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SPATIOTEMPORAL CHANGES IN COTTON GROWING AREAS IN XINJIANG (2000-2015)

JINQIU ZOU, SHI CHEN*, YINLAN HUANG AND QIANGUO XING

Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

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Abstract

Cotton planting is the important basis of local and national economic development. In this study, cotton growing areas were first regionalized according to environmental, social and economic conditions, and then an optimized model of extracting cotton growing area from MODIS data was constructed for each individual region. The method was used to map the cotton growing area in Xinjiang, over the past 16 years and to analyze the spatiotemporal changes in cotton growing area and the related environmental and socio-economic drivers behind these changes. The results show that: (1) the method of extracting cotton growing area has a high accuracy at a regional level with a determination coefficient R^2 of 0.983 for the linear correlation between the growing areas obtained from remote-sensing and statistical data; (2) the cotton growing area in Xinjiang showed an upward trend during the period of 2000 - 2015 with a major increase in southern Xinjiang, a substantial increase in the east, and a relatively smaller increase in the north; (3) the spatial pattern of change in cotton growing area in the southern Xinjiang Aksu and Kashi regions exhibited the most significant spatial expansion, followed by the Tacheng, and Bortala Mongol Autonomous Prefecture region in northern Xinjiang; and (4) from 2000 to 2013, the natural factors have little effect on cotton growing area changes. However, socio-economic factors, such as the agricultural output value, total power of agricultural machinery, and effective irrigation area, significantly affected the spatial and temporal changes in cotton growing area.

Introduction

Cotton is one of the main economic crops in Xinjiang, China and its development plays an important strategic role in the economic development of Xinjiang (Muhammad *et al.* 2015). Rapid and accurate estimation of cotton growing area, as well as its spatiotemporal changes and drivers underlying changes, provides the basis for decision making and management in the agricultural production sector, government departments, agricultural insurance industry, and on the farm.

Remote sensing provides a quick and efficient tool to identify cotton growing area over large areas (Liu *et al.* 2015a, Liu *et al.* 2015b). Several remotely sensed data have been used to extract the cotton growing area. For instance, Landsat TM and CBERS-1 images were widely used to monitor cotton growing area in Xinjiang (Yang *et al.* 2003, Cao *et al.* 2004). Identification and area extraction of different cotton varieties from ASTER images (Liu *et al.* 2005) expands the data combination characteristics of the multi temporal HJ satellite to achieve the extraction of cotton growing area by removing interference (Wang *et al.* 2012). NOAA, AVHRR, and MODIS data have been applied in studies aimed at extracting large-scale crop growing areas (Hame 1997, Zou *et al.* 2007, Becker-Reshef *et al.* 2010, Franch *et al.* 2015). In recent years, MODIS data have been widely applied in the field of large-scale remote sensing monitoring of crops. With the help of MODIS data, the cotton area extraction model for Xinjiang was established to obtain the spatial

*Author for correspondence: <shic11@126.com>.

distribution information for cotton growing area and growth (Huang *et al*. 2011). In addition, cotton growth monitoring using MODIS leaf area index can also better reflect the actual growth of cotton (Lv *et al*. 2004). Time series of MODIS EVI data is reconstructed to acquire the information for the extraction model of cotton with high precision (Hao *et al*. 2013). Therefore, MODIS data has become increasingly prominent in large-scale agricultural remote sensing monitoring. How to use MODIS data to analyze the interannual variation of cotton growing area and spatial pattern and to explore the reasons for its change is worth our further study.

Tremendous improvements have been made in the study of extraction and monitoring of cotton growing area and growth by MODIS; however, at the regional large-scale, it is lack of the continuous monitoring of cotton growing area with high temporal resolution. In this study, with MODIS 13Q1 16 day NDVI as the remote sensing data source, the cotton planting region in Xinjiang was divided into three different districts based on environmental and socio-economic differences to explore the relationship between cotton phenology/growth period and the corresponding NDVI in various cotton growing districts. An optimal model for remote sensing monitoring of cotton growing area was constructed in each district to extract the cotton growing area over the last 16 years. Furthermore, characteristics of the spatial and temporal evolution in cotton growing area were analyzed, and the main drivers of change in cotton growing area were assessed from the perspective of environmental and socio-economic factors by combining meteorological and agricultural data. Finally, relevant suggestions were proposed with the intention of ensuring the security of cotton supply and agricultural structural adjustment in China.

