Changes Detection and Object-Oriented Classification of Major Wetland Cover Types in Response to Driving Forces in Zoige County, Eastern Qinghai–Tibetan Plateau

Xuexia Zhang, Shujing Fu, Zheyuan Hu, Jinxing Zhou, and Xue Zhang

***Abstract*—The Zoige alpine wetland of eastern Qinghai–Tibetan Plateau is one of the most important wetlands in the world, which suffered stronger human regulations of decades' drainage and recent restoration. It is so fragile that great efforts should be made to strengthen wetland protection. Based on wetland type classification for seven periods by the object-oriented classification method, we quantitatively discussed dynamically changes of wetland cover types and their driving forces. Conclusions show that alpine meadows accounts for 44.59% of the whole area of the county, and the transition between alpine meadows and swamp meadows mostly occurs in the process of wetland landscape changes. Changes of wetland cover types have taken place in Zoige County from 1990 to 2018 in which wetland loss was mainly caused by the decrease of marsh areas during 1995–2005. Particularly, shift from alpine meadows to swamp meadows led to wetland slightly expansion in two periods, i.e., 1990–1995 and 2005–2018. There is a significant negative correlation between marsh area and average temperature in growing season, average wind speed and rural population, and a significant negative correlation between water area and maximum wind speed. The increase of air temperature and wind speed lead to an enhancement of surface evapotranspiration and a decrease of water retention capacity. Whereas, positive feedback of ecosystem lead to an increase in air temperature and a decrease of marsh area. Both climatic changes and human activities have caused changes in wetland cover type, especially temperature in growing season, wind speed, agricultural development, and animal husbandry.**

***Index Terms*—Driving factors, object-oriented classification, swamp meadow, wetland cover types, Zoige alpine wetland.**

I. Introduction

As a highly productive and sensitive ecosystem, plateau wetland is vulnerable to wetland degradation and wetland loss for slow growth rate and short growth period of vegetation under alpine and harsh ecological conditions. The Zoige Wetland is a peat bog wetland, and its unique hydrological landscape affects the growth of peat soil and hygrophyte [1]. As an important water source conservation area in the upper reaches of the Yellow River, Zoige Wetland has stored about 5×10^9 m³ of groundwater and replenished about 4×10^9–5×10^9 m³ of groundwater to the headwaters of the Yellow River [2].

To objectively assess wetland changes and dynamic monitoring, it is extremely urgent to explore rapid and accurate methods of identification and extraction of wetland information. Wetland structure is reflected in the characteristics of hydrology, soil, and vegetation, whose interpretation signs behave same object with different spectrums and mixed spectral phenomena. Therefore, it is not suitable for remote sensing images to do simple automatic classification with digital number of the pixel elements. The existing literatures mostly adopt field investigation and visual interpretation of remote sensing images for the identification and extraction of wetlands on the Zoige Plateau. The visual interpretation has a generally higher accuracy than computer automated classification, but it is both subjective and highly laborious [3]. With the development of computer image processing technology, many one-class classification algorithms are used for extracting wetland cover types, such as object-oriented classification, spectral angle mapping classification, classification based on decision tree expert knowledge, artificial neural network classification, support vector machine classification [4]–[7]. The object-oriented multiscale segmentation algorithm can select an appropriate segmentation accuracy of a specific object at any specific spatial scale, which solves the problem of same object with different spectrums caused by pixel-based classification, and is consequently widely used [8], [9].

The driving factors of wetland cover type change consist of both natural environment and human activity [10], [11]. Previous studies have reported that the wetland ecosystem of Poyang Lake in China is a complex system under the influence of climate changes and environmental factors [12]. Hydrological conditions, topography, and species invasion are the main natural driving factors of coastal wetlands in Hangzhou Bay of China, while population, economy, policy, reclamation, urban construction, and aquaculture are the main anthropogenic driving factors [13].

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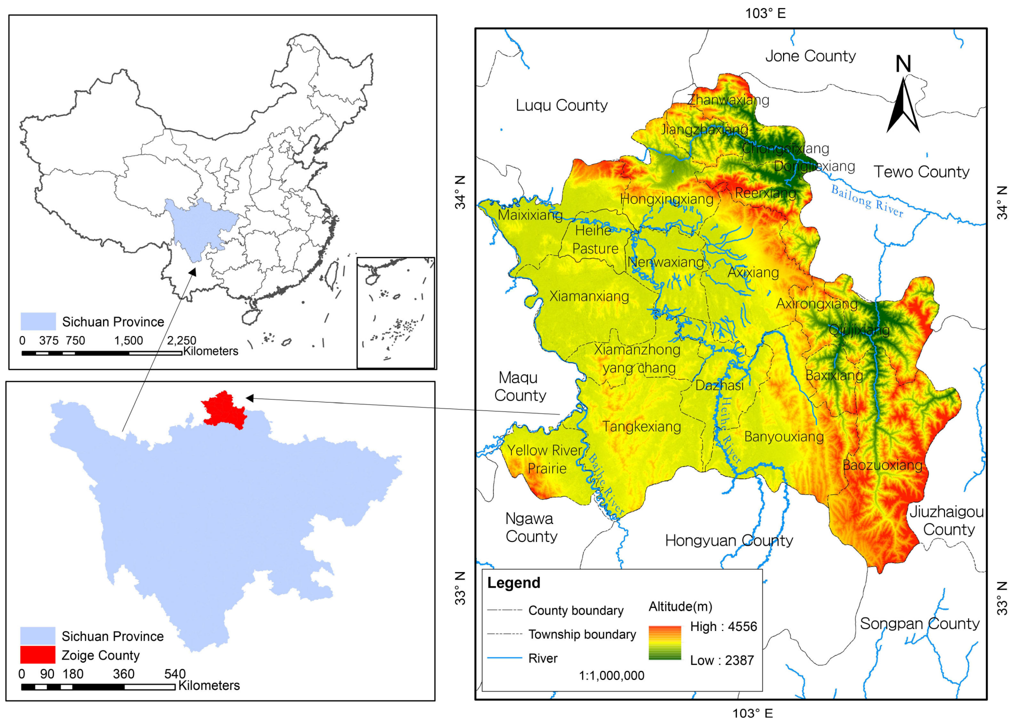

Fig. 1. Location map of the study area.

