The Detecting of Irrigated Croplands Changes in 1987–2015 in Zhangjiakou

ZIJUAN ZHU1,2, ZENGGXIANG ZHANG1, LIJUN ZUO1, FEIFEI SUN1, TIANSHI PAN1,2, JUN LI3, XIAOLI ZHAO1, AND XIAO WANG1

1Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100093, China
2University of Chinese Academy of Sciences, Beijing 100093, China
3Zhangjiakou Academy of Agricultural Sciences, Zhangjiakou 075000, Hebei, China

Corresponding author: Lijun Zuo (zuolj@radi.ac.cn)

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ABSTRACT The distribution of irrigated and rained croplands has a large impact on agricultural production and ecological systems. Zhangjiakou, which is the water conservation area of Jing-jin-ji agglomeration and the host city for the 2022 Winter Olympic Games, has large irrigated croplands and a fragile ecological environment. The methods of sample selection based on spectral analysis and partitioned extraction of irrigated croplands were proposed with medium-high-resolution images, then the spatiotemporal changes of irrigated and rainfed croplands were explored in Zhangjiakou. The growing season time series curves of normalized difference vegetation index (NDVI) and normalized difference water index (NDWI) based on Landsat images were employed to distinguish irrigated and rainfed croplands in 1987, 2000, and 2015. Through transfer matrix analysis of the three stages of classification results, it was found that the irrigated croplands of Bashang, a semi-arid region, increased sharply (66025 hectares, 7.55%), while the irrigated croplands of Baxia, a mountainous region with small basins and plains, decreased slightly (~8239 hectares, ~0.60%). From the perspective of temporal changes, irrigated croplands grew rapidly in the early stage and slowly decline in the later stage, peaking at 377,117 hectares in 2000. According to the analysis, the decline of irrigated croplands was due to a project employed to quit irrigation and return to drought, and further analyses should be conducted in order to realize the rational utilization of water resources and guarantee ecological security. This paper is helpful in supporting extraction methods of irrigated croplands for semi-dry and arid areas, especially when historical samples are lacking. It is also helpful for policy adjustments of agricultural structure of Zhangjiakou and other similar areas.

INDEX TERMS Irrigated croplands, Zhangjiakou, spatial–temporal change, time series.

I. INTRODUCTION

In the same geographic unit, the yield of grain in irrigated croplands is more than twice that of rainfed croplands [1]–[3]. In the vast arid and semi-arid regions of northwest of China, irrigated croplands are the main source of food production [4], [5]. Therefore, the distribution of irrigated and rainfed croplands not only has huge impacts on agricultural production but also has a special impact on the rural economy. The effects of irrigated and rainfed croplands on the ecological environment vary greatly because of different cultivation methods, crop types, and production factors. Agricultural irrigation consumes more than 50% of the total water consumption [2], [6], which causes further water shortages in areas where resources are already scarce [7], especially in areas where surface water is scarce and there is a large dependence on groundwater for irrigation. For example, due to the excessive exploitation of groundwater, the shallow groundwater levels in Hebei and Beijing have generally decreased by 20 ~ 40 m in the past 30 years [8]. In addition, the average amount of fertilizer applied to irrigated croplands is approximately 6 times that of rainfed croplands, and the risk of water pollution increases as fertilizer moves with the water flow in the basin. Soil and water loss of cultivated land are further aggravated because of irrigation, especially flood irrigation and
overirrigation [9], [10]. In croplands, surface runoff (such as large-scale surface irrigation) can lead to water loss, soil erosion, and nutrient loss [11].

At present, due to the yield difference between irrigated and rainfed croplands, irrigation facilities are widely constructed, especially in the northwest arid and semi-arid areas of China [12]. At the same time, some scholars and governments have realized that irrigating too much croplands leads to imbalances in the local natural ecological conditions. Thus, local croplands have begun to adjust, such as overall reduction in irrigation croplands, in order to achieve sustainable agricultural development and harmony between economic development and the ecological environment. To sum up, there are large differences between irrigated and rainfed croplands in terms of grain yield, water resource utilization, soil and water pollution, and soil erosion. In order to shape suitable cropland structures in different regions and balance economic and ecological interests, it is necessary to clarify the current distribution pattern of irrigated and rainfed croplands. Currently, reliable monitoring methods of irrigated croplands in China, and around the world, are still not precisely determined, and spatial–temporal patterns still need to be studied.

As an important protective belt and water conservation area of the Jing-jin-ji region, Zhangjiakou provides ecological services for the Jing-jin-ji agglomeration. It is located in arid and semi-arid regions in China and agro-pastoral transition zone with a fragile ecological environment [13]. However, the irrigation expanded largely since recent decades, along with dramatic increases in pesticides and fertilizers use, leading to degradation of water environment. Irrigation has caused many serious problems to the fragile environment of Zhangjiakou [14]. In recent years, the return of irrigation to drought has been encouraged and accessed to certain achievements yet. Expanding and withdrawing of irrigated croplands in this region led a complex impact on the local economy and ecological security. However, there has been no reliable study on the temporal and spatial variation of irrigated and rainfed croplands helping for the future ecological conservation.

Remote sensing technology can acquire synchronous data over a large area efficiently and accurately thanks to the advantages of wide coverage areas, short revisit cycles, and objectivity [15]. Therefore, remote sensing technology has been widely used in land use and land cover studies [16]. Although more attention is paid to agricultural land, there is less attention paid to its subcategory, such as irrigated croplands, partly because irrigated and non-irrigated croplands are difficult to map and distinguish from remote sensing satellite images [17], [18]. Comparing land cover and land use, sizes of irrigated croplands are smaller which need higher resolution images for extraction.; and they mix with rainfed croplands and they contain diverse crops with different spectral signatures. Thus, most of the earlier spatial distribution maps of irrigated croplands are spatialized by statistical data [19]. However, calculations depend mainly on access to publications, online data collection, and field surveys, and this results in shortcomings such as lack of real-time data and deviations due to various statistical methods used in different countries and regions.

