Spatiotemporal Variation Characteristics and Trend Analysis of Vegetation and Water Bodies in the Bosten Lake Region Based on Multiple Endmember Unmixing Model: Postprint

Authors: Yashar Esker, Yusupjan Rosul

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Abstract

High-precision remote sensing monitoring of dynamic changes in wetlands holds significant practical importance for wetland conservation and restoration. Taking the Bosten Lake wetland in Xinjiang as the study area, this study employs the Multiple Endmember Spectral Mixture Analysis (MESMA) model to extract vegetation, water body, and bare land areas from Landsat imagery. Following accuracy validation using UAV imagery and combining trend analysis methods, the spatiotemporal variation characteristics and trends of the Bosten Lake wetland from 2000 to 2022 were investigated. The results indicate: (1) In the MESMA classification results validated through resampling accuracy assessment using UAV imagery, the coefficient of determination (R^2) for vegetation pixels is 0.75, and for water body pixels is 0.84, demonstrating that the classification results align with actual ground features. (2) From 2000 to 2022, the vegetation area in the Bosten Lake wetland increased by a total of 536.65 km^2, representing an increase of 183.14%; the water area decreased by 595.76 km^2, representing a decrease of 37.07%; and the bare land area increased by 99.12 km^2, representing an increase of 25.42%. (3) Areas showing an increasing trend in vegetation coverage account for 30.6% of the total wetland area, located in the northwestern part of the main lake region and the northern part of the small lake region; conversely, areas showing a decreasing trend in water coverage account for 34.6% of the total area, located along the northern and eastern shores of the main lake and in the small lake wetlands. Accurately understanding the spatiotemporal changes and trends of the Bosten Lake wetland can provide a reference basis for monitoring and protecting inland wetlands in arid regions.

Full Text

Spatiotemporal Variation Characteristics and Trend Analysis of Vegetation and Water Area in the Bosten Lake Region Based on Multiple Endmember Spectral Mixture Analysis Model

Yaxiaer AISIKEER[1], **Yusufjiang RUSULI**[1,2]

[1]College of Geography and Tourism, Xinjiang Normal University, Urumqi 830054, Xinjiang, China
[2]Key Laboratory of Arid Zone Environment and Resources, Xinjiang Normal University, Urumqi 830054, Xinjiang, China

Abstract

High-precision remote sensing monitoring of dynamic wetland changes is of great practical significance for wetland conservation and restoration. This study focuses on the Bosten Lake wetland in Xinjiang, employing the Multiple Endmember Spectral Mixture Analysis (MESMA) model to extract vegetation, water body, and bare land areas from Landsat imagery. After validating the accuracy with UAV imagery and combining trend analysis methods, we investigated the spatiotemporal variation characteristics and trends of Bosten Lake wetland from 2000 to 2022. The results demonstrate that: (1) The MESMA classification results, verified through resampling of UAV imagery, showed a goodness-of-fit (R^2) of 0.75 for vegetation pixels and 0.84 for water body pixels, indicating that the classification results align well with actual ground features. (2) From 2000 to 2022, the vegetation area in Bosten Lake wetland increased by 536.65 km^2 (183.14%), the water area decreased by 595.76 km^2 (37.07%), and the bare land area increased by 99.12 km^2 (25.42%). (3) Areas with increasing vegetation trends accounted for 30.6% of the total wetland area, primarily located in the northwestern part of the Great Lake region and the northern part of the Small Lake region. Conversely, areas with decreasing water area trends accounted for 34.6% of the total area, mainly distributed along the northern and eastern shores of the Great Lake and in the Small Lake wetlands. Accurately understanding the spatiotemporal changes and trends of Bosten Lake wetland provides a valuable reference for monitoring and protecting inland wetlands in arid regions.

Keywords: MESMA; mixed pixel; wetland; spatiotemporal variation; Bosten Lake

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Introduction

Wetlands serve as natural gene banks for species and play crucial roles in water purification, flow regulation, nutrient retention, climate stabilization, and tourism. According to the definition in the Ramsar Convention, wetlands refer to natural or artificial, permanent or temporary, static or flowing, fresh, brackish, or saltwater areas, including marshes, wet meadows, peatlands, or water bodies, with depths not exceeding six meters at low tide. Bosten Lake, located in the lowest part of the Yanqi Basin in Xinjiang, has been designated as a National Wetland Park and currently represents China's largest national wetland park by area.