Materials and Methods

Xinjiang, located between 73°40′E - 96°18′E and 3425′N - 48°10′N, is selected as study area (Fig. 1). With an area of 1.66 million square kilometers, Xinjiang is the largest provincial administrative area in China. An alternating arrangement of basin and mountains in Xinjiang precludes climatic influences from the ocean, resulting in temperate continental climate, with arid climate, high levels of evapotranspiration, abundant sunlight, little rainfall, and a large range in temperature. Annual sunshine is around 2500 - 3500 hours, temperatures range between 0 and 50°C, and the average annual rainfall is about 150 mm with a relatively large discrepancy between different regions. The area of directly usable land for agriculture, forestry, and animal husbandry in Xinjiang is 0.69 billion hm², accounting for more than 1/10 of the land area in China. Xinjiang reserves cultivated land of 0.015 billion hm², ranking first in China, providing a large growing area for cotton.

Large imaging range and high temporal resolution are the characteristics of MODIS medium resolution imaging data, providing a rare, inexpensive, and practical data resource for remote sensing monitoring of cotton growing area. The MODIS 13Q1 data was downloaded from the National Aeronautics and Space Administration (NASA) with a spatial resolution of 250 m × 250 m, a temporal resolution of 16 days (https://ladsweb.modaps.eosdis.nasa.gov), and a time dimension of 81 - 321 volume each year during 2000 - 2015. The pre-treatment, including image mosaic, data format, projection conversion, and maximum value composite, was performed using software (MODIS Reprojection Tools, MRT) to complete an image space mosaic and re-sampling. The HDF format was converted to TIFF format and the SIN (Sinusoidal) map projection was converted to Albers Equal Area Conic/WGS84 projection to obtain the NDVI index data sets for Xinjiang since 2000 by utilizing the administrative boundaries in Xinjiang.

Precipitation and air temperature and other meteorological data of Akesu and Tacheng during 1970 - 2013 were downloaded from the Chinese meteorological science data sharing service network (http://data.cma.gov.cn), and were processed using a replacement of missing values, test of abnormal values and abnormal time values (Cao *et al*. 2008, Chen *et al*. 2014), and data homogeneity test for quality control to establish the meteorological element database for Akesu and Tacheng.

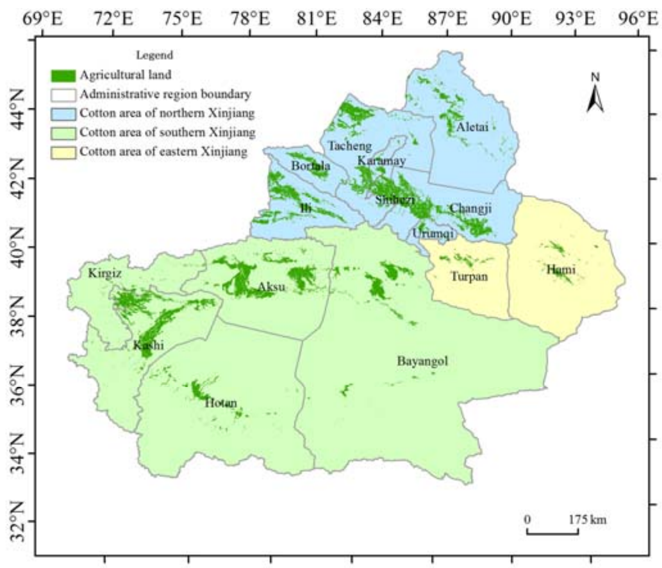

Fig. 1. Overview map of the cotton growing districts in Xinjiang.

The data of agricultural land in this paper is derived from the Globe Land30 product and the data interpretation time is 2010 (Chen *et al*. 2014 and 2015, Xing and Hu 2016).