Most of the abovementioned studies focus on coastal wetlands and lake wetlands, while relatively few studies have addressed the factors of peat swamp of Zoige alpine wetlands.

In recent years, due to the impact of climate changes and human activities, Zoige alpine wetland is facing a series of problems, such as decline of water levels, rapid shrinkage and degradation of wetlands, desertification of wetlands, weakening of ecological functions, and reduction of biodiversity. In this article, object-oriented multiscale segmentation algorithm is selected to classify the wetland cover types in Zoige County, Sichuan Province. And several driving factors of wetland degradation in the Zoige Plateau are analyzed by selecting multiple indicators of climate changes and human activities. The diagnosis has certain guiding significance for better protection and utilization of wetland resources in the Zoige Plateau.

II. Study Area

Zoige alpine wetland, between 32°03′12″–34°18′19″N and 102°08′–103°48′E, is situated in the northern part of the Aba Tibetan and Qiang Autonomous Prefecture of Sichuan Province of China and the eastern margin of Qinghai–Tibetan Plateau in Fig. 1. The total area of study area is 1.04×10^4 km^2 with an average elevation of 3450 m above sea level. There are two main tributaries of upper reach of the Yellow River: Heihe River and Baihe River, which breed Zoige prairie and are important water conservation areas of the Yellow River. There is a cold plateau temperate climate, with an annual mean temperature of 1.1 °C, annual precipitation between 494 mm and 837 mm [14], and atmospheric relative humidity between 55% and 90%.

According to wetland cover data from image interpretation, alpine meadows, woodlands, and unique alpine wetlands are the dominant, occupying 44.59%, 30.19%, and 23.72% of the whole region, respectively. Plant communities are mainly dominated by perennial or annual marsh plants or alpine meadows, including the Carex muliensis community, the Kobresia tibetica community, and the Carex lasiocarpa community. Known for its abundant biodiversity and sensitive ecosystem, Zoige Wetland National Nature Reserve, located in the central of Zoige County, is built in 1998 and listed in The List of Wetlands of International Importance in China in 2008. However, wetland degradation and wetland loss continue to constrain sustainable socio-economic development in this region due to the contribution of global environmental changes and human activities.

III. Materials and Methods

A. Data Sources

The image data selected in Table I comes from Geospatial Data Cloud.[1] Including 7 periods of 21 scenes Landsat TM/OLI data in 1990, 1995, 2000, 2005, 2010, 2015, and 2018 (mostly from June to September), the path/row numbers of images covering the study area are 130037, 131036, 131037, respectively. High-quality images with cloud cover less than 10% were selected, and suitable time for images with excessive cloud cover were slightly adjusted by the adjacent temporal data. We used radiometric correction of fast line of sight atmospheric analysis of spectral hypercube (FLAASH) and georeferenced calibration with a root mean square (RMS) less than 15 m (0.5 pixels) at the image preprocessing stage for high-visible image dataset.

The meteorological data of monthly mean temperature, monthly total precipitation and monthly average wind speed were downloaded from China Meteorological Data Service

[1][Online]. Available: http://www.gscloud.cn/

TABLE I
INFORMATION OF REMOTE SENSING IMAGES USED IN THE ARTICLE

Path/Row	Landsat 5 TM						Landsat 8 OLI		
	Acquisition date					Spatial resolution	Acquisition date		Spatial resolution
130/37	90/08/18	96/07/17	00/07/12	06/07/29	11/07/27	Band1-Band5 (30m)	15/08/06	17/07/11	Band1-Band7 (30m)
131/36	90/07/08	95/08/07	01/07/22	06/08/05	10/07/31		15/07/29	18/07/21	
131/37	89/08/22	95/08/07	01/07/22	06/08/05	10/07/31		15/07/29	17/07/18	

Centre.[2] The socio-economic data of Zoige County from 1990 to 2018 were from Statistical Yearbook of Zoige County.

B. Methods

1) Object-Oriented Remote Sensing Image Classification: Object-oriented remote sensing image classification is a classification method that extracts features from homogeneous object units formed by image segmentation and establishes a multi-featured object classification system to process images, which proved better for land covers with characteristics of spatial continuous distribution, such as lake wetland [15]. Feature space, such as mean object spectral value, standard deviation, and object compactness are considered, so it can effectively reduce the phenomena of same objects with different spectrums and lack of information on the structure of the feature based on pixel classification.

With reference to Ramsar convention [16], investigation criteria of wetland resources in China and the local distribution characteristics of wetland distribution [17], we formulated a wetland classification system, which includes natural wetlands (lakes, rivers, marshes, swamp meadows) and constructed wetlands (paddy fields). In this article, Landsat TM /OLI was used as data source, and object-oriented remote sensing image classification method was used to classify the wetland cover types to discuss the spatial distribution characteristics and changes of Zoige alpine wetlands from 1990 to 2018.