Remote sensing observation of wetland changes requires precise identification of wetland feature types. Due to the spatial resolution limitations of remote sensing imagery, a single pixel often contains multiple ground feature types, creating what is known as a "mixed pixel." Classifying mixed pixels as any single feature type is inherently erroneous because they do not belong exclusively to one category. The presence of mixed pixels affects the accuracy of remote sensing-based feature classification. Wetlands exhibit complex biodiversity and high landscape fragmentation, making mixed pixels ubiquitous in remote sensing imagery and severely interfering with wetland feature classification accuracy.

Numerous experts have conducted extensive research on mixed pixel decomposition of remote sensing data. Wu et al. improved the linear spectral unmixing model for agricultural-pastoral ecotones in arid regions, extracting more accurate grassland vegetation spectral information while reducing interference from soil endmembers, thereby improving classification accuracy for meadow types in arid zones. Li et al. applied fully constrained least squares mixed pixel technology to pixel-based classification of coastal wetlands in China, providing theoretical support for coastal wetland classification. Li et al. combined object-oriented methods with multiple endmember unmixing models to invert vegetation coverage in Zhalong Wetland, achieving favorable results. These studies have improved feature information extraction accuracy through mixed pixel decomposition methods, but they have primarily focused on coastal wetlands, natural swamp areas, and river delta regions, with very limited research on arid zone wetlands, particularly Bosten Lake.

Bosten Lake has evolved from a freshwater lake to a brackish lake, with shrinking water area and large-scale disappearance of surrounding wetlands. In recent years, the local government has actively promoted comprehensive ecological environment management in the Bosten Lake basin, resulting in significant improvements in wetland ecological functions and water body restoration. Conducting long-term, high-precision wetland change observation is crucial for further protection and restoration of Bosten Lake wetland. Zeng et al. analyzed the evolution patterns and development trends of Bosten Lake wetland using remote sensing data, providing a theoretical basis for formulating reasonable and effective wetland protection measures. Wang et al. studied the spatial variation of vegetation coverage in the Bosten Lake basin, providing references for assessing future hydrological and water resource changes. However, most scholars have conducted classification only at the traditional pixel scale, ignoring the impact of mixed pixels on feature extraction accuracy.

MESMA (Multiple Endmember Spectral Mixture Analysis) is an improved mixed pixel decomposition method based on the Linear Spectral Mixture Analysis (LSMA) model. By employing various endmember spectral combinations for decomposition, MESMA extracts the percentage of each feature within a pixel, effectively reducing the salt-and-pepper effect. This study addresses the current characteristics of Bosten Lake wetland, using Landsat TM/ETM+/OLI imagery as data sources. Through MESMA mixed pixel decomposition, we obtain abundance values of typical feature types in Bosten Lake wetland, construct an unmixing model with vegetation, water body, and bare land as components, invert feature classification results, and validate them using UAV imagery captured in the study area. This approach enables sub-pixel level information extraction, dynamic monitoring of wetland evolution, and clarification of spatiotemporal variation patterns. The objective is to explore a method for improving feature type information extraction in arid zone wetlands while providing effective theoretical basis and data support for Bosten Lake wetland monitoring and protection.

1. Study Area Overview

Bosten Lake is located in the lowest part of the Yanqi Basin in Xinjiang, with terrain sloping from high in the northwest to low in the southeast. It serves as the terminal lake of the Kaidu River and the source of the Kongque River (Figure 1). The wetland vegetation is dominated by *Phragmites australis* (common reed), supplemented by *Typha angustata* and *Typha angustifolia*, forming China's fourth largest reed wetland area. The study area features an arid climate with scarce rainfall and strong evaporation, characterized as a temperate continental desert climate with hot, dry summers and cold, snowy winters. Annual precipitation is 68.2 mm, while annual evaporation reaches 2200 mm.

In recent decades, rapid socioeconomic development around Bosten Lake has led to continuous population growth and expanding farmland area. The vegetation, bare land, and water body are interspersed, increasing landscape fragmentation and causing various features to mix within single pixels, resulting in severe mixed pixel phenomena. Traditional pixel-scale classification algorithms struggle to effectively address the mixed pixel problem in wetland feature interpretation. MESMA, an improved mixed pixel decomposition method based on linear spectral mixing, employs multiple endmember spectral combinations to decompose mixed pixels. This study focuses on the main water bodies of the Great Lake and Small Lake regions of Bosten Lake, using the Baolangsumu water diversion hub station on the Kaidu River (elevation approximately 1050 m) as a benchmark to determine the study area boundary and distinguish between Great and Small Lake regions using the middle line between the east and west branches of the Kaidu River. Bosten Lake covers a total area of 2450.65 km^2, with the Great Lake area measuring 1777.43 km^2 and the Small Lake area 673.22 km^2.