Since the 1990s, remote sensing data have been used to extract irrigated croplands information on a global scale. Based on remote sensing images and other data, the International Water Management Institute (IWMI) used an unsupervised classification method to obtain a global irrigation area distribution map [1]. Recent years, spatial and temporal changes of irrigated farmlands based on medium- and high-resolution images on local scale have been widely studied [20]–[23]. Although these studies use deep learning with high accuracy, they require large sample sizes and do not have information on time series changes. For the research of long time series, unsupervised classification is mostly used at present due to the lack of historical samples [23]–[25]. The more accurate classification method based on samples is rare. Collecting or generating samples from different periods and using supervised classification methods to extract irrigated croplands can improve the accuracy of irrigated land change extraction.

The studies of irrigated cropland patten began later in domestic China, and the researches were not real spatialization. The data analysis and dynamic analysis were just based on the area data of administrative districts [26], [27]. Remote sensing technology was explored to distinguish irrigated farmlands in the later. Existing researches pay more attention to major grain producing areas and staple crops on a large scale. Thus, they focus on large-scale irrigated area extraction, rather than small irrigated fields extraction. For example, Zhu et al. obtained the distribution of irrigated land in China in 2000, but the resolution was only 10 km and 1 km [28]. Afterwards, some researchers did that work using MODIS, and improved the resolution to 250m, but it was still not enough [1], [29], [30]. We also noticed that Digital Global Map of Irrigation Areas (GMIA) Version 5 has been updated in 2013 with 5 arc-minute resolution [31]. They still failed to distinguish small irrigated plots. In fact, irrigated plots are always mixed with rainfed plots, especially in a small-scale peasant economy that follows traditional agricultural planting practices [32]. Irrigated croplands are far less than the area of each pixel (250m*250m), so higher-resolution data are needed to meet the actual demand when zoom into local studies [33], [34]. In local scale, the extraction of irrigated farmlands can usually acquire a high precision. Vegetation water supply index and temperature drought index were used to achieve high accuracy of 85.3% and 89.7% [35]. These research focuses on the extraction method of irrigated farmlands and the distribution of that time. Some researchers have begun to pay attention to changes in the total amount of irrigated farmlands, but they pay less attention to the changes of its spatial patten [36]. The existing changes analysis were almost based on the statistical data [37]. However, the studies of its spatial patten changes are beneficial to optimize the distribution of irrigated and rainfed croplands according to
the local ecological environment characteristics, and they can help balance the environmental and economic benefits.

In this study, we developed methodologies based on decision tree for classification of irrigated croplands and rainfed croplands. Samples were developed by the indexes features of time series when there was lack of historical data. Based on this, we investigated the temporal-spatial patterns of irrigated croplands and rainfed croplands in 1987, 2000, and 2015 in Zhangjiakou. Driving forces of the changes were also discussed to offer implications on future development of sustainable agriculture, as well as management of water resources and economic policy making.

II. STUDY AREA AND DATA

A. STUDY AREA

Zhangjiakou is in the northwest of Hebei Province (FIGURE 1). It is bordered by Beijing in the southeast and Inner Mongolia autonomous region in the north and northwest. It occupies the boundary zone between arid and semi-arid regions in China and is staggered with agricultural and animal husbandry zones with a fragile ecological environment [14], [38]. Zhangjiakou is classified in the temperate continental monsoon climate zone where summer is hot with concentrated precipitation. The region is crossed by Yanghe River and Sanggans River, and it is divided by the Yinshan Mountain crossing the central area into Bashang in the northwest and Baxia in the southeast. Bashang is on the southern edge of the Inner Mongolia plateau, and this subarea is notable for its low temperature, rich light resources, and dryness because of the low precipitation and high evaporation [39]. Vegetables, potatoes, and sunflowers are mainly planted in large-scale irrigation croplands of Bashang, which is irrigated by drilling groundwater, while naked oats, flax, and green maize are always planted in rainfed croplands by traditional household farmers. Baxia, which belongs to the North China plain, contains the Taihang Mountain range with small basins in the mountains. Compared with Bashang, Baxia is generally lower in elevation and latitude, which contributes to more precipitation and higher temperatures. In Baxia, corn is widely planted, and sunflowers, orchards, rapeseed, and vegetables are raised locally [40], [41]. Thus, in this paper, Zhangjiakou was divided into Bashang and Baxia subareas depending on the distinct natural geographical conditions and long-term agricultural practices.

Zhangjiakou has witnessed rapid socio-economic development in recent years because it has provided a large number of agricultural products, of which most are grown in irrigation croplands for the Jing-jin-ji city agglomeration, and it is known as a “vegetable basket” [34], [42]. Since 1987, Zhangjiakou’s irrigation croplands have increased by 45%, of which 78% is contributed by the arid and semi-arid ecological function zones of Bashang whose irrigation area has increased by 425% in the study period [43], [44]. At the same time, a surge in irrigation has led to water shortages, since irrigation water accounts for 68% of the city’s total, of which about two-thirds comes from groundwater [45], [46]. Research on the extraction methods of irrigated croplands in this region would be better extended to other regions because of the complexity and diversity of agriculture and environment.

B. DATA INTRODUCTION

Landsat data: Croplands in Zhangjiakou are small patches, and irrigated and rainfed croplands always interact with each other. Thus, mid-high-resolution images are needed to identify irrigated or rainfed croplands. Therefore, Landsat data (30 ×30 m) were selected. Landsat images whose track number is 12332/12431/12432/12531/12532 from the 1985-2017 growing season (May to September) were used for the extraction of irrigated farmlands. 1987/2000 and 2015 were used as benchmarks. Pixels with abnormal values (blocked by clouds, etc.) would be instead by the pixels in the same position and period of adjacent years with valid value. The priority of the replacement was one year before, one year after, two years before, and two years after.