Statistical yearbook data was based on the Xinjiang statistical yearbook, downloaded from the Statistics Bureau of Xinjiang Autonomous Region website (http://www.xjtj.gov.cn/). According to the statistical yearbook data over the years (CSY 2015), relevant data, such as agricultural investment, agricultural production, total power of agricultural machinery, effective irrigation area, etc. were downloaded and organized to establish the statistical database of Xinjiang during 2001 - 2015.

Due to the outstanding geographic and climatic variations in Xinjiang, there might be some errors in the estimation of cotton growing area by remote sensing. Therefore, to accurately interpret Xinjiang cotton and to improve the extraction accuracy of cotton growing area, we combined the average temperature, accumulated temperature, frost free climate conditions, geographical differences, crop phenology, and growing patterns and distribution in Xinjiang to scientifically divide it into northern Xinjiang, southern Xinjiang, and eastern Xinjiang cotton growing area. The administrative region in the northern Xinjiang cotton growing area includes Aletai, Tacheng, Mongolia Bortala Autonomous Prefecture, Ili Kazak Autonomous Prefecture, Changji Hui Autonomous Prefecture, Urumqi City, Karamay City, Shihezi city. The administrative region in southern Xinjiang cotton growing area includes Aksu Prefecture, Kashi, Hotan, Kirgiz Autonomous Prefecture, and Bayangol Mongol Autonomous Prefecture. The administrative region in eastern Xinjiang cotton growing area includes Turpan and Hami (Fig. 1).

The advantage of MODIS 13Q1 NDVI remote sensing data in the monitoring of cotton over large scales and long time periods is clear; however, the resulting NDVI data showed irregular fluctuations because of the large amount of noise from the mutual reflection of objects, interference from clouds, atmospheric aerosol, as well as sensor and data transmission failure, which all contributed to interfere with the identification of cotton crops. Thus, a smoothing and filtering process of the NDVI data is required to reflect the real growth characteristics and patterns of phenology change of the cotton crop.

The Harmonic Analysis of Time Series uses the spatial and temporal characteristics of the remote sensing image to connect its spatial distribution and temporal variation. Firstly, the amplitude and phase of non-zero frequency are obtained by Fourier transform; then, all the points are fitted with the least two square method and to compare the observed data and the fitting curve. For those points that are significantly below the fitting curve, they are regarded as the point of cloud contamination and rejected as participating in the fitting of the curve by assigning their weights as zero. Based on the remaining points, the new curve fitting is carried out. The reconstruction of the image is realized by the iterative process. As shown by the shape of the curve (Fig. 2), the smoothed curve is closer to the original value when the harmonic number is 3 (Zuo *et al*. 2008, Hou *et al*. 2010).

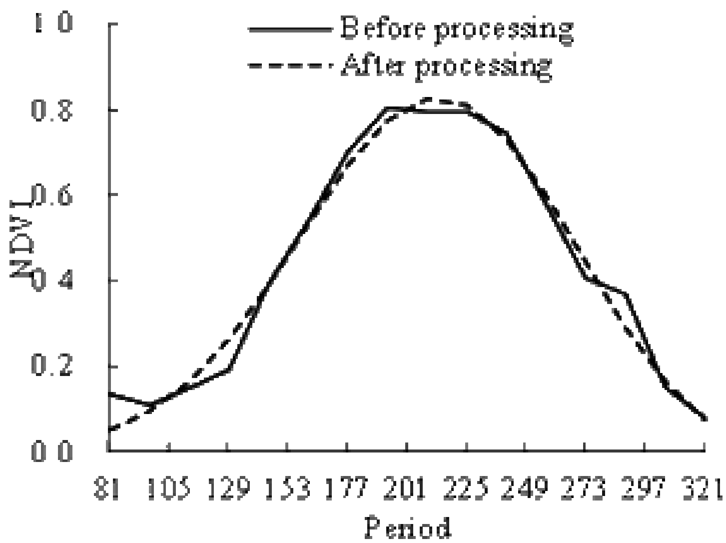

Fig. 2. NDVI curve change growth chart with Harmonic Analysis of Time Series.