2) Multiscale Segmentation Algorithm: Multiscale segmentation is a method of segmenting images into patches of different sizes that roughly conform to the shape of the feature based on the principles of intraobject homogeneity and interobject heterogeneity [18]. The determination of the segmentation parameters depends on spatial resolution of the remote sensing image and characteristics of the features. In this article, with reference to various research proposals and several attempts, we used brightness value in spectral features, shape parameter in spatial features, image contrast and entropy in texture features to identify various types of wetlands by multiscale segmentation [19], the segmentation scale was finally set to 15, the shape factor to 0.2, and the tightness to 0.1.

After the multiscale segmentation of image, the remote sensing image band synthesis features, spectral features of the image object, etc. (normalized difference vegetation index, normalized difference water index) are fully utilized to select classification samples. According to the main feature information contained in the image and the feature parameter selection principle of the nearest neighbor classification method, we selected four feature parameters in Table II.

Manually editing the classified features can effectively reduce the phenomenon of misclassification and omission of image objects. In this article, 200 samples of each period were obtained from Google Earth high-resolution images to establish a sample library for wetland accuracy evaluation. The confusion matrix (predicted classes versus observed classes) was built to evaluate the classification accuracy of the final wetland distribution map of Zoige County.

3) Changes of Contribution Ratios of Wetland Cover Type: Through defining the formulas of transfer-in contribution ratio of major wetland cover (T_{in}), transfer-out contribution ratio of major wetland cover (T_{out}), and the contribution ratio of specific conversion process (T_{ij}), the transformation of wetland cover is quantitatively analyzed. Transfer-in contribution ratio refers to the ratio of conversion area, which is from other wetland cover types to a specific wetland cover type to total area where wetlands have existed. The specific formula is as follows:

$$T_{\text{in}} = \sum\nolimits_{j=1}^{n} \frac{A_{ji}}{A_t} \tag{1}$$

where T_{in} is the transfer-in ratio of the *i*th wetland cover type, A_{ji} is the area of transition from type *j* to type *i*, and $\mathrm{A_t}$ is the total area where wetlands have existed.

Transfer-out contribution ratio refers to the ratio of conversion area, which is from a specific wetland cover type to other wetland cover types to total area where wetlands have existed. The specific formula is as follows:

$$T_{\text{out}} = \sum\nolimits_{j=1}^{n} \frac{A_{ij}}{A_t} \tag{2}$$

where T_{out} is the transfer-out ratio of the *i*th wetland cover type, A_{ij} is the area of transition from type *i* to type *j*, and A_t is the total area where wetlands have existed.

The contribution ratio of specific conversion process is the ratio of the transition area of the specific conversion process to total area where wetlands have existed. The specific formula is as follows:

$$T_{ij} = \frac{A_{ij}}{A_t} \tag{3}$$

[2][Online]. Available: http://data.cma.cn/

TABLE II
DESCRIPTION OF CLASSIFICATION FEATURE SET IN ZOIGE COUNTY

Feature	Feature description
Luminance value	$Bright = \frac{1}{12}\sum_{i=1}^{12}\left(\frac{1}{n}\sum_{j=1}^{n}\overline{C_{i,j}}\right)$
Contrast	$Contract = \sum_{i=0}\sum_{j=0} p(i,j)\times(i-j)^2$
Entropy	$Entropy = -\sum_{i=0}\sum_{j=0} p(i,j)\times \ln p(i,j)$
Shape index	$Shape = \sqrt{S}/A$

Note a: In the luminance value formula, i is the sequence number of the band, $i = 1, 2, \ldots 14$, j is the sequence number of the object, $j \in [1,n]$; n is the number of layers; and C_{ij} is the gray value of the i-band.
Note b: In the contrast and entropy formula, $p(i, j)$ denotes the (i, j) elements of the grayscale matrix, a pair of image elements of the graph, one of which is i grayscale and the other is the frequency of occurrence of j grayscale.
Note c: In the shape index formula, S is the area and A is the perimeter.

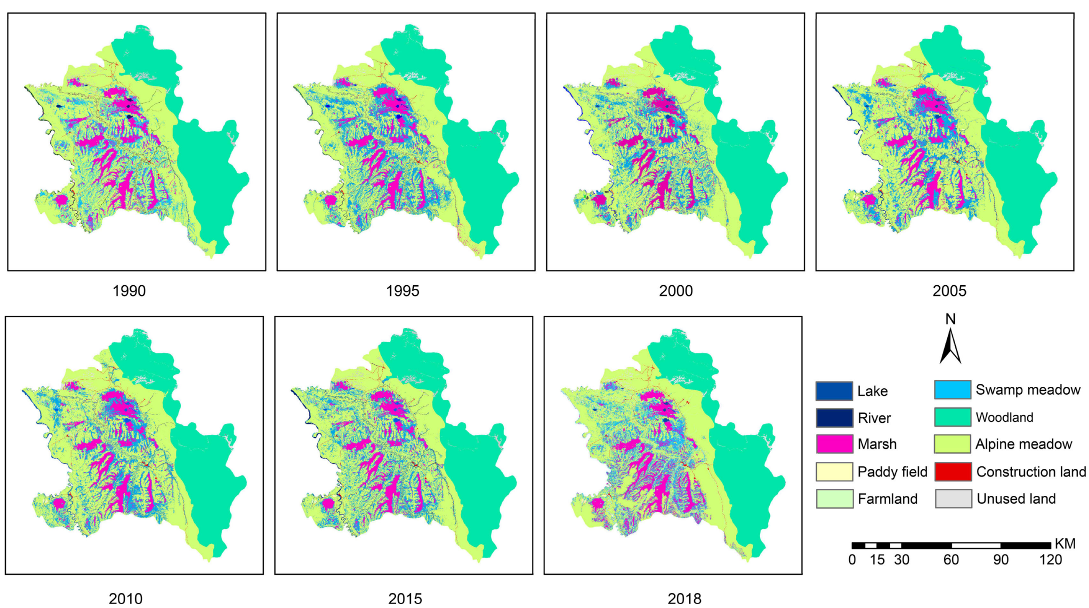

Fig. 2. Wetland cover map of Zoige County in seven periods.

where T_{ij} is the contribution ratio of conversion process from type i to type j, A_{ij} is the area of transition from type i to type j, and A_t is the total area where wetlands have existed.