Gaofen (GF) images: GF images in 2015, including GF-1 (8M) and GF-2 (4m), were used to select samples of irrigated farmlands and rainfed croplands combined with field survey data.

Land cover data: Land cover data was the basis in this study. Irrigated farmlands and rainfed croplands would be further extracted from the farmland category. The land cover data was extracted from the national land use/cover database of China (NLUD-C, hereafter) at 1:100000 scale that contains Chinese land use/cover data of six periods (1980s, 1995, 2000, 2005, 2010 and 2015). It was visually interpreted from Landsat data using the natural law, the spectral characteristics of land use types and the prior knowledge of the Chinese Academy of Sciences. The accuracy is above 95% [47].

DEM data: DEM data is from Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation (ASTER GDEM). It would be used to generate slope data to assist the identification of irrigated and rainfed croplands. The spatial resolution is 30 m.
Field sampling data and questionnaire data: In order to collect samples of 2015, we did field surveys and collected 60 questionnaires from local farmers. Their texture features and location distribution were analyzed to help get more samples by visual interpretation from GF images. 1,651 samples in total (FIGURE 2) of 2015 were obtained randomly, including field investigation samples, visual interpretation results from GF-1 images (8 m × 8 m) and samples from 60 questionnaires. Among them, 116 (7% of all the samples) samples for irrigated croplands and 127 (8%) samples for dry croplands were used as training samples in Bashang; and 360 (22%) samples for irrigated croplands and 354 (21%) samples for rainfed croplands were used as training samples in Baxia. The remaining 694 samples (42%) were used for verification.

Statistical data: Statistical data is from statistical yearbook used for verification of classification results. The classification results of irrigated farmlands were verified by the county-level irrigated farmlands area proportion and the irrigated farmlands area proportion in sub-regions of each county calculated from statistical data in 1987, 2000 and 2015. Due to the lack of statistical data of 1987, the interpolation method was used to generate the data of adjacent years.

III. METHODOLOGY

In this paper, irrigated farmlands and rainfed farmlands would be distinguished from farmlands, and their spatiotemporal variation characteristics would be analyzed (FIGURE 3). After literature analysis and field investigation, the classification features were determined, and then the remote sensing images were processed to obtain the selected classification features. In order to obtain the samples of historical years, the samples of 2015 were analyzed to obtain the time series characteristics of irrigated farmlands and rainfed croplands in the selected classification features. The time series characteristics of the samples from irrigated rainfed croplands were used to select the samples in historical years, then we can classify the historical data and analyze the spatial–temporal changes of croplands pattern.

In order to obtain an effective classification method of irrigated rainfed croplands in historical years, the experiment was done using 2015 data first. After the samples of 2015 analyzed and the time series characteristics of irrigated farmlands and rainfed croplands obtained, the samples of 2015 were expanded using the sample characteristics obtained. Then part of the samples was selected for classification of 2015 data. To verify the validity and accuracy of the sample acquisition method and classification method, remaining field samples and statistical data were used. In addition, it would be compared with the classification accuracy using the original samples and the same classification method. Then, samples of irrigated farmlands and rainfed croplands for 1987 and 2000 were derived using the sample characteristics obtained. They were used in classification for 1987 and 2000 data respectively. Finally, statistical data were used to verify the classification accuracy of 1987 and 2000. In addition, we obtained different thresholds for Bashang and Baxia region because of the differences in natural and cultural conditions in these two regions.

A. CLASSIFICATION METHOD

1) FEATURE SELECTION

The essential difference between irrigated and rainfed croplands is soil moisture, but soil moisture is blocked by vegetation and is poorly reflected in remote sensing imageries. In addition, the moisture content of soil changes too fast to be captured by remote sensing images in time. Generally, soil moisture is closely related to vegetation growth and vegetation moisture content. Therefore, indexes reflecting vegetation growth and water indexes reflecting vegetation moisture content were used here [48]. For vegetation, NDVI is widely considered to be a good indicator of vegetation and is widely used because it is sensitive to chlorophyll [49]. NDWI is based on the normalized ratio index of middle infrared and near infrared bands. Compared with NDVI, NDWI can reflect the moisture content of the vegetation canopy effectively. When the vegetation canopy is under water stress, NDWI can respond in time, which is of great significance in drought monitoring [50], [51]. Knowledge was gained through field investigations in an area with similar geographical conditions, where crops are thicker in the irrigated croplands than rainfed croplands, especially in arid and semi-arid regions where precipitation is limited.

To calculate the NDVI, a series of processes were performed on the Landsat data. Radiometric calibration and quick atmospheric correction were carried out on the remote sensing images before correcting for geometric precision and cutting out black edges in each period. The real reflectivity values obtained using ENVI through radiometric calibration and atmospheric correction were relatively standard and comparable [18], [52], [53]. Then, the NDVI and NDWI of each image were calculated. Invalid NDVI and NDWI values were removed based on mask files made by the QA bands of Landsat images. Then, data from 1987/2000 and 2015 were used.
used as the benchmark, and values from adjacent years in the same period were used to supplement invalid values; the supplementary priority order was as follows: the year before, the year after, two years before, and two years after. Few data were missing after supplementing data of four years in the same period, and it was enough to meet the demand of extracting irrigated croplands. Finally, ten phases (two phases per month from May to September) of NDVI and ten phases of NDWI were combined into the characteristic remote sensing factor data as a time sequence to extract irrigated croplands. The formulas of NDVI and NDWI are as follows [49], [51]:

$$\text{NDVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}}$$  \hspace{1cm} (1)$$

$$\text{NDWI} = \frac{\rho_{\text{NIR}} - \rho_{\text{SWIR}}}{\rho_{\text{NIR}} + \rho_{\text{SWIR}}}$$  \hspace{1cm} (2)$$

where $\rho_{\text{NIR}}$ is the surface reflectance of near infrared band; $\rho_{\text{RED}}$ is the surface reflectance of red band; $\rho_{\text{SWIR}}$ is the surface reflectance of short-wave infrared band.