Cotton is mostly planted in April in Xinjiang with emergence around late April, trefoil and the five-leaf stage in mid-May, budding in early June, the blossom peak stage in late July, bell cracking stage in late August, and the end of the growth period in early October. The NDVI index was relatively low from the growing stage to emergence stage, but the index increased significantly during the rapid growth of cotton in the budding stage. The NDVI index reached its peak in the period from the blossom stage to bell cracking stage, which was followed by a decrease with the reduction of chlorophyll content in cotton leaves. With analysis of the corresponding relationship between the phenological calendar/growth period/NDVI vegetation index and phenology (Fig. 2), several key phases of remote sensing data for the spatial information of cotton growing area were obtained from the MODIS data to establish the extraction model for the cotton growing area.

In the study area, if the pixel value simultaneously meets the following criteria, $NDVI_{97} < V_1$, $NDVI_{113} < V_2$, $NDVI_{145} > V_3$, $NDVI_{209} > NDVI_{177}$, $NDVI_{209} > NDVI_{241}$, $NDVI_{225} > NDVI_{193}$, $NDVI_{225} > NDVI_{257}$, $NDVI_{289} > V_4$, $NDVI_{321} < V_5$, then the pixel is classified as cotton. In the model, $NDVI_x$ represents the NDVI value of different phases, showing an NDVI value of 16 days in 81–321 days. V_1–V_5 represents the cutoff for different NDVI growth periods. On the basis of the phenological growth pattern in northern, southern, and eastern Xinjiang, and the influence of natural and human factors, we combined the statistics data of cotton growing area at county level to adjust the identification of cotton NDVI period and threshold. Satisfying results were achieved for cotton identification based on the above model. The decision tree classification rules built in ENVI 5.1 were used to obtain the grid map of the cotton growing area in the study region via post-processing by classification.

Results and Discussion

The statistical data of cotton growing area at county level from 2000 to 2015 were collected, and, the statistical data of 55 county-level cotton growing areas were used to verify the interpretation accuracy of the cotton growing area. The root mean square error (RMSE) and mean relative error (MRE) were used to analyze remote sensing interpretation precision (Jin *et al*. 2014). Table 1 shows that the goodness of fit between the remotely detected cotton area and cotton growing statistical area at the county level are high in the northern, southern and eastern Xinjiang, R^2 are 0.806, 0.800 and 0.938, respectively. The RMSE in each partition is not significantly different. The RMSE in the eastern Xinjiang is 1.737 × 103hm^2, and the errors in the northern and southern Xinjiang is 8.895 × 103hm^2 and 8.940 × 103hm^2. Shown by the MRE and precision, the accuracy of remote sensing monitoring in each area is high, which is above 93%. From the analysis with the remote sensing interpretation of cotton growing area, it can be seen that the goodness of fit R^2 of the whole area is 0.789, RMSE and MRE are 8.839 × 103hm^2 and 4.641% respectively, and the overall accuracy reaches 95.389%. After the cotton growing area is partitioned, the cotton growing area extraction model can be used to interpret the growing area of Xinjiang, and the recognition accuracy in the remote sensing of cotton growing area is high.

Table 1. Accuracy analysis on remote sensing monitoring of the cotton growing area.

Districts	R^2	RMSE (10^3hm^2)	MRE (%)	Accuracy (%)
Northern Xinjiang	0.806	8.895	2.99	93.001
Southern Xinjiang	0.800	8.940	3.183	96.817
Eastern Xinjiang	0.938	1.737	0.136	99.864
Whole district	0.789	8.839	4.641	95.389

Cotton growing area in northern Xinjiang, southern Xinjiang, eastern Xinjiang and Xinjiang overall all exhibited an increase in cotton growing area during 2000 - 2015. Of these, southern Xinjiang showed the most significant increase in cotton growing area with a determination coefficient R^2 of 0.675 and a maximum increase rate of 230.734%. Cotton growing area in eastern Xinjiang also showed a substantial increase ($R^2 = 0.604$) a maximum increase rate of 211.750%.