2.1 Data Sources

Landsat Series Data: We selected Collection 2 Level 2 Tier 1 Landsat TM/ETM+/OLI surface reflectance products, which offer excellent geometric and radiometric calibration accuracy and high consistency across sensors. Considering the phenological characteristics of vegetation in Bosten Lake wetland, we chose images from July to September each year with cloud cover less than 10%.

UAV Aerial Photography Data: Field surveys were conducted on July 20, 2021, with clear skies and high visibility. A DJI UAV was used with a flight altitude of 100 m, side overlap of 70%, forward overlap of 80%, shooting angle of -90°, covering an area of 41,400 m^2 with a spatial resolution of 2.73 cm. After the flight mission, Argisoft PhotoScan software was used to process the aerial images and obtain orthophotos.

Digital Elevation Model (DEM): The DEM data were obtained from the Geospatial Data Cloud website with a spatial resolution of 30 m.

2.2 Research Methods

MESMA is a mixed pixel decomposition method that improves feature classification accuracy by extracting abundance values of various features within mixed pixels. The specific steps include: First, preprocessing multi-spectral imagery; then creating random sampling points based on NDVI results; extracting spectral values from vegetation, bare land, and water body sampling points; using MESMA in Python to decompose mixed pixels and extract typical feature information; calculating areas of three feature types based on pixel abundance; conducting object-oriented classification of higher-resolution UAV imagery; resampling and co-registering with Landsat pixels; using UAV classification results as reference "true" pixel abundance values; calculating goodness-of-fit between MESMA-derived vegetation and water abundance values and actual area proportions to validate the model; and finally performing unary linear regression trend analysis to determine change trends of typical features in Bosten Lake wetland.

2.2.1 Multiple Endmember Spectral Mixture Analysis (MESMA) Model

The MESMA model selects endmember combinations with the smallest least squares error to extract the percentage of different endmembers within pixels. This study selected three endmember combinations. Mixed pixel decomposition consists of two main steps: endmember determination and extraction, followed by mixed pixel unmixing.

Endmember Spectral Determination and Extraction: Endmember selection involves identifying feature types and quantities contained in mixed pixels as characteristic components, which directly influences component data accuracy in mixed pixel decomposition. When applying the MESMA model to Landsat imagery, selecting three endmember components is reasonable based on feature categories in the study area. According to NDVI results from Bosten Lake wetland remote sensing data and following the three-endmember modeling principle, we created random sampling points using the multi-value extraction method, obtaining 150 vegetation endmember points, 100 water body endmember points, and 100 bare soil endmember points.

The NDVI calculation formula is:

$$NDVI = \frac{R_{NIR} - R_{Red}}{R_{NIR} + R_{Red}}$$

where R_{NIR} and R_{Red} represent reflectance in the near-infrared and red bands of Landsat imagery, respectively.

Mixed Pixel Decomposition: This process analyzes spectral characteristics of mixed pixels to determine the percentage of each endmember (i.e., endmember abundance). MESMA employs multiple endmember spectra to decompose mixed pixels for each feature type. The most widely used method was proposed by Roberts et al. Model fitting quality is typically evaluated using Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{\lambda=1}^{S} \varepsilon_\lambda^2}{S}}$$

where S is the number of remote sensing image bands, λ is the band, and ε_λ is the residual for band λ.

2.2.2 Unary Linear Regression Trend Analysis

This study employed unary linear regression trend analysis to examine vegetation coverage changes temporally and spatially. The method combines vegetation coverage values derived from pixel decomposition with temporal changes to determine overall regional trends:

$$slope = \frac{n \times \sum_{i=1}^{n} i \times fvc_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} fvc_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where *slope* represents the linear fitting slope of multi-year vegetation coverage, n is the monitoring period, and fvc_i is the vegetation coverage in year i.