IV. Statistical Analysis

The method of Pearson correlation analysis is performed and the method of the Least Significant Difference (LSD) is applied to test the significance of the differences between areas of different wetland cover types and driving forces. A statistical significance level of $\alpha = 0.05$ is viewed as some standard and fast threshold, which is the default value in most statistical software applications. Therefore, we use the statistical significance level of 0.05 in the thesis.

V. Results

A. Changes of Wetland Cover Types

1) Spatial Distribution of Wetland Cover Types: Fig. 2 shows the spatial distribution of wetland cover types in the study area in various periods from 1990 to 2018, which presents geographic features with mosaic-distribution of marshes, swamp meadows, and alpine meadows. Marshes are mostly distributed in pools zone, lowlands, riverbanks, and closed depressions. Alpine meadows are mainly distributed in the hilly grassland flat ridges, terraces, and subalpine belt. Lakes are distributed in the middle and north of the county, including the two main tributaries of upper reach of the Yellow River, which is Heihe river and Baihe river in Fig. 1.

TABLE III
AREAS OF DIFFERENT WETLAND COVER TYPES FOR SEVEN PERIODS IN ZOIGE COUNTY

Period	Area(km^2)										
	Marsh	Lake	River	Swamp meadow	Paddy field	Woodland	Alpine meadow	Farmland	Construction land	Unused land	Marsh ratio(%)
1990	1000.38	19.51	97.29	1397.09	1.71	3108.91	4490.67	0.26	27.90	100.82	24.5
1995	839.72	18.73	90.84	1652.78	2.11	3110.76	4405.79	2.53	29.93	91.33	25.4
2000	814.69	18.47	95.80	1390.86	6.01	3037.93	4774.07	2.97	39.24	94.49	23.1
2005	814.02	18.47	95.23	1380.09	8.81	3112.15	4688.67	2.84	39.95	84.29	22.5
2010	804.96	18.60	99.59	1421.23	6.98	3089.24	4646.32	2.77	42.42	112.42	22.8
2015	789.31	17.49	104.38	1431.43	7.80	3097.16	4620.56	5.78	44.28	126.32	22.8
2018	832.30	17.33	95.89	1557.16	3.90	3097.13	4468.10	6.07	45.40	121.25	24.4
ratio	8.22	0.18	0.95	14.37	0.05	30.19	44.59	0.04	0.38	1.04	/

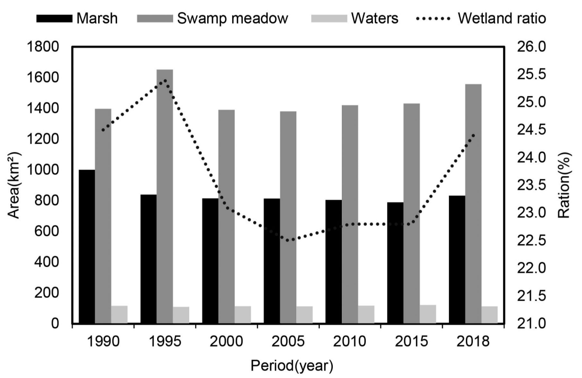

Fig. 3. Major wetland types and areas in Zoige County of Sichuan Province.

2) Temporal Changes of Wetland Cover Types: From Table III, it can be seen that land cover types of Zoige County are mainly alpine meadows and woodlands, and the annual average area accounts for 44.59% and 30.19%, respectively. On the whole, the wetlands' area increases slightly between 1990 and 1995, shrank from 1995 to 2005, and boom between 2005 and 2018. Among wetland cover types, marsh shows the greatest change of area from 1990 to 2018, with an overall shrinkage of 168.08 km^2 by 2018, of which dropped 160.66 km^2 from 1990 to 1995. However, the areas of swamp meadow increased by 160.07 km^2 from 1990 to 2018, especially expansion by 177.07 km^2 from 2005 to 2018. The area of rivers and lakes had fallen by 1.4 km^2 and 2.18 km^2, respectively, by 2018.

According to interpretation signs of wetland cover types in Zoige County, the areas of various types of natural wetlands are calculated. Considering that both lakes and rivers are open water, the two categories are grouped as waters. Therefore, natural wetlands are divided into three categories: marsh, swamp meadow, and waters. Fig. 3 shows that the areas of wetlands occupy 23.72% of the total area of Zoige County. The area of wetlands decreased 11.4% from 1995 to 2005, however, increased by 8.4% from 2005 to 2018. Among the wetland types, swamp meadow is the largest, accounting for 60.58%, followed by marsh, accounting for 34.65%.

The decrease of marshes in the early stage mainly led to the decrease of wetlands, while a small rise of wetland areas in the late stage was mostly due to the increase of swamp meadows. Literature shows that the peat bogs of Zoige Plateau behave a significant reduction trend of 29.9% between 1990 and 2011 [20]. Similar conclusions indicate that the human activities, such as wetland drainage and restoration, land reclamation around lake for construction, peat mining as a fuel are the main causes of the changes of wetland area [21], [22].