NDVI and NDWI time series curves of some samples were selected (shown in the FIGURE 4). Curves of rainfed cropland samples either have lower NDVI peak, such as line 4, 10, and 75, 73, or have higher peaks, but the duration of the high values is short, such as line 2, 12, 78 and 77. Compared with rainfed croplands, the higher value of irrigated land comes earlier and last for a longer time, basically with a duration of phase 4-8 in Bashang and 3-7 in Baxia. NDWI of rainfed croplands samples are relatively low and the higher values have a short duration, generally one phase, such as line 31, 32, 91 and 101. Irrigated cropland samples experienced the higher peak than rainfed croplands samples. In Bashang, some of them experienced longer time with high values, such as 57 and 54. Some have the higher peaks, such as 51, 56 and 60. In Baxia, the relative high value of the irrigated croplands lasted for phase 3-7, and the peak values are above 0.2 mainly. That is to say, the NDVI and NDWI values were higher, and these high values last longer in irrigated croplands compared to rainfed croplands. Thus, we chose the peak value of NDVI, duration of relatively high value of NDVI, peak value of NDWI, and duration of relatively high value of NDWI as the features used in extracting irrigated croplands [54]. Elevation and slope were also employed since irrigated croplands are only distributed on level ground and terraces located on the slopes according to investigation. We used this information to refine the results.

2) HISTORICAL SAMPLE SELECTION METHOD

The category characteristics were obtained through the samples analyzing of 2015, and the historical year samples were selected accordingly. Combined with field survey and GF-1 images (8×8 meters), a total of 1,651 samples were selected in 2015 to develop the methodology and conduct verification. Among them, 116 (7% of all the samples) samples for irrigated croplands and 127 (8%) samples for rainfed croplands were used as training samples in Bashang;...
and 360 (22%) samples for irrigated croplands and 354 (21%) samples for rainfed croplands were used as training samples in Baxia. The remaining 694 samples (42%) were used for verification. Variations in topographic, climatic, and economic situations were considered in choosing samples. Knowledge of characteristics of different types of cropland

FIGURE 4. NDVI and NDWI time series curves of some samples in Bashang in 2015.

FIGURE 5. NDVI and NDWI time series curves of some samples in Baxia in 2015.

Note: Time phase were sorted from May to September as twice a month. 1 means first half of the month and 2 means second half of the month.
was gained beforehand by analyzing the time-series curves of NDVI and NDWI in the growing season (from May to September). This knowledge was then used to select samples for 2000 and 1987. There are four steps:

Step 1. The NDVI and NDWI of every samples at each time phase in 2015 were extracted.

Step 2. These values were analyzed statistically, and the algorithm separating irrigated cropland and rainfed cropland was developed respectively for Bashang and Baxia.

The NDVI and NDWI time series curves of irrigated farmlands and rainfed farmlands samples in 2015 were statistically analyzed. As shown in FIGURE 6, FIGURE 7 and Table 1, 71.65% of rainfed croplands samples have zero or one occurrence of NDVI > 0.7, compared with 23.28% of irrigated farmlands samples. The probability of irrigated farmlands samples with two or more occurrences of NDVI > 0.7 was much higher than that of rainfed croplands. When the threshold value is 1, the difference between the two was the largest, so the occurrence of one or less times was classified as rainfed.

FIGURE 6. Sample Characteristics Analysis in Bashang in 2015.

FIGURE 7. Sample Characteristics Analysis in Baxia in 2015.
TABLE 1. Characteristics of samples.

| Index                     | Bashang          | Baxia            |
|---------------------------|------------------|------------------|
|                          | NDVI>0.7         | NDVI>0.65        |
| Occurrence times          | <=1              | <=2              |
| Irrigated croplands       | 23.28%           | 31.03%           |
| Cumulative percentage     |                  |                  |
| Rainfed croplands         |                  |                  |
| <=2                       | 35.34%           |                  |
| <=0                       | 19.83%           | 20.47%           |
| <=4                       | 23.44%           | 16.32%           |
| <=0                       | 16.32%           | 42.43%           |
| <=3                       |                  |                  |

croplands, while the occurrence of two or more times would be classified as irrigated farmlands samples. Some other critical features were also found as shown in TABLE 1. Therefore, taking the different characteristics of NDVI and NDWI into account, in Bashang, samples whose NDVI>0.7 appears more than once or NDVI>0.65 appears more than twice, and NDWI>0 appears more than twice or NDWI>0.2 appeared were considered as irrigated farmlands samples. In Baxia, samples whose NDVI>0.7 appeared more than 3 times or NDVI>0.6 appeared more than 4 times, and NDWI>0.2 appeared more than 3 times or NDWI>0 appeared from June to July, were considered as irrigated farmlands samples.

Step 3. In order to verify the sample selecting rule, classification accuracies using the samples selected by this rule and using the samples collected by field investigation in 2015 were compared. The classification method, validation samples and validation methods used in both classifications were the same shown in subsection 3 and 4.

Step 4. Use the above method to obtain samples of 2000 and 1987.

3) DECISION TREE CLASSIFICATION METHOD
According to the training samples of each stage, automatic decision trees were established on the synthesized data of each stage. A CART model was used to automatically generate a regression decision tree [55]. Thus, six decision trees of Bashang and Baxia in 1987/2000/2015 were preliminarily obtained, respectively. Then, irrigated croplands distributions of the three periods were extracted.

The preliminary results were further screened by DEM. The classification rule is: irrigated croplands are only located in the flat ground with less than 5 degrees or slop with 15-25 degrees (terraced fields may be built).

4) ACCURACY VERIFICATION
The results of 2015 were verified by a confusion matrix using the verification samples. Meanwhile, the results of 1987/2000/2015 were verified by statistical data. We adopted the county-level irrigated farmlands area proportion and the irrigated farmlands area proportion in sub-regions of each county statistical data to compare with the results. They were also evaluated by STDEV (Standard Deviation), R^2 (Coefficient of Determination) and RMSE (Root Mean Squared Error).