The increase in northern Xinjiang was relatively small ($R^2 = 0.578$) a maximum increase rate of 177.080%. However, the increase of cotton growing area in Xinjiang overall for the past 16 years was significant ($R^2 = 0.662$) a maximum increase rate of 210.684% (Fig. 3), Xinjiang cotton industry development is more rapid.

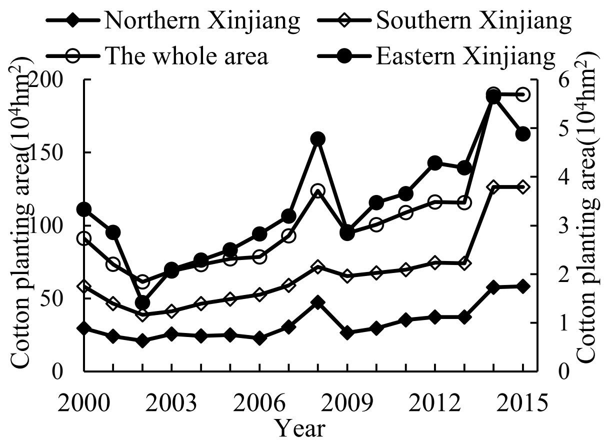

Fig. 3. Cotton growing area estimated by remote sensing in different districts (2000 - 2015). (Eastern Xinjiang line belongs to the second y axis)

To study the spatial variation in cotton growing area in Xinjiang, the years of 2000, 2010, and 2015 were selected as time fractions for analysis of the spatial variation of cotton growing area based on development planning in Xinjiang and national agricultural economic policy (Li *et al*. 2014). In 2000, cotton-growing areas were mainly located in Shihezi, Akesu, and Kashi (Fig. 4a). Cotton growing spread to the Bayangol Mongolia Autonomous Prefecture in 2005 (Fig. 4b), but the cotton growing area in Hotan and Kashi declined. In 2010, growing areas in Akesu, Bayangol Mongolia Autonomous Prefecture, Hotan Prefecture, Kashi, and Tachen increased considerably (Fig. 4c). In addition, the growing area in all districts in Xinjiang showed a significant increase with the greatest growth occurring in the Bortala Autonomous Prefecture of Mongolia, Shihezi, Akesu, and Hotan In 2015, (Fig. 4d).

Statistical analysis of these four time periods 2000, 2005, 2010 and 2015 demonstrated that Akesu and Kashi in southern Xinjiang exhibited the most significant change in growing area during 2000 - 2015, with an increase of 395.9 thousand hectares and 305.7 thousand hectares, respectively, an increase by 198% for both areas. A large increase in cotton growing area was observed in Tacheng and Bortala Mongolia Autonomous Prefecture of northern Xinjiang during the past 16 years, with increases of 124.3 and 89.0 thousand hectares and rates of increase of 117.72% and 278.08%, respectively. The spatial variation of cotton growing area in the different districts suggested southern Xinjiang is the main region for cotton development in Xinjiang, while the northern region is a supplement.

Analysis of the spatiotemporal variation characteristics of the cotton growing area in Xinjiang revealed a obviously change of cotton growing area in both southern and northern Xinjiang cotton growing regions during the past 16 years. To discuss the drivers of spatiotemporal variation in both cotton-growing districts, we mined the related literature and identified the environmental factors affecting cotton growing, including precipitation, temperature, sunshine, and topography. In addition, the impact of socio-economic factors in cotton cultivation was mainly reflected in agricultural investment, agricultural production, the total power of agricultural machinery, and effective irrigation area. From a socio-economic and environmental perspective, the Akesu area in southern Xinjiang and the Tacheng area in northern Xinjiang served as characteristic research units to examine the major drivers of spatiotemporal variation in both cotton growing area.

