

## Article

# Monitoring and Analysing Land Use/Cover Changes in an Arid Region Based on Multi-Satellite Data: The Kashgar Region, Northwest China

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**Abstract:** In arid regions, oases ecosystems are fragile and sensitive to climate change, and water is the major limiting factor for environmental and socio-economic developments. Understanding the drivers of land use/cover change (LUCC) in arid regions is important for the development of management strategies to improve or prevent environmental deterioration and loss of natural resources. The Kashgar Region is the key research area in this study; it is a typical mountain-alluvial plain-oasis-desert ecosystem in an arid region, and is one of the largest oases in Xinjiang Uyghur Autonomous Region, China. In addition, the Kashgar Region is an important cotton and grain production area. This study's main objectives are to quantify predominant LUCCs and identify their driving forces, based on the integration of multiple remote sensors and applications of environmental and socio-economic data. Results showed that LUCCs have been significant in the Kashgar Region during the last 42 years. Cultivated land and urban/built-up lands were the most changed land cover (LC), by 3.6% and 0.4% from 1972 to 10.2% and 3% in 2014, respectively. By contrast, water and forest areas declined. Grassland and snow-covered areas have fluctuated along with climate and human activities. Bare land was changed slightly from 1972 to 2014. According to the land use transfer matrix, cultivated land replaced grass- and forestland. Urban/built-up land mainly expanded over cultivated and bare land. LUCCs were triggered by the interplay of natural and social drivers. Increasing runoff, caused by regional climate changes in seasonal variation, and snow melt water, have provided water resources for LC changes. In the same way, population growth, changes in land tenure, and socio-economic development also induced LUCCs. However, expansion of cultivated land and urban/built-up land led to increased water consumption and stressed fragile water systems during on-going climate changes. Therefore, the selection of adaption strategies relating to climate change and oasis development is very important for sustainable development in the Kashgar Region.

**Keywords:** arid region; LUCC; driving forces; snow index; SPOT VGT; Kashgar Region

## 1. Introduction

LUCC studies have emerged in research on global environmental changes via their interactions with climate, ecosystem processes, biogeochemical cycles, biodiversity, and human activities [1]. Therefore, for the last several years, numerous researchers have improved measurement of LUCCs by integrating environmental, human, and remote sensing/GIS science to answer various questions about LUCC and its driving forces [2]. Scholars believe the most common driving forces of LUCC have included population growth [3], human settlement and land tenure policy [4,5], changes in technology [6], culture [7], and political and economic changes [8]. Apart from that, climate-related

changes, such as rainfall variability [9], drought [10], and fire [11] were recognized as major LUCC drivers. While those research efforts have suggested that LUCC drivers differ depending on location, drivers remain contentious issues, and clearly their dynamics still requires analysis [12].

Located in the southwestern Xinjiang Uyghur Autonomous Region, China, the Kashgar Region is characterized by high mountains with snow/ice and an arid basin. Mountain uplift, westerly circulation, and the East Asian monsoon have determined its climate, creating a unique geographical unit—a mountain-alluvial plain-oasis-desert system. During the last half-century, rapid population growth and economic development have led to the modification of natural ecological processes. Increasing number of reservoirs and over-irrigation for cultivated land leads decreasing water flow in rivers by  $1.5 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ . Consequently, a 240 km distance in the Kashgar and Yarkant Rivers has dried up, leading to the desert area's expansion towards the north [13]. Over-cutting of desert vegetation and trees along rivers resulted in the activation of 80% sand, which is moving towards the oasis at a rate of 5–10 m/year [14], and the salinization area has expanded into 59.17% of arable land ( $3.38 \times 10^5 \text{ ha}$ ; [15]).