3) Wetland Transfer in/Out Contribution Ratio: Changes of wetland cover types have taken place in Zoige County in which wetland loss is mainly caused by the decrease of marsh areas from 1995 to 2005. The increase of swamp meadow areas led to slight wetland expansion in two periods, this is 1990–1995 and 2005–2018. Table IV shows the transfer-in contribution ratio ($T_{\rm in}$ and transfer-out contribution ratio ($T_{\rm out}$) of major wetland types (river, lake, marsh, swamp meadow) in the study area.

From 1990 to 1995, $T_{\rm in}$ of 41.72% is greater than $T_{\rm out}$ of 33.67%. By comparing the contribution ratio of specific transfer process, it can be seen that the transfer contribution ratio of alpine meadow to swamp meadow reaches 39.77%, which is the main form of wetland transfer-in during 1990 to 1995.

$T_{\rm in}$ of 30.62% is less than $T_{\rm out}$ of 53.32% from 1995 to 2000, while $T_{\rm in}$ and $T_{\rm out}$ from 2000 to 2005 show the similar characteristics with the number of 44.22% and 46.62%. The transfer of swamp meadows into alpine meadows is the main form of wetland transfer-out during 1995 to 2005.

From 2005 to 2010, $T_{\rm in}$ of 45.79% is greater than $T_{\rm out}$ of 37.55%. During the transfer-in progress of various types of wetlands, the contribution ratio of landscape conversion from alpine meadows to swamp meadows is the largest, reaching 44.31%. Changes of wetland from 2010 to 2015 maintain basically stable status. From 2015 to 2018, $T_{\rm in}$ of 43.49% is greater than $T_{\rm out}$ of 33.91%. And the changes wetland is mainly transferred in. Among them, the transfer of alpine meadows to swamp meadows had the largest contribution ratio, reaching 36.14%, which is the main transfer-in form of wetlands during 2015 to 2018.

Fig. 4 shows that changes of the wetland are mainly transferred out, whose major form is landscape transition from swamp meadows to alpine meadows during 1995–2005. The opposite happens in other periods.

B. Driving Forces of Changes of Wetland Area

From 1990 to 2018, the spatial distribution pattern of wetland in Zoige county shows that natural wetland is the main type of wetland. The changes of wetland areas present a shape of "S" curve and are affected by human activities, climate changes,

TABLE IV
CONTRIBUTION RATIO OF TRANSFER IN/OUT IN ZOIGE COUNTY WETLANDS FROM 1990 TO 2018

Period(year)	1990-1995	1995-2000	2000-2005	2005-2010	2010-2015	2015-2018
Wetland-Alpine meadow	33.32	52.6	45.73	34.24	47.42	33.88
Wetlands-Other non-wetlands	0.35	0.72	0.88	3.31	0.09	0.03
Alpine meadow-Wetland	40.66	30.44	44.03	45.48	47.25	43.45
Other non-wetlands-Wetlands	1.06	0.18	0.19	0.31	0.09	0.04
Transfer-in contribution rate	41.72	30.62	44.22	45.79	47.34	43.49
Transfer-out contribution rate	33.67	53.32	46.62	37.55	47.51	33.91

TABLE V
LIST OF DRIVING FACTORS OF WETLAND FACTORS OF WETLAND COVER CHANGES

Category	Code	Name	Unit
Human activities	X1	Total population	Person
	X2	Urban population	Person
	X3	Rural population	Person
	X4	Regional GDP	10,000 yuan
	X5	Added value of primary industry	10,000 yuan
	X6	Added value of secondary industry	10,000 yuan
	X7	Added value of tertiary industry	10,000 yuan
	X8	Fixed asset investment	10,000 yuan
	X9	Number of large livestock on hand at the end of the year	10,000 heads
	X10	Total meat production	ton
Climate change	X11	Annual mean temperature	0.1°C
	X12	Average temperature in growing season	0.1°C
	X13	Average annual precipitation	0.1mm
	X14	Total precipitation in growing season	0.1mm
	X15	Average wind speed	0.1m/s
	X16	Maximum wind speed	0.1m/s

etc. The former include population growth, grazing, and wetland conservation and the latter contain increasing temperature, increasing precipitation, etc. [16], [23].

The area of marshes, swamp meadows, and waters is calculated, respectively. Then, the relationship between the area of different wetland types and various factors is discussed quantitatively by Pearson correlation coefficient.

According to the principles of data accessibility, consistency, and quantification, 16 indicators are selected in Table V for driving factors from the social, economic, and climate aspects: total population (X1), urban population (X2), rural population (X3), regional gross domestic product (GDP) (X4), added value of primary industry (X5), added value of secondary industry (X6), added value of tertiary industry (X7), fixed asset investment (X8), number of large livestock on hand at the end of the year (X9), total meat production (X10), annual mean temperature (X11), average temperature in growing season (X12), average annual precipitation (X13), total precipitation in growing season (X14), average wind speed (X15), and maximum wind speed (X16).

Fig. 5 shows the following three conclusions.

1) Average temperature in growing season ($r=-0.71$) and average wind speed ($r=-0.82$) are significantly negatively correlated with marsh area, and maximum wind speed ($r=-0.74$) is significantly negatively correlated with water area. It may be due to the increase of air temperature and wind speed, resulting in a rise of surface evapotranspiration and a decrease of water retention capacity, and then the shrinkage of marshes. Whereas, positive feedback of ecosystem leads to a continuous increase in air temperature and a decrease of marsh area. In addition, artificial drainage and livestock trampling in the process of grazing destroy the surface of wetland landscape, resulting in hardening, and crusting of bare surface soil. It also decreases soil water holding capacity, increase surface roughness and reflectance. Effective radiation decreases, which accelerates the evolution process from marsh transition zone to swamp meadow and meadow [24]–[26].
2) There is a significant negative correlation between rural population and marsh area, which may be the result of uncontrolled use of marshes by agricultural development and use, such as grazing, and peat resource extraction and its application.