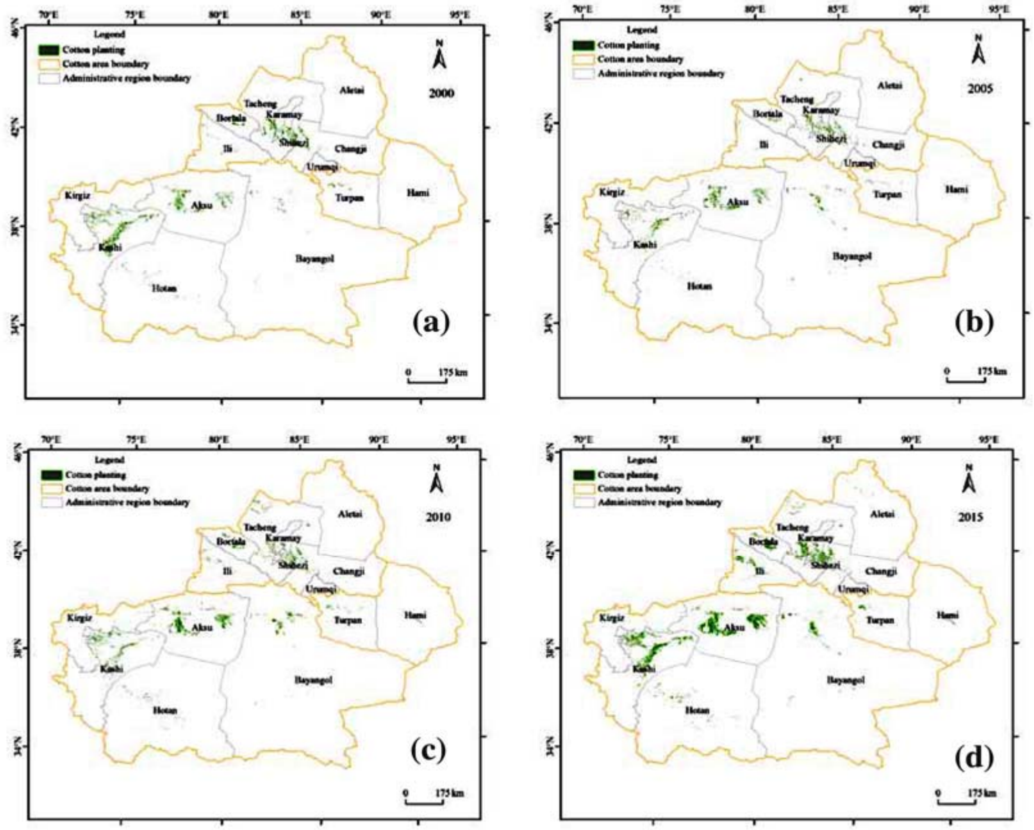

Fig. 4. Spatial distribution of cotton growing area by remote sensing monitoring.

Since the cotton growth process is sensitive to influences from temperature and precipitation, the aridity index (AI) and the standardized precipitation index (SPI) were used to assess the effect of these climate factors on cotton growing area (Chen *et al*. 2015). The AI reflects the degree of dryness of the cotton growing area for a certain period of time. The AI in the Akesu area and the Tacheng area during 2000 - 2013 was calculated by an empirical formula (Chen and Zheng 2008). It was found that the AI of the two areas did not change significantly and had little effect on the cotton growing area.

The SPI not only reflects water availability for cotton during the growth period, but also explains the change of groundwater. The SPI in the Akesu and Tacheng areas during 2000 - 2013 was obtained using the monthly rainfall data from 1970 - 2013. The variation patterns of SPI in the two areas were similar over the past 14 years. Therefore, from the analysis of AI and SPI, the natural climatic conditions in the Aksu and Tacheng areas from 2000 - 2013 had little effect on cotton growth.

To investigate the influence of the AI and the SPI on cotton growing area in two typical areas, the correlation between cotton growing area and natural factors in Akesu and Tacheng areas was analyzed. The correlation analysis between cotton growing area and the AI, the SPI, showed that Aksu area was higher than that in Tacheng area, and the goodness of fit R^2 of cotton growing area and the AI, SPI was 0.336 and 0.431 respectively. The goodness of fit R^2 of cotton growing area and AI, SPI was 0.243 in Tacheng area. It shows that the cotton growing area in southern Xinjiang is more dependent on natural factors than northern Xinjiang. Comparing the AI and the SPI in two areas, it can indirectly reflect the influence of air temperature on cotton growth.