B. ANALYSIS OF SPATIAL AND TEMPORAL CHANGES
The statistical area of field type changes can only represent net changes in the area; it cannot reflect the changing direction of each type. So, the real situation of its changes cannot be reflected. Therefore, the transfer matrix analysis method based on system analysis will be used. This method can quantitatively describe system states and transitions [56]. The transfer matrix includes the transfer area and the transfer probability. The formula of transfer probability is as follows:

\[ P_{ij} = \left( A_{ij}/A_i \right) \times 100\% \]  
(3)

where \( P_{ij} \) is the change rate of class i to j from the start time to the end time; \( A_{ij} \) is the area of class i to j from start time to end time; and \( A_i \) is the area of class i at the start time.

The contribution rate is the proportion of one type converted to a certain type in the transferred area during the period. It can represent the transferred source for that certain type. The formula of contribution rate is as follows:

\[ R_{ij} = \left( A_{ij}/\sum_{i=1}^{m} A_{ij} \right) \times 100\% \]  
(4)

where \( R_{ij} \) is the contribution rate of changing from class i to class j during the studied period; \( A_{ij} \) is the area of class i to j during the studied period; \( m \) is the amount of class; and i \( \leq \) m, j \( \leq \) m, i \( \neq \) j.

IV. RESULTS
A. AVAILABILITY VERIFICATION OF SAMPLE SELECTING RULE
As the TABLE 2 shows, the two classification results (using original samples and selected samples by method in this paper) both have high precision with an overall accuracy above 80% and kappa coefficient above 0.64 in Bashang, and 89% and 0.75 for Baxia. Therefore, this rule was feasible to be used as the historical samples selecting method.

B. ACCURACY VERIFICATION OF HISTORICAL CLASSIFICATION RESULTS
The results showed that (FIGURE 9, TABLE 3), in 2015, only Shangyi, Huailai, Zhangjiakou, and Zhuolu had more than 10% difference in the proportion of irrigated croplands to the total cultivated area of the county. The maximum standard deviation was 0.16, and the mean standard deviation was 0.054. The maximum standard deviation of the irrigated croplands proportion of each county in the sub-area was...
In the results of the proportion of irrigated croplands in the total cultivated land in each county in 2000 (FIGURE 9, TABLE 3), only one counties’ gap was larger than 20%. The maximum standard deviation was 0.155, and the average standard deviation was 0.058. The largest standard deviation of the irrigated croplands proportion of the sub-area was 0.074 in Kangbao. The mean standard deviation of these values was 0.021. Verification of 1987 only contained three values whose distance from the statistical data was more than 10%, and the mean standard deviations of the two groups were 0.036 and 0.031, respectively. According to the R² (0.905, 0.914, 0.795, 0.648, 0.752 and 0.849) and RMSE (0.068, 0.098, 0.095, 0.077, 0.045, and 0.033) of these six sets of data, the classification results using this method are very close to the statistical data. Thus, the results could be considered desirable.

To sum up, the verification results including the confusion matrix in 2015 and comparisons between the statistical yearbook and classification results in 1987, 2000, and 2015 showed that the classification method could achieve a high accuracy, especially in the historical years when there was a lack of field survey samples. This demonstrated that reliable classification results can be obtained.

We also compared our results (2000) with GMIA v5 which reflects the irrigation percentage from 2000 to 2008 (FIGURE 8) [31]. Though the resolution of GMIA and our results is different, we compared the distribution patterns of these two products. According to GMIA, irrigated croplands of Zhangjiakou are mainly distributed in Yanghe River Basin, the vicinity of the Guanting Reservoir and the low-lying flat areas of the southwest (Wanquan, Zhuangjiakou, Xuanhua, Huai’an, Huailai, Yangyuan, Yuxian and Zhuolu) and scattered in Bashang. It is consistent with our results.

As FIGURE 10 and FIGURE 11 show, the irrigated croplands of Zhangjiakou are largely distributed in the small intermontane basin in Baxia. Only a small part of irrigated croplands was in Bashang, especially in 1987. In 2015, there was 85,482 hectares of irrigated croplands in Bashang, accounting for a minor proportion (only 9.82%), while Baxia had 908,113 hectares, accounting for 29.06% of the cultivated land. In 2000, there was 75,589 hectares of irrigated croplands in Bashang, accounting for 8.75%, among which the irrigated area in Zhangbei was the largest, accounting for 34.91% of the irrigated area in Bashang. In this period, it reached 273,415 hectares in Baxia, accounting for 30.11% of the total cultivated land. The least irrigated area of Bashang was during the first period, merely 19,457 hectares accounting for only 2.27%, mainly concentrated in Zhangbei, whereas the data of Baxia in this period were close to that of the next two periods. Overall, the irrigated croplands of Bashang had no obvious spatial aggregation and were relatively scattered and interlaced with rainfed croplands. Contrarily, the irrigated croplands of Baxia had a very conspicuous spatial aggregation, mainly concentrated in the central area around the Yanghe River basin and in the vicinity of the Guanting reservoir (concentrated in Wanquan, Huai’an, Zhuangjiakou, Xuanhua, Zhuolu, and Huailai), showing a large area of contiguous distribution. Irrigated croplands were also distributed in the low-lying flat areas of the southwest (Yangyuan and Yu counties), while in the mountain area of the northeast (Chicheng, Chongli) merely a few of them were distributed along the gully.