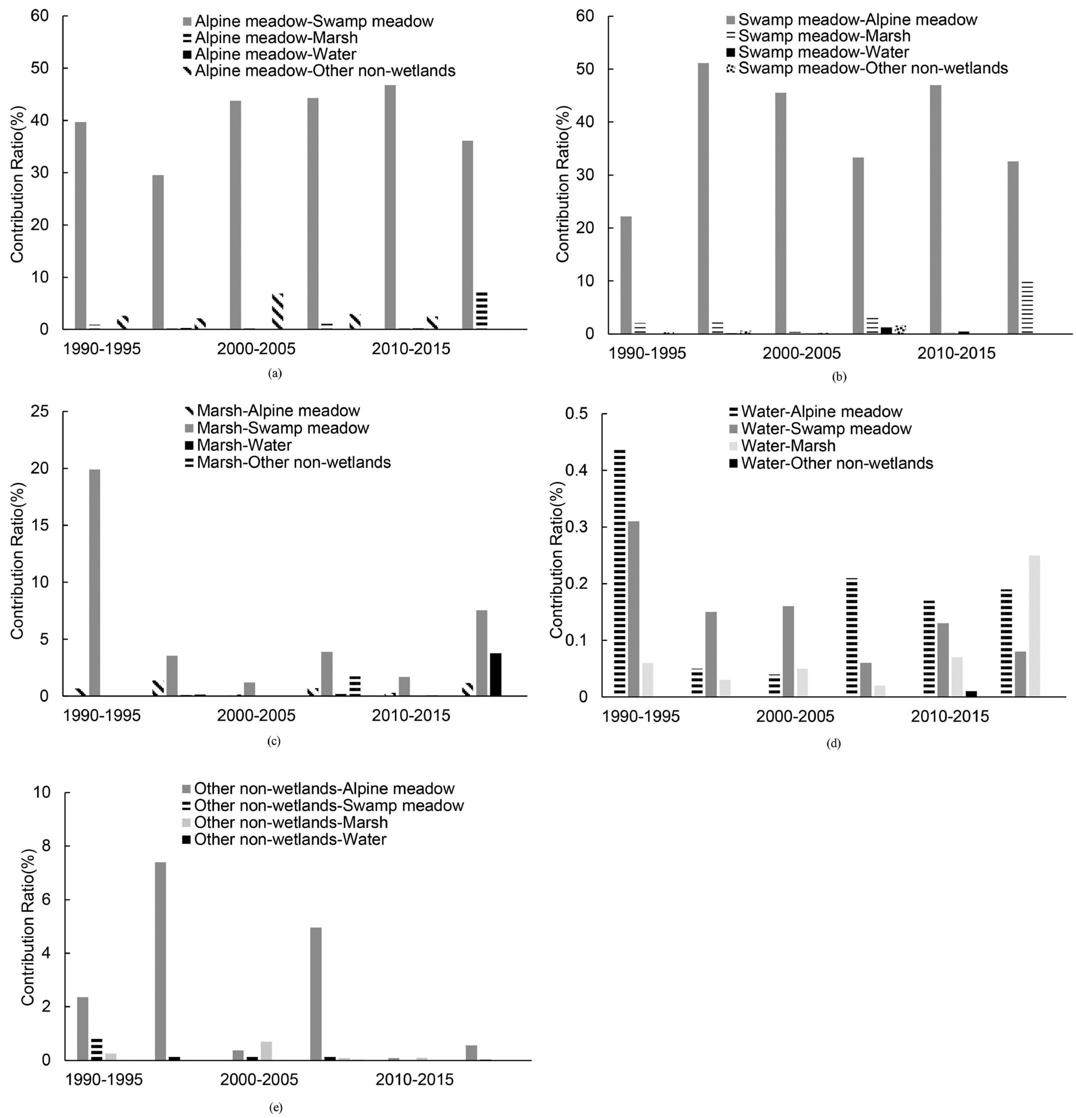

Fig. 4. Contribution ratio of Zoige wetland conversion process.

3) The swamp meadows in the study area presents alternative distribution feature with marshes and meadows. Their area shows no statistically significant correlation with the driving factors, but there is still a dynamic change of swamp meadows with marshes and meadows. Since the 1970s, Zoige County has excavated ditches and drained marshes in order to improve livestock carrying rate and utilization rate of the grassland. The groundwater level of alpine meadows flowing through the crisscross drainage ditches rose, and alpine meadows transformed into swamp meadows in a short time. In the 1990s, drainage made the marshes dry, the groundwater level dropped, and the peat layer damaged. The area of lakes in the Reer Dam, such as Huahu Lake, Cuolajian Lake, and Haqiu Lake, gradually decreased, and the water level of the lakes decreased. Swamp meadows gradually transformed into alpine meadows. After 2000, Zoige National Nature Reserve and Kaharjo Wetland County Nature Reserve were established in Zoige County. Various forms of wetland restoration and restoration projects were carried out, and the alpine meadows were gradually restored to swamp meadows.