The linear fitting slope reflects vegetation coverage change trends and magnitudes in Bosten Lake wetland from 2000 to 2022. A positive slope indicates increasing coverage, while a negative slope indicates decreasing coverage. Larger absolute slope values represent more significant changes. Based on slope values, trends are categorized as: significant decrease (-0.040 to -0.003), slight decrease (-0.003 to 0.005), no change (0.005 to 0.014), slight increase (0.014 to 0.024), and significant increase (0.024 to 0.055).

2.2.3 Object-Oriented Classification Method

UAV imagery employs object-oriented classification methods, which are widely used in wetland classification. In this study, eCognition software was used for UAV image classification. The process involves fusing visible light imagery with DEM features, segmenting the imagery, selecting characteristic samples for classification, and performing supervised classification based on feature space distances and established classification rules.

2.2.4 Accuracy Evaluation

UAV Image Accuracy Evaluation: Before using UAV classification results to validate the mixed pixel decomposition model, we evaluated the accuracy of UAV object-oriented classification results. Key metrics include producer's accuracy, user's accuracy, overall accuracy, and Kappa coefficient:

$$\text{Producer's Accuracy} = \frac{P_{ii}}{P_i} \times 100\%$$

$$\text{User's Accuracy} = \frac{P_{ii}}{P_j} \times 100\%$$

$$\text{Overall Accuracy} = \frac{\sum_{i=1}^{n} P_{ii}}{N} \times 100\%$$

$$Kappa = \frac{N\sum_{i=1}^{n} P_{ii} - \sum_{i=1}^{n}(P_i \times P_j)}{N^2 - \sum_{i=1}^{n}(P_i \times P_j)} \times 100\%$$

where P_{ii} is the number of correctly classified samples in row i column i, P_i is the total number of verification samples for a certain class, P_j is the total number of verification samples for a certain class, n is the number of types, and N is the total number of verification samples.

Mixed Pixel Decomposition Accuracy Evaluation: UAV classification results were resampled and co-registered with Landsat imagery to obtain vegetation and water area proportions corresponding to Landsat pixels. These served as references to validate the accuracy of vegetation and water features extracted by the MESMA model.

3.1.1 UAV Classification Accuracy

After classifying UAV imagery, we quantitatively evaluated the accuracy of wetland feature information extraction. Based on visual interpretation, 1000 random sample points were selected for accuracy assessment (Table 1). The overall accuracy reached 97.09% with a Kappa coefficient of 0.95, demonstrating that UAV imagery classification results are reliable for validating mixed pixel decomposition accuracy.

3.1.2 Mixed Pixel Decomposition Accuracy

Based on MESMA-derived abundance values for vegetation, water body, and bare land components (ranging from 0 to 1, where higher values indicate greater feature proportion within the pixel), comparison with true-color imagery shows that vegetation, bare land, and water body types are more distinctly classified and reflect actual ground feature distributions. Using high-precision UAV classification results resampled as reference data, we evaluated the extraction accuracy of features after MESMA decomposition. The goodness-of-fit between MESMA classification results and UAV classification results was high, with R^2 of 0.84 for water pixels and 0.75 for vegetation pixels. This analysis confirms that the MESMA model meets accuracy requirements and can effectively classify different features in the study area, representing an ideal feature classification method.

3.2 Spatiotemporal Variation Characteristics of Typical Features in Bosten Lake Wetland

From 2000 to 2022, vegetation area in Bosten Lake wetland increased from 453.58 km^2 to 990.23 km^2, water area decreased from 1607.2 km^2 to 1011.44 km^2, and bare land area increased from 389.87 km^2 to 448.99 km^2. The variation characteristics differ across periods, with changes divided into three stages using 2007 and 2016 as boundaries.

Stage 1 (2000-2007): Vegetation area showed a significant increasing trend, growing from 453.58 km^2 to 854.12 km^2 (an increase of 400.54 km^2). Water area continuously decreased from 1607.20 km^2 to 1113.14 km^2 (a reduction of 494.06 km^2). Vegetation increased substantially in the northwestern lakeshore wetlands of the Great Lake region and northern part of the Small Lake region, while water area decreased significantly in the northwestern lakeshore wetlands of the Great Lake region, the southern narrow water zone of Bosten Lake, and the eastern edge.

Stage 2 (2007-2016): Wetland vegetation area dropped sharply from 854.12 km^2 to 489.93 km^2 (a decrease of 364.19 km^2). Water area surged from 1113.14 km^2 to 1419.86 km^2 (an increase of 306.72 km^2). Vegetation decreased substantially in the northwestern lakeshore wetlands of the Great Lake region and throughout the Small Lake region, with corresponding water area increases.