Water resources in the Kashgar Region depend mainly on snow melt from the mountain glacier, snow, and ice, which are major supply sources of surface runoff, ground water storage, and drinking water for the large population in this area. In the Kashgar Region, therefore, water is a major limiting resource, not only as a precious natural resource, but also as an important social factor for economic development [16]. Besides human activities, climate changes have also affected the hydrological cycle in the Kashgar Region. Global warming accelerates the process of atmospheric circulation and the hydrological cycle, subsequently affecting spatial and temporal distribution of water resources and exacerbating water shortages, especially in arid regions [17]. The occurrence of surface water in the Kashgar Region is strongly related to climatic, hydrological, and geomorphological factors.

In recent decades, increases in the Kashgar Region's social and economic activities and environmental changes have posed a great challenge to its sustainable development strategy, and extensive research has been conducted regarding this region. Anwaer et al. (2010) [18] analyzed total water uses in the Kashgar Region from 2001 to 2007. Results showed that agricultural water consumption increased most rapidly, from  $76.78 \times 10^8 \text{ m}^3$  to  $91.06 \times 10^8 \text{ m}^3$  during the six-year period. Anwaer et al. (2011) [19] also noted a significantly high correlation between urbanization and water utilization. Mansuer et al. (2011) [20] analyzed spatio-temporal dynamic changes of groundwater in the Kashgar Region, finding that cultivated land had been increasing continually, resulting in decreased groundwater levels midstream and downstream of the Kashgar and Yarkant Rivers, respectively. Rapid urbanization, socio-economic development, expansion of agricultural areas, and other anthropogenic activities played an important role in LUCCs. The Kashgar Region's arid environmental landscape has undergone tremendous LUCCs. However, the region's changes and drivers are not understood clearly. Most studies on the Kashgar Region have focused on individual factors, such as water stress [18,19], groundwater [20], and climate change [21]. However, few studies have shown that changes in climate and human activities have interacted over time to influence LUCC patterns in the region on different spatial and temporal scales. Therefore, this study's main objectives are to quantify LUCCs and to identify these changes' main driving forces. To achieve these goals, first LC maps are produced to provide a broad, synoptic perspective of land use measurements and mapping of environmental change. Then, investigation results of snow cover changes can strengthen knowledge of this region's water resources. Accumulation of snow cover and snow melt water are the main sources for rivers, groundwater recharges, and agriculture in the Kashgar Region. Finally, driving forces are identified based on integrated LC maps, snow cover monitoring, and environmental (temperature, precipitation, evaporation, and runoff) and socio-economic datasets (population, GDP, primary industry, and policy changes). This study's findings form a basis for a better understanding of the Kashgar Region's LUCCs and provide information to assist policymakers' decisions on future strategic management and sustainable development.

## 2. Materials and Methods

### 2.1. Study Area

The Kashgar Region, located in Northwest China, is in the southwest Xinjiang Uyghur Autonomous Region (Figure 1). The study area's administrative boundary lies within the range of  $71^{\circ}39' - 79^{\circ}52'$  E and  $35^{\circ}28' - 40^{\circ}18'$  N. Its administrative divisions include 11 counties and one city within a  $113,913 \text{ km}^2$  area. According to 2014 census statistics, the total population was 4,683,114; the non-agricultural population accounts for 22.23%, and the agricultural population accounts for 77.66% [22]. Three mountains surround the Kashgar Region: Tainshan Mountain to the north, the Kunlun Mountain to the south, and the Pamir peaks to the west, stretching to  $4.25 \times 10^4 \text{ km}^2$ . Water vapor from the Indian Ocean and the Arctic Cold Front has difficulty penetrating the area due to the high mountain barriers. Thus, the study area has a typical inner-continental climate, with annual precipitation of less than 100 mm and evaporation of higher than 2000 mm annually in the plain, while permanent snow and glaciers exist at higher altitudes. The study area consists mainly of the Kashgar River and Yarkant River Alluvial Plains. The water supply along the Kashgar and Yarkant Rivers depends mainly on glaciers and snow melt water from the mountains. The average annual surface runoff of the Kashgar and Yarkant Rivers is  $4.5$  and  $7.5 \times 10^9 \text{ m}^3$ , respectively [23]. Water from these rivers is used mainly for irrigation, groundwater recharge, and hydropower generation.