VI. Discussion

Human disturbance to natural ecosystem has advantages and disadvantages to wetland restoration. Statistics illustrate that population growth is 47.2% (41.4% in China, 71.3% in the world) in Zoige County from 1980 to 2018. 84.6% of the population engaged in animal husbandry in Zoige County in 2018. GDP was 4.2 times (195 times in China, 1.55 times in the world) from 1980 to 2018 in Zoige County. Overgrazing and population growth are driving factors of wetland loss, degradation, and even sandification. Besides, the sustainability of wetland resources is threatened by other human activities, such as trenching or excavating marsh wetlands, unreasonable exploitation of peat resources, strong interference from human construction activities and unrestrained tourism. In particular, it needs to be emphasized that drainage of wetland from 1960 to

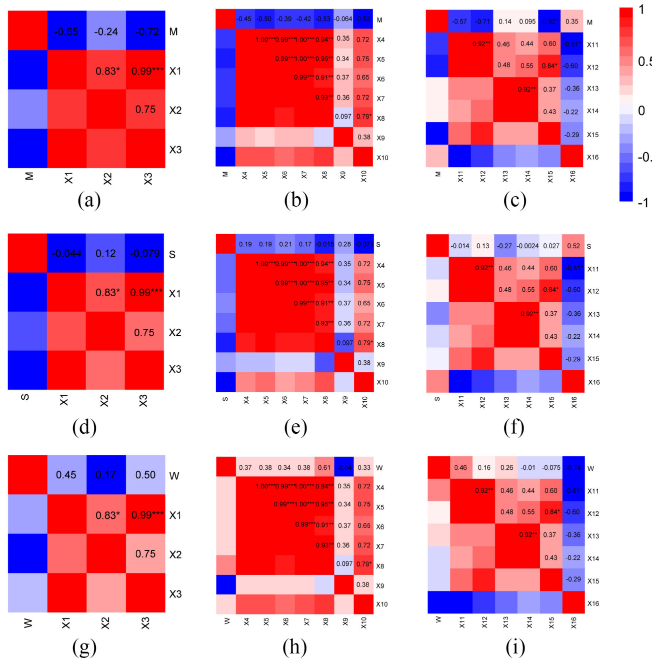

Fig. 5. Heat maps of correlation analysis between different types of natural wetland area and various factors.

2000 changed hydrological connectivity, a large amount of surface water has been drained [27]. Then, the peatlands gradually became bare and dry, causing wetland to shrink [28]. Peatlands or mires are a large carbon reservoir whose presence in anoxic conditions leads to the release of large amounts of greenhouse gases into the atmosphere, thus giving a positive feedback on climate warming [29].

We quantitatively analyzed the driving forces of wetland cover type changes. Based on the available data, we chose many indices. However, the selection of indices and spatial differences are limited, especially policies that are difficult to quantify and not fully considered. These factors should play a considerable role in the change of wetland cover types. In the future, how to further quantify such impact should be taken into account.

VII. Conclusion

This article adopted an object-oriented classification method to obtain the spatial distribution of wetland cover types in seven periods in Zoige County, and then explored reasons for changes in wetland types from perspectives of both climatic changes and human activities. The land cover types in the study area are mainly alpine meadows and woodlands. Area of marshes decreased a lot during 1995–2005 while shift from alpine meadows to swamp meadows led to wetland slightly expansion in two periods, i.e., 1990–1995 and 2005–2018.

There is a significant negative correlation between marsh area and average temperature in growing season, average wind speed and rural population, and a significant negative correlation between water area and maximum wind speed. Both climatic changes and human activities have caused changes of wetland cover type, especially temperature in growing season, wind speed, agricultural development, and animal husbandry. They have accelerated changes of the transition zone from marsh to swamp meadow or meadow. Therefore, it is necessary to make full use of wetland resources, give full play to the conservation role of Wetland Reserve, further curb the trend of wetland degradation, promote green development in the study area, and achieve sustainable socio-economic development.

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References

[1] G. Hu, Z. Dong, J. Lu, and C. Yan, "Driving forces of land use and land cover change (LUCC) in the Zoige wetland, Qinghai-Tibetan Plateau," *Sci. Cold Arid Regions*, vol. 4, no. 5, pp. 422–430, Oct. 2012.

[2] Y. You, Z. Li, and M. Chen, "Distribution of man-made ditches and their displacement estimation Riganqiao peat bog, Zoigê Plateau," *Wetland Sci.*, vol. 16, no. 2, pp. 223–230, Apr. 2018, doi: 10.13248/j.cnki.wetlandsci.2018.02.017.

[3] P. F. Houhoulis and W. K. Michener, "Detecting wetland change: A rule-based approach using NWI and SPOT-XS data," *Photogrammetric Eng. Remote Sens.*, vol. 66, no. 2, pp. 205–211, Feb. 2000.

[4] G. Xu and Z. Zhao, "Remote sensing classification of surface features on the Roige plateau," *J. Geomechanics*, vol. 10, no. 4, pp. 351–356, Dec. 2004.

[5] C. Wang, "Analysis of risk assessment and evolution of Zoige plateau marsh wetland degradation," M.E. thesis, Dept. Geomatics Eng., China Univ. Geosci., Beijing, China, 2015.

[6] J. Zhang, J. Gong, M. Huang, and W. Lin, "Application of remote sensing image based on knowledge decision tree classification in identifying the habitat of oncomelania snails in Poyang lake region," *Chin. J. Schistosomiasis Control*, vol. 2008, no. 1, pp. 70–84, Feb. 2008, doi: 10.16250/j.32.1374.2008.01.007.

[7] S. Zhang, X. Gao, and W. Hua, "Remote sensing image information extraction method based on clustering and artificial neural network," *Electron. Des. Eng.*, vol. 28, no. 15, pp. 106–109, Aug. 2020, doi: 10.14022/j.issn1674-6236.2020.15.024.

[8] J. Cheng, "Research on building extraction based on object-oriented high-resolution remote sensing image," M.E. thesis, Dept. Surveying Mapping Eng., Xi'an Univ. Sci. Technol., Xi'an, China, 2020.

[9] L. Hong, S. Chu, S. Peng, and L. Xu, "Multiscale segmentation-optimized algorithm for high-spatial remote sensing imagery considering global and local optimizations," *J. Remote Sens.*, vol. 24, no. 12, pp. 1464–1475, Dec. 2020.