Stage 3 (2016-2022): Wetland vegetation area showed a significant increasing trend, growing from 489.93 km^2 to 990.23 km^2 (an increase of 500.3 km^2). Bare land area increased from 389.87 km^2 to 448.99 km^2 (an increase of 59.12 km^2). Water area continued to decrease from 1419.86 km^2 to 1011.44 km^2 (a reduction of 408.42 km^2). Vegetation increased significantly in the northwestern lakeshore wetlands of the Great Lake region and northern part of the Small Lake region, while water area decreased mainly in the northwestern lakeshore wetlands of the Great Lake region, southern Bosten Lake, and eastern shore, though showing an increasing trend in the northern part of the Great Lake.

3.3 Vegetation Abundance Change Trends in Bosten Lake Wetland

Trend analysis of vegetation abundance in Bosten Lake wetland reveals that areas with significant vegetation decrease (−0.040 to −0.003) account for 5.7% of the total area, mainly in the central part of the Small Lake region and the southern Aibila reed area at the water inlet. Areas with slight decrease (−0.003 to 0.005) account for 29.5%, including lakeshore wetlands along the northern and eastern shores of the Great Lake region. Areas with slight increase (0.014 to 0.024) and significant increase (0.024 to 0.055) account for 23.4% and 34.8% respectively, including the northwestern part of Bosten Lake wetland and the northern part of the Small Lake region. Areas with essentially no change account for 6.6%, primarily farmland and desert areas in the southern Great Lake region.

4 Discussion

Wetlands are crucial components of terrestrial ecosystems and indicators of climate change. Scientifically and accurately obtaining water body and vegetation information and understanding wetland change patterns are essential for ecological environmental protection. This study, based on the MESMA model, investigated the extraction accuracy of typical features in Bosten Lake wetland and analyzed their spatiotemporal variation characteristics. The results show that from 2000 to 2022, vegetation area in Bosten Lake wetland increased by 536.65 km^2 (183.14%), water area decreased by 595.76 km^2 (37.07%), and bare land area increased by 99.12 km^2 (25.42%). The spatiotemporal change trends of water bodies in Bosten Lake wetland exhibited alternating expansion and contraction patterns, while vegetation and bare land areas showed inverse relationships.

This study addresses the low classification accuracy caused by traditional methods ignoring mixed pixels. By introducing the MESMA model based on vegetation-water-bare land three-component models and extracting pixel abundance values, we resolved mixed pixel issues in medium spatial resolution remote sensing imagery classification. Validation against UAV imagery classification results showed high goodness-of-fit: R^2 of 0.84 for water pixels and 0.75 for vegetation pixels. The MESMA model employs different endmember combinations for different pixel types, improving classification accuracy. However, feature abundance extracted from mixed pixels cannot achieve precise boundary segmentation between features. Using extensive measured data to obtain dynamic water body information could further improve classification accuracy.

Overall increasing vegetation areas are located in the northwestern Huangshugou lakeshore wetlands and northern Small Lake region, while decreasing areas are mainly in the junction zone between Great and Small Lakes, central Small Lake wetlands, and the southern water inlet area of the Aibila reed region in northwestern lakeshore wetlands. First, local government ecological restoration projects have promoted wetland recovery. The National Development and Reform Commission approved the Bosten Lake water environment protection and management project in 2000. In 2011, the "Research and Engineering Demonstration on Comprehensive Water Environment Management and Ecological Restoration Technology in Arid and Semi-arid Regions" project was implemented, with Bosten Lake as the demonstration area. In 2013, Bosten Lake was listed among the first batch of 12 "ecological environment protection pilot" lakes in China. Through multi-level, multi-channel industrial structure adjustment and engineering/non-engineering measures to reduce pollution load and restore lakeshore wetlands, the lake's salinization trend has been effectively curbed, particularly in Huangshugou lakeshore wetlands.

