved if additional factors are considered, such as groundwater level, agricultural equipment, agriculture irrigation regime and land use policy. Because of these additional important considerations, the predominant driving forces to the decline of marsh area in different historical periods may differ from results of this study.

The MLOR analysis are exemplary for understanding the complexity in marsh reduction in the region. This methodology was a powerful tool for analyzing the combined effect of driving forces on marsh reduction and identifying what driving forces have played key roles on the reduction in some specific period, but it may lack a well-defined physical mechanism that degraded the marsh ecosystem. Consequently, interpretations of the statistical results still need to be supported with information obtained by other data such as field surveys and historical literatures in the area. Because of limited statistical and monitoring data, results from the multivariate statistical analysis would also be helpful for understanding the causes of spatio-temporal variations in marsh reduction and providing appropriate wetland conservation and management schemes in the typical wetland region.

Conclusions

In this study, the spatial and temporal variation of marsh reduction in a typical wetland region have been briefly analyzed. Besides analyzing the hypothesized driving forces separately, the authors focused on the combined impact and the relative significance of these driving forces in explaining spatio-temporal variations of marsh reduction by using a multivariate statistical model. Interpretations of the statistical results were supported with information obtained by field surveys and historical literatures in the area. Based on remote sensing techniques with GIS data and statistical yearbooks on natural and anthropogenic factors, the methodology adopted in this study was proven to be powerful for analyzing the complex causes of spatio-temporal variations in wetland reduction.

These results indicate that all of the variables, including precipitation, temperature, precipitation anomaly, population density, agricultural population density, Per capita GDP, distance to road, distance to canal and distance to settlement, were significantly related with the occurrence of reduction in marsh area in the Honghe region. In addition, the driving forces that have crucial roles in driving the reduction of marshland varied largely from 1975 to 2006. For example, both the construction of canal and road networks in farms surrounding the HNNR and the annual precipitation played key roles in driving the loss of marshland during 1975–1989, while the decrease of marsh areas was mainly attributed to the agricultural activities (e.g., agricultural population density and per capita GDP) and the settlements from 1989 to 2006. These findings may help understand the spatio-temporal variations and driving forces of declines in the marsh landscape in other areas with wetlands in China or in other countries, and could be helpful for managers, who design and implement natural wetland management and planning.

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