As TABLE 4 and TABLE 5 show, from 1987 to 2000, the area of croplands in Zhangjiakou remained stable. The rainfed croplands decreased by 84,386 hectares(5.53%), while the irrigated croplands increased by 83,069 hectares(28.25%). The rainfed croplands were mainly converted into irrigated croplands, reaching 179,192 hectares with a conversion rate of 11.74%. It was more obvious in the southwest of Kangbao, the north of Shangyi, and the middle of Guyuan. At the same time, expansion of irrigated croplands mainly occurred near the original irrigated areas in Baxia. In addition, there was some expansion of irrigated croplands in the southwest (Chongli County and Yu County). There was 99,225 hectares(33.74%)of irrigated croplands converted to rainfed croplands in all. Irrigated croplands were
TABLE 3. Comparison of classification results and statistical data.

|                | The proportion of irrigated croplands to the total cultivated area | The irrigated farmland proportion in Bashang or Baxia |
|----------------|---------------------------------------------------------------|-----------------------------------------------------|
|                | 1987 | 2000 | 2015 | 1987 | 2000 | 2015 | 1987 | 2000 | 2015 | 1987 | 2000 | 2015 |
|                | CR  | SD  | DP  | STDDEV | CR  | SD  | DP  | STDDEV | CR  | SD  | DP  | STDDEV | CR  | SD  | DP  | STDDEV |
| Guyuan         | 0.029 | 0.036 | 0.72% | 0.005 | 0.062 | 0.140 | 0.055 | 0.141 | 0.160 | 1.82% | 0.013 |
| Kangbao        | 0.010 | 0.019 | 0.87% | 0.006 | 0.100 | 0.098 | 0.011 | 0.060 | 0.097 | 4.62% | 0.033 |
| Shangxi        | 0.007 | 0.058 | 5.10% | 0.036 | 0.096 | 0.141 | 0.032 | 0.126 | 14.30% | 0.101 |
| Zhangbei       | 0.036 | 0.042 | 0.65% | 0.005 | 0.091 | 0.137 | 0.032 | 0.086 | 0.100 | 1.41% | 0.010 |
| Chicheng       | 0.042 | 0.164 | 12.21% | 0.086 | 0.110 | 0.220 | 0.078 | 0.081 | 0.040 | -4.10% | 0.029 |
| Chongli        | 0.072 | 0.110 | 3.86% | 0.027 | 0.080 | 0.187 | 0.075 | 0.079 | 0.140 | 6.07% | 0.043 |
| Huailai        | 0.459 | 0.425 | -3.39% | 0.024 | 0.392 | 0.453 | 0.028 | 0.420 | 0.380 | -4.00% | 0.028 |
| Huailai        | 0.319 | 0.479 | 16.00% | 0.119 | 0.501 | 0.528 | 0.019 | 0.446 | 0.553 | 10.68% | 0.076 |
| Wangquan       | 0.540 | 0.642 | 10.28% | 0.073 | 0.538 | 0.664 | 0.089 | 0.530 | 0.604 | 7.39% | 0.052 |
| Yangyuan       | 0.368 | 0.304 | -6.43% | 0.045 | 0.197 | 0.416 | 0.155 | 0.282 | 0.306 | 2.45% | 0.017 |
| Yuxian         | 0.265 | 0.252 | -1.29% | 0.009 | 0.263 | 0.340 | 0.055 | 0.275 | 0.182 | -9.24% | 0.065 |
| Zhangjiakou    | 0.448 | 0.482 | 3.41% | 0.024 | 0.388 | 0.472 | 0.059 | 0.364 | 0.590 | 22.62% | 0.160 |
| Zhuolu         | 0.406 | 0.377 | -2.92% | 0.021 | 0.481 | 0.543 | 0.044 | 0.387 | 0.492 | 10.57% | 0.075 |
| Xuanhua        | 0.377 | 0.424 | 4.76% | 0.034 | 0.379 | 0.510 | 0.092 | 0.338 | 0.255 | -8.34% | 0.059 |

- **R²**: 0.905 | 0.914 | 0.795
- **RMSE**: 0.068 | 0.098 | 0.095
- **STDDEV**: 0.036 | 0.058 | 0.054

Note: "CR" represents the abbreviation of classification results, "SD" represents the abbreviation of statistical data, DP represents the difference of proportion between SD and CR in TABLE 3.

hardly converted to rainfed croplands in Bashang, and this mainly occurred on the hills and mountains concentrated in Yangyuan County and Yu County. During this stage, some non-cultivated lands were converted to cultivated lands in the northeast, mainly in Guyuan and Chicheng (FIGURE 12).

From 2000 to 2015 (TABLE 4, TABLE 5), the net change area of rainfed croplands increased slightly, while irrigated croplands decreased by 21,294 hectares, accounting for 5.65%. Irrigated croplands widely transformed into rainfed croplands with a conversion rate of 44.17%, mainly occurring...
in the northwest of Bashang, Guyuan County, as well as the mountainous area of Baxia (FIGURE 12). The irrigated cultivated land of Bashang grew rapidly in the first stage, by 56,132 hectares (288.49%), but grew slowly in the second stage, by 9,893 hectares (13.09%).

Overall, as TABLE 4 and TABLE 5 show, from 1987 to 2015, the total amount of cultivated land remained stable, among which the rainfed croplands decreased by 69,688 hectares (4.78%), while irrigated croplands increased by 61,802 hectares, or (17.37%). In the former stage, the irrigated croplands increased sharply, and the rainfed croplands decreased generally. In the latter stage, irrigated croplands decreased, and the rainfed croplands increased slightly. During the entire study period, the conversion of rainfed croplands to irrigated croplands was 177,489 hectares, and the opposite was 111,669 hectares; conversion rate of the former was 11.63%, but the latter was as high as 37.97%. Combined with the transfer probabilities of rainfed croplands and irrigation croplands at 86.13% and 59.75% separately, irrigation croplands had poor stability, caused by the falling ground water level, reduction of surface runoff, or collapse of irrigation facilities (well, channels, etc.). In consequence, the ratio of its transformation to others was higher, at 42.35%, compared to 16.24% of rainfed croplands.