However, the construction of the Great Lake-Small Lake separation dike and sluice gate, along with water transfer to the Tarim River, reduced water volume in the Small Lake region, causing reed wetland decline. Changes in reed wetland and water area in Bosten Lake show opposite trends, as reeds grow in shallow water where excessively high water levels restrict growth, consistent with findings by Chen and Maimaitihan. Human activities and climate change have both positive and negative impacts on Bosten Lake wetland. The Great Lake water area reached its maximum in 2005 due to catastrophic flooding in 2002. The Tarim River ecological water conveyance project in 2000 increased outflow from Bosten Lake, while decreased regional precipitation intensified drought frequency, and increasing agricultural irrigation area led to subsequent water area reduction, mainly along the Great Lake shores. In 2016, increased inflow from the Kaidu River combined with controlled outflow enabled rapid water area recovery. In summary, climate change and human activities jointly influence Bosten Lake wetland changes, with both positive and negative effects. Targeted effective measures based on specific spatiotemporal distribution characteristics and dominant influencing factors are crucial.

5 Conclusions

(1) The MESMA model employs different endmember models for different pixels, decomposing mixed pixels in remote sensing imagery and improving feature classification accuracy. Compared with UAV object-oriented classification results (overall accuracy 97.09%, Kappa coefficient 0.95), the goodness-of-fit for vegetation pixels is 0.75 and for water pixels is 0.84. Applying MESMA to Landsat series imagery is suitable for scattered arid zone wetlands, improving classification accuracy.

(2) From 2000 to 2022, Bosten Lake wetland vegetation area increased by 536.65 km^2 (183.14%), mainly in the northwestern Great Lake wetlands and northern Small Lake region. Water area decreased by 595.76 km^2 (37.07%), with significant reductions in northwestern lakeshore zones, southern Bosten Lake, and eastern shores, though showing an increasing trend in the northern Great Lake. Bare land area increased by 99.12 km^2 (25.42%), mainly in the northern Great Lake region.

(3) Vegetation trends show 30.6% of the area increasing (mainly in northwestern wetlands and northern Small Lake region) and 34.6% decreasing (mainly in Small Lake region, northern Great Lake Huangshugou inlet, and eastern shore zones).

References

[1] Hui Weiwei, Yi Deping, Liao Caixia, et al. The study of decomposing mix element[J]. Forestry Science and Technology Information, 2007, 39(1): 2-3.

[2] Wu Jian, Peng Daoli. Wetland information extraction based on improved linear spectral mixture model[J]. Journal of China Agricultural University, 2011, 16(3): 140-144.

[3] Li Wei, Liu Weinan, Chen Guanbin, et al. Classification of Liaohe Estuary Coastal Wetlands based on image analysis with decomposition of mixed pixels[J]. Wetland Science & Management, 2017, 13(1): 25-28.

[4] Li Zhe, Gong Zhaoning, Liu Xianlin, et al. Vegetation coverage retrieval and spatio temporal distribution based on object oriented multi terminal mixed model[J]. Remote Sensing Technology and Application, 2018, 33(6): 1149-1158.

[5] Chen Yiyu, Lü Xianguo. The wetland function and research tendency of wetland science[J]. Wetland Science, 2003(1): 7-11.

[6] Tan Zhiqiang, Li Yunliang, Zhang Qi, et al. Progress of hydrological process researches in lake wetland: A review[J]. Journal of Lake Sciences, 2022, 34(1): 18-37.

[7] Ma Wei, Zhou Tianyuan, Jiang Yafang, et al. Protection status and future protection objectives of the wetlands in China[J]. Wetland Science, 2021, 19(4): 435-441.

[8] You Xiaobin, You Xianxiang, Xiang Yingying. Mixed pixel and mixed pixel analysis[J]. Journal of Beijing Forestry University, 2003(12): 28-32.

[9] Zhang Haonan, Wen Xingping, Xu Junlong, et al. Influence factors of decomposition precision of mixed pixels based on CLSMM[J]. Remote Sensing Information, 2019, 34(3): 48-53.

[10] Ma Mengli, Zhu Yan, Li Wenlong, et al. Extracting area information of paddy rice based on stratified multiple endmember spectral mixture analysis[J]. Transactions of the Chinese Society of Agricultural Engineering, 2012, 28(2): 154-159.

[11] Yang Chao, Wang Jinliang, Qu Liquan, et al. Research on the extraction of surface feature abundance based on the least square mixed pixel decomposition[J]. Science of Surveying and Mapping, 2017, 42(9): 143-150, 157.

[12] Wang Hao, Wu Bingfang, Li Xiaosong, et al. Extraction of impervious surface in Hai Basin using remote sensing[J]. Journal of Remote Sensing, 2011,

15(2): 388-400.

[13] Ding Jianli, Yao Yuan. Research on pixel unmixing of typical surface features in oasis based on the MESMA model[J]. Journal of Geo-information Science, 2013, 15(3): 452-460.