Socio-economic factors play an important role in the change in cotton growing. To evaluate the relationship between the change of cotton growing and socio-economic factors, we analyzed agricultural investment data, agricultural output value, total power of agricultural machinery, and effective irrigation area.

Agricultural investment data and agricultural output values showed that agricultural investments were volatile during 2000 - 2007 in both areas, while a significant difference was observed between the two areas in 2008. Agricultural investments in the Akesu area exhibited a steady improvement during 2008 - 2013, with a rate of increase rate of 321.66% (Fig. 5a), but agricultural investments declined in the Tacheng area (Fig. 5b). However, agricultural output values in both the Akesu and Tacheng areas showed a significant increasing trend, which is consistent with the increase in cotton growing area, indicating that cotton profits are important components of agricultural output value in both areas.

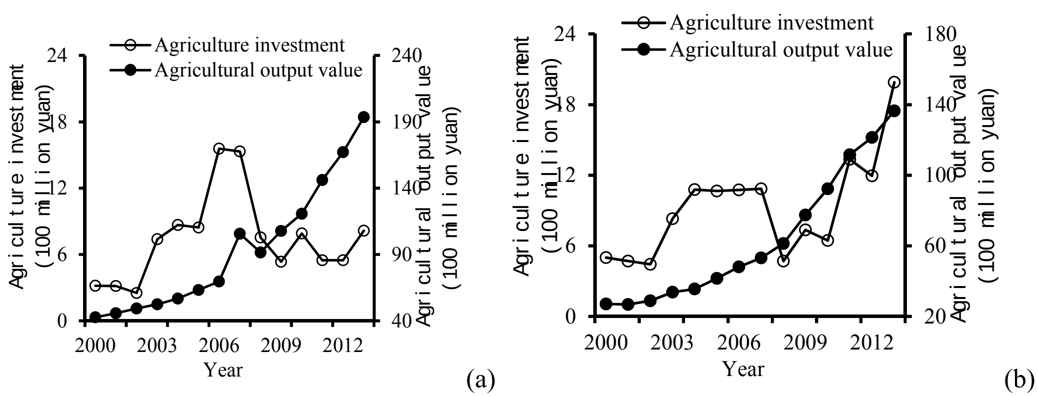

Fig. 5. Patterns of variation in agricultural investment and agricultural output values in the Akesu and Tacheng areas.

The total power of agricultural machinery and effective irrigation area has a great impact on cotton growing area. Analysis of these two aspects over the past 14 years showed that the total power of agricultural machinery and effective irrigation area were all elevated in both the Akesu and Tacheng areas, with a rate of increase in the total power of agricultural machinery of 214.38 %and 110.48% (Fig. 6a), respectively, and a rate of increase in the effective irrigation area of 53.24% and 56.57% for Akesu and Tacheng (Fig. 6b), respectively. Data on the cotton growing area in Akesu and Tacheng areas suggests a strong effect for the total power of agricultural machinery and the effective irrigation area on the expansion of cotton growing area.

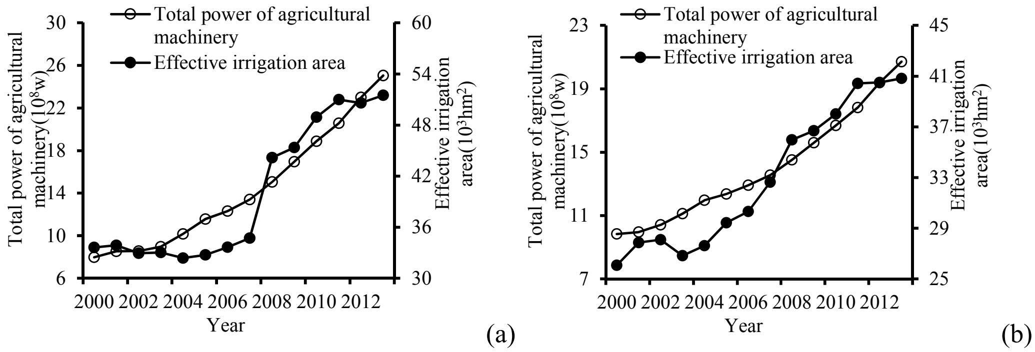

Fig. 6. Patterns of variation of the total power of agricultural machinery and effective irrigation area: (a) Akesu, and (b) Tacheng.