[10] L. Han, "A study on temporal and spatial dynamic distribution and biogeochemical characteristics of Hulun Buir grassland wetland," Ph.D. dissertation, Dept. Agrostol., Beijing Forestry Univ., Beijing, China, 2019.

[11] J. Yang, "Extraction and analysis of remote sensing information of the Baiyangdian wetland variation in Xiong' an new area in the past twenty," M.E. thesis, Dept. Geol. Eng., China Univ. Geosci., Beijing, China, 2020.

[12] X. Han, "Spatio-temporal dynamics of Poyang lake wetland landscape patterns based time series optical remote sensing data in Poyang lake," Ph.D. dissertation, Dept. GIS, Wuhan Univ., Wuhan, China, 2017.

[13] N. Li, "Long-term remote sensing dynamic monitoring and ecological assessment of coastal wetland in Hangzhou bay," Ph.D. dissertation, Dept. Ecol., Nanjing Forestry Univ., Nanjing, China, 2020.

[14] C. Wu, W. Chen, C. Cao, R. Tian, D. Liu, and D. Bao, "Diagnosis of wetland ecosystem health in the Zoige wetland, Sichuan of China," *Wetlands*, vol. 38, no. 3, pp. 469–484, Jun. 2018, doi: 10.1007/s13157-018-0992-y.

[15] R.-M. Yang, R. An, H.-L. Wang, Z.-X. Chen, and J. Quaye-ballard, "Monitoring wetland changes on the source of the three rivers from 1990 to 2009, Qinghai, China," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 6, no. 4, pp. 1817–1824, Aug. 2013, doi: 10.1109/JSTARS.2012.2222354.

[16] K. Chen, "Ramsar Convention-introduction to convention on wetlands," *Chin. Biodiversity*, vol. 3, no. 2, pp. 2–121, May 1995.

[17] Y. Zheng *et al.*, "A method for alpine wetland delineation and features of border: Zoigê plateau, China," *Chin. Geographical Sci.*, vol. 27, no. 5, pp. 784–799, Oct. 2017.

[18] P. Shi, "Multi-level segmentation classification method research based on remote-sensing image," M.A. thesis, Dept. Forest Management, Chin. Acad. Forestry, Beijing, China, 2018.

[19] I. Dronova, G. Peng, and W. Lin, "Object-based analysis and change detection of major wetland cover types and their classification uncertainty during the low water period at Poyang lake, China," *Remote Sens. Environ.*, vol. 115, no. 12, pp. 3220–3236, Jun. 2011, doi: 10.1016/j.rse.2011.07.006.

[20] Y. You, Z. Li, and X. Li, "Land cover change in Zoige plateau during 1990-2011," *Adv. Sci. Technol. Water Resour.*, vol. 38, no. 2, pp. 62–69, Mar. 2018.

[21] A. Armstrong, "DITCH: A model to simulate field conditions in response to ditch levels managed for environmental aims," *Agriculture Ecosyst. Environ.*, vol. 77, no. 3, pp. 179–192, Jun. 2000, doi: 10.1016/S0167-8809(99)00082-1.

[22] X. Zhang, X. Tang, C. Li, L. Cui, and X. Wang, "Comparison of the drainage effects on ecological characteristics in Sanjiang plain and Zoige plateau," *Chin. J. Ecol.*, vol. 34, no. 7, pp. 2030–2040, Jun. 2015, doi: 10.13292/j.1000-4890.20150615.019.

[23] M. Wang, S. Qi, and X. Zhang, "Wetland loss and degradation in the yellow river delta, Shandong province of China," *Environ. Earth Sci.*, vol. 67, no. 1, pp. 185–188, Sep. 2012, doi:10.1007/s12665-011-1491-0.

[24] F. He *et al.*, "The environmental effects of grazing and its negative influence on conservation," *J. Sichuan Forestry Sci. Technol.*, vol. 30, no. 3, pp. 43–54, Jun. 2009, doi: 10.16779/j.cnki.1003-5508.2009.03.007.

[25] X. Li, "Effects of grazing disturbance on soil properties in Zoige plateau wetland," *Agriculture Technol.*, vol. 35, no. 5, pp. 44–59, Mar. 2015.

[26] G. Chen *et al.*, "The response of soil water-holding capacity to different livestock patterns in plateau Napahai wetland," *J. Soil Water Conserv.*, vol. 30, no. 4, pp. 123–141, Aug. 2016, doi: 10.13870/j.cnki.stbcxb.2016.04.021.

[27] Z. Li and P. Gao, "Impact of natural gullies on groundwater hydrology in the Zoige peatland, china," *J. Hydrol., Regional Stud.*, vol. 21, pp. 25–39, Feb. 2019, doi: 10.1016/j.ejrh.2018.12.001.

[28] J. KvaRner and P. Snilsberg, "The Romeriksporten railway tunnel-drainage effects on peatlands in the lake northern Puttjern area," *Eng. Geol.*, vol. 101, no. 3/4, pp. 75–88, Oct. 2008, doi: 10.1016/j.enggeo.2008.04.002.

[29] D. Wei, H. Zhao, L. Huang, Y. Qi, and X. Wang, "Feedbacks of alpine wetlands on the Tibetan plateau to the atmosphere," *Wetlands*, vol. 40, pp. 1–11, Oct. 2019, doi: 10.1007/s13157-019-01220-4.

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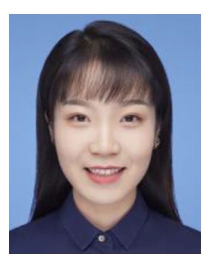

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