[14] Franke J, Roberts D A, Halligan K, et al. Hierarchical multiple endmember spectral mixture analysis (MESMA) of hyperspectral imagery for urban environments[J]. Remote Sensing of Environment, 2009, 113(8): 1712-1723.

[15] Liao Chunhua, Zhang Xianfeng, Liu Yu. Remote sensing retrieval of vegetation coverage in arid areas based on multiple endmember spectral unmixing[J]. Chinese Journal of Applied Ecology, 2012, 23(12): 3243-3249.

[16] Yan Xiaoxiao, Li Jing, Yang Zhen. Dynamic remote sensing monitoring on the temporal spatial changes of vegetation coverage in Chen Barag Banner from 2000 to 2016[J]. Journal of China Agricultural University, 2018, 23(6): 121-129.

[17] Liu Ying, Zhong Ruisen, Duan Yongchao, et al. Threshold of ecological water demands for the small lake wetland of Bosten Lake[J]. Arid Land Geography, 2021, 44(6): 1525-1533.

[18] Geng Renfang, Fu Bolin, Jin Shuanggen, et al. Object based karst wetland vegetation classification using UAV images[J]. Bulletin of Surveying and Mapping, 2020(11): 13-18.

[19] Maimaitihan Maierhaba. Dynamic monitoring and driving factors of Phragmites australis wetland in Bosten Lake[D]. Urumqi: Xinjiang Normal University, 2017.

[20] Jiang Leipeng, Ding Jianli, Bao Qingling, et al. Runoff estimation with low altitude remote sensing and satellite images[J]. Arid Land Geography, 2023, 46(3): 385-396.

[21] Zhang Ruijie, Li Lili, Li Li, et al. Rapeseed growth monitoring using UAV imagery[J]. Journal of Geomatics, 2021, 46(Suppl. 1): 227-231.

[22] Quintano C, Fernandez-Manso A, Roberts D A. Burn severity mapping from Landsat MESMA fraction images and land surface temperature[J]. Remote Sensing of Environment, 2017, 190: 83-95.

[23] Chen Ang. Desertification information extraction based on Google Earth Engine and UAV images: A case study of Zhenglan Banner, Inner Mongolia[D]. Beijing: Chinese Academy of Agricultural Sciences, 2020.

[24] Wang Junqi, Wang Guangjun, Liang Sihai, et al. Extraction and spatiotemporal analysis of vegetation coverage from 1996 to 2015 in the source region of the Yellow River[J]. Journal of Glaciology and Geocryology, 2021, 43(2): 662-674.

[25] Roberts D A, Gardner M, Church R, et al. Mapping chaparral in the Santa

Monica Mountains using multiple endmember spectral mixture models[J]. Remote Sensing of Environment, 1998, 65(3): 267-279.

[26] Chen Yuanpeng, Yun Wenju, Zhou Xu, et al. Classification and extraction of land use information in hilly area based on MESMA and RF classifier[J]. Transactions of the Chinese Society of Agricultural Machinery, 2017, 48(7): 136-144.

[27] Peng Yanfei, Li Zhongqin, Yao Xiaojun, et al. Area change and cause analysis of Bosten Lake based on multi-source remote sensing data and GEE platform[J]. Journal of Geo-information Science, 2021, 23(6): 1131-1153.

[28] Li Yujiao, Chen Yaning, Zhang Qifei, et al. Analysis of the change in water level and its influencing factors on Bosten Lake from 1960 to 2018[J]. Arid Zone Research, 2021, 38(1): 48-58.

[29] Maimaitihan Maierhaba, Rusuli Yusufujiang, Abudureyimu Anniwaer, et al. Dynamic variation of Phragmites australis wetland in the Bosten Lake Basin and its driving factors in recent 26 years[J]. Arid Zone Research, 2016, 33(4): 797-804.

[30] Kattenborn T, Javier F, Michael B, et al. UAV data as alternative to field sampling to map woody invasive species based on combined Sentinel-1 and Sentinel-2 data[J]. Remote Sensing of Environment, 2019, 227: 61-73.

[31] Liu Yaohui, Yu Xianghui, Fan Jiejie, et al. Rapid estimation of rural homestead area in western China based on UAV imagery and object oriented method[J]. Bulletin of Surveying and Mapping, 2022(6): 125-129.

Note: Figure translations are in progress. See original paper for figures.