V. DISCUSSION
A. CLASSIFICATION METHOD
Differences in topography, climate, soil ponds, and economic and cultural levels often lead to differences in agricultural production activities. The distribution of irrigated and rainfed croplands is also influenced by the above factors. In order to more accurately explore classification methods of irrigated and rainfed croplands, many studies have developed regional-specific classification methods [57]. Annual precipitation, a key determinant in irrigation applications, was usually adapted in separating different regions used in irrigated croplands identification. Tingting Dong divided China into irrigation and supplementary irrigation areas with
an annual equal precipitation line of 280 mm, and irrigated croplands extraction was carried out in the supplementary areas [1]. Xie et al. [57] divided the study area into two regions by the degree of wetness. In this paper, the study area was near the border of arid and semi-arid areas of China, which includes complex and diverse topography and climate, so it could not be divided by a precipitation line only. In consideration of the regional climate, terrain, crop types, and farming practices, the study area was divided into Bashang on the Inner Mongolia plateau and Baxia in the north China plain [39]. According to the results, the spectral characteristics of irrigated and rainfed croplands in the two sub-areas were quite different: the crops in the irrigated croplands of Bashang had NDVI $>0.7$ twice or more per year, and the value in Baxia was three times or more. NDWI $>0.2$ appeared once a year or more for irrigated crops in Bashang, while it appeared three times or more in Baxia. The crop types are diverse in Bashang, but they are subject to water and heat resource restrictions, so mostly smaller plants such as vegetables, potatoes, naked oats, buckwheat, and flax are present. Therefore, NDVI values were considerably lower. Relatively speaking, NDWI was more differentiated in Bashang, whereas both NDVI and NDWI were strongly differentiated in Baxia due to the relatively uniform crop types. The classification results verified that the region division in this paper was necessary and reasonable.

Remote sensing data in a time series are the basis for extracting irrigated croplands according to crop phenology. Prasad et al. [58] used nearly continuous time series (8-day synthesis) MODIS land data from 2001 to 2002 for a
TABLE 4. Area and transfer probability of each type (ha).

|                      | 1987-2000 | Probability | 2000-2015 | Area     | Probability | 1987-2015 | Area     | Probability |
|----------------------|-----------|-------------|-----------|----------|-------------|-----------|----------|-------------|
| Non-cultivated land  | 1963370   | 96.16%      |           | 1966940  | 96.38%      |           | 1965360  | 96.35%      |
| Non-cultivated land to irrigated croplands | 67568 | 3.31% | 65595.4 | 3.21% | 65888.9 | 3.22% |
| Non-cultivated land to irrigated croplands | 10899 | 0.53% | 8287.4 | 0.41% | 8857.61 | 0.43% |
| Irrigated croplands to non-cultivated land | 71987.2 | 4.72% | 65675.7 | 4.56% | 69556.6 | 4.56% |
| Irrigated croplands | 1275140 | 83.54% | 1223370 | 84.90% | 1278440 | 83.76% |
| Irrigated croplands to irrigated croplands | 179192 | 11.74% | 151853 | 10.54% | 177489 | 11.63% |
| Irrigated croplands to non-cultivated land | 7796.14 | 2.65% | 14845.6 | 3.94% | 12875.7 | 4.38% |
| Irrigated croplands | 99225.5 | 33.74% | 166589 | 44.17% | 111669 | 37.97% |
| Irrigated croplands | 187065 | 63.61% | 195682 | 51.89% | 169536 | 57.65% |

TABLE 5. Rate of contribution of transfer type.

|                      | 1987-2000 | 2000-2015 | 1987-2015 |
|----------------------|-----------|-----------|-----------|
| Non-cultivated land to irrigated croplands | 40.51% | 28.25% | 37.04% |
| Non-cultivated land to irrigated croplands | 5.73% | 5.18% | 4.75% |
| Irrigated croplands to non-cultivated land | 90.23% | 81.56% | 84.38% |
| Irrigated croplands to non-cultivated land | 94.27% | 94.82% | 95.25% |
| Irrigated croplands to non-cultivated land | 9.77% | 18.44% | 15.62% |
| Irrigated croplands to irrigated croplands | 59.49% | 71.75% | 62.96% |

multi-time irrigated croplands extraction. Murali et al. [59] mapped irrigated croplands by MODIS 250 m time series data combined with vegetation phenology. In this paper, according to previous experience and combined with the growing season of local crops, the time series indexes of the annual growth season were used. Xie et al. [57] derived the annual maximum green rate and enhanced vegetation index by dividing Landsat images. Zhu et al. [28] believed that under the same regional conditions irrigated cropland crop yields are higher and more stable, so three irrigation potential indexes were developed by using time series NDVI and precipitation data. In this study, considering that the main restricting factor of vegetation is water, NDVI and NDWI were tested to reflect crop growth. It was also found that the duration of the two indexes with relatively high values had a good distinction through the spectral analysis. This is consistent with the conclusion of Zhu [28]. The results of classification verification also proved that the time series curves of NDVI and NDWI in the growing season could distinguish irrigated and rainfed crops well and achieve good classification results in regions where water is the restriction factor of vegetation growth.

B. EXTRACTION ACCURACY OF IRRIGATED CROPLANDS

The classification accuracy in this paper in 2015, in terms of the overall accuracy and the kappa coefficient at upper levels were comparable to some studies at local scale. The overall accuracy of irrigated croplands in the Indo-Ganges Basin, the map of which was drawn by Murali et al. [59] based on MODIS data with 250 m resolution, reached 73% and the kappa coefficient reached 0.71. Five countries in west Africa were classified by Samasse et al. [60] using GEE (Google earth engine) and a random forest model, and the accuracy of farmlands (rainfed and irrigated) types was 79%. Xie et al. [57] rapidly mapped irrigated croplands in the continental United States at a 30 m resolution, with an average Kappa value of 0.88 and an overall accuracy of 94%. In comparison, the slight precision gap may be partly due to the small patches, variety of crops, and a variety of terrain (especially the influence of the mountain) in Zhangjiakou. However, the above researches focus on the extraction of irrigated croplands with a large area. In addition, these study areas have flat terrain and single crop type. Further studies are needed to identify tiny patches in Zhangjiakou for better precision.