In order to study the impact of socio-economic factors, such as agricultural investments, agricultural output values, total power of agricultural machinery, and effective irrigation area on cotton growing area, the relationship between cotton growing area and different social factors in Akesu and Tacheng areas was evaluated with SPSS statistical software (Fig. 7). All social factors, except for agricultural investment, showed an extremely high correlation to cotton growing area in Akesu and Tacheng with a R^2 larger than 0.8. The correlation coefficient of the social factors, agricultural output value, total power of agricultural machinery, and effective irrigation area, and cotton growing area in Akesu area was higher than that in the Tacheng area. Although the correlation coefficient R^2 of the agricultural investment and cotton growing area was relatively low in both Tacheng and Akesu, the R^2 of Tacheng was higher than that of Akesu.

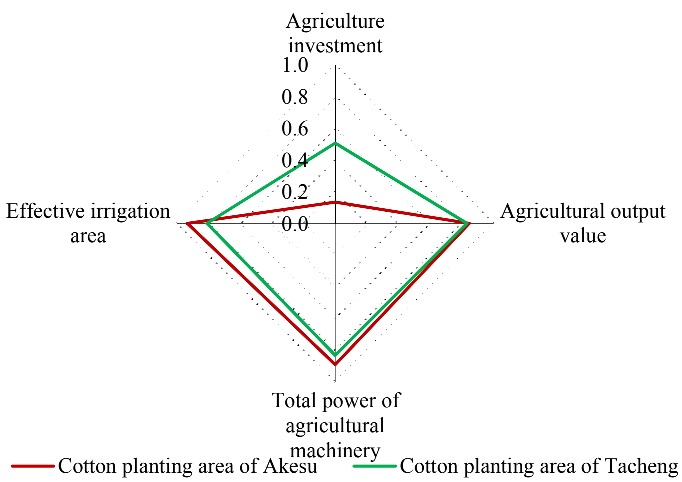

Fig. 7. Relationship between changes in cotton growing area and socio-economic factors in Akesu and Tacheng.

The relatively stable climatic conditions over the past 14 years played an important role in cotton growing area. The discussion of the association between the social factors and cotton growing area demonstrated that the agricultural output value, total power of the agricultural machinery, and effective irrigation area significantly influenced the spatio-temporal variation of cotton growing area.

In this study, the time series of MODIS 13Q1 data during cotton growth period in Xinjiang was used. According to the differences in cotton phenology, growing law and distribution in Xinjiang, the growing area of Xinjiang was divided into regions. According to the cotton growing area extraction model, the cotton growing area in Xinjiang is interpreted. Then according to the interpretation results from 2000 to 2015, the temporal and spatial variation characteristics of cotton growing area in Xinjiang were discussed. Finally, taking two typical regions of the Akesu and Tacheng as examples, the inter-annual change of cotton growing area and the spatial variation pattern in two regions were analyzed, and the reason of the change was analyzed. The following conclusions are made:

(1) 55 county-level cotton growing area data were acquired and used to verify the cotton growing area from remote sensing interpretation. With the 13Q1 MODIS data, a cotton growing area extraction model with high accuracy is obtained, and it is suitable for the identification of cotton growing area at the macro scale.

(2) Southern Xinjiang exhibited the most significant increase in cotton growing area during 2000 - 2015, and eastern Xinjiang also showed a substantial increase, while the increase was relatively small in northern Xinjiang.

(3) The Akesu and Kashi areas in southern Xinjiang experienced the most significant increases in cotton growing area, followed by the Tacheng area and Bortala Mongolia Autonomous Prefecture in northern Xinjiang, which indicats that southern Xinjiang is the main region for cotton industrial development with the northern Xinjiang as a supplement.

(4) The natural climatic conditions in the Aksu and Tacheng areas from 2000 to 2013 had little effect on cotton growth. However, agricultural output value, total power of agricultural machinery, and effective irrigation area had a substantial impact on the spatiotemporal variation of cotton growing area, which plays an essential role in cotton growth.

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