There are also some discrepancies when comparing with statistical yearbook data, mainly in Chicheng, Huai’an, Yangyuan, and Shangyi. Through the investigation, these discrepancies may come from the different parameters used for identifying irrigated croplands. Statistical yearbook data were collected according to whether there was irrigation, whereas in this paper, it referred to the fields fully irrigated [61]. Thus, some croplands with canals or wells in highlands and on slopes showed similar characteristics as rainfed croplands in the southwest mountainous area of Baxia and in western Bashang (Shangyi), as there was insufficient irrigation water for some years because of expensive costs. Consequently, the proportions of irrigated cropland in Shangyi, Chicheng, and Chongli in were slightly less than values in statistical yearbooks.

C. DRIVING FACTOR ANALYSIS

From 1987 to 2000, rainfed croplands decreased, while irrigated croplands increased. The rainfed croplands were mainly converted into irrigated croplands, mainly related to
the vigorous development of water conservancy projects during this period [62]. There were 127 reservoirs, 213 pumping stations and 12,822 wells in 1993 [63]. In addition, some non-cultivated and cultivated lands converted between each other. The conversion between cropland and other land use types was mainly due to the Grain for Green project and urbanization expansion. Meanwhile, grasslands and wetlands were the main sources of cropland expansion, accounting for 8667.67 and 3290.33 hectares respectively, because of the growth of the population, and food demand [32], [47]. The crop yield was improved a lot through dramatic increases in irrigating cultivated lands and water conservation projects in this stage [62].

From 2000 to 2015, the net change of rainfed croplands increased slightly, while that of irrigated croplands decreased. During this period, negative impacts of irrigated croplands were realized gradually by local governments, since the groundwater table decreased dramatically because of agricultural irrigation, and the policies of reducing irrigation and returning to rainfed croplands were gradually implemented [33]. In addition, the conversion of cultivated land to non-cultivated land was mainly due to the expansion of urbanization and population growth [64]. The urban population increased from 1.07 million to 2.31 million, and the urban land expanded by 26,480.89 hectares [32], [44], [62]. At the same time, most of the conversion from non-cultivated land to cultivated land was mainly sourced from grassland and wetland [14], [32]. The land pressure from urbanization and population growth eventually was transferred to wetlands and grasslands in this period.

In the entire period, the transformations of rainfed croplands into irrigated croplands and non-cultivated land into rainfed croplands were primarily seen in Bashang. In recent years, Bashang has vigorously developed large-scale vegetable planting and the yield reached 4,102,278 tons in 2015 [42], [44], [65]. According to surveys, the profit from irrigation vegetable planting is several times, or even more than 10 times. Therefore, a large cropland area is contracted and transferred to irrigated croplands. Because the main irrigation resource in this region is groundwater [66], the local groundwater level was seriously reduced, and the ecological security was threatened [46]. Recently, reversing irrigation and returning to drought has been proposed by the local government [67], and certain results showed 166589 hectares (44.17%) of irrigated croplands has been converted to rainfed croplands. However, the conversion of rainfed croplands to irrigated croplands is serious as well, with an area of about 151853 (10.54%) hectares. Non-arable land has been converted to rainfed croplands with about 65688 (3.22%) hectares, which primarily was in Bashang. According to land cover changes, grasslands and wetlands have been reclaimed as cultivated land, which is a considerable threat to ecological security [14], [68].

The irrigated and rainfed croplands in mountains in the southwest and north of Bashang were poorly stable. Most of the rainfed croplands in gullies were converted to irrigated croplands; meanwhile, many irrigated croplands were changed into rainfed croplands. The former may be due to the development of water conservation facilities (drilling wells, etc.) in recent years, while the latter may result from the falling ground water level, reduction of surface runoff [66], collapse of irrigation facilities (wells, channels, etc.), and the high price of water [69]. In the vicinity of Yanghe River and Guanting Reservoir, the irrigated croplands using rivers and reservoirs as the water source in the plain area of Baxia were relatively stable in the past 30 years because their water is stable enough. However, the absolute value of the conversion from rainfed croplands to irrigated croplands and non-cultivated land was greater than the reverse due to the low productivity of rainfed croplands, farmers’ willingness of waste croplands, the national policy of returning croplands to forest, the construction of water conservation projects, and the development of productivity and local large-scale planting industry. Only a few irrigated croplands were converted into non-cultivated land, and they were mainly converted into urban construction land according to the land cover data. This was related to the rapid urban population growth (from 0.77 to 2.31 million) and the rapid economic growth (GDP raised from 3.1 billion to 136.354 billion RMB) during the study period owing to China’s reform and opening up. From 1987 to 2015, the urban population increased from 0.77 million to 2.31 million, and the GDP rose from 3.1 billion to 136.354 billion RMB [44], [62].

VI. CONCLUSION
The aim of this paper was to develop a method to extract irrigated croplands with mid- to high-resolution images and to explore the spatio–temporal changes in Zhangjiakou. An effective classification method for irrigated and rainfed croplands based on Landsat images was obtained by studying the time series curves of NDVI and NDWI in the annual growing season. Furthermore, the spectral curve characteristics of irrigated and non-irrigated farmlands can be obtained by sample analysis. Samples selected from historical data depending on the spectral curve characteristics were used in classification, which can address the lack of sample data in historical years and obtain good classification results. This method can be extended to other areas in semi-arid and arid regions, especially in long time series studies of dynamic changes to irrigated and non-irrigated farmlands.

After analyzing the classification results of 1987, 2000, and 2015, it was found that the irrigated croplands of Bashang increased sharply, while the irrigated croplands of Baxia decreased slightly, with an overall increase of 17.37%. From the perspective of temporal changes, irrigated croplands experienced a rapid growth in the early stages and a slow decline in the later stages, peaking at 377117 hectares in 2000. According to the analysis, the main reason for the decline of irrigated croplands was the project to quit irrigation and return to drought, and this should be continued in order to realize the rational utilization of water resources and guarantee ecological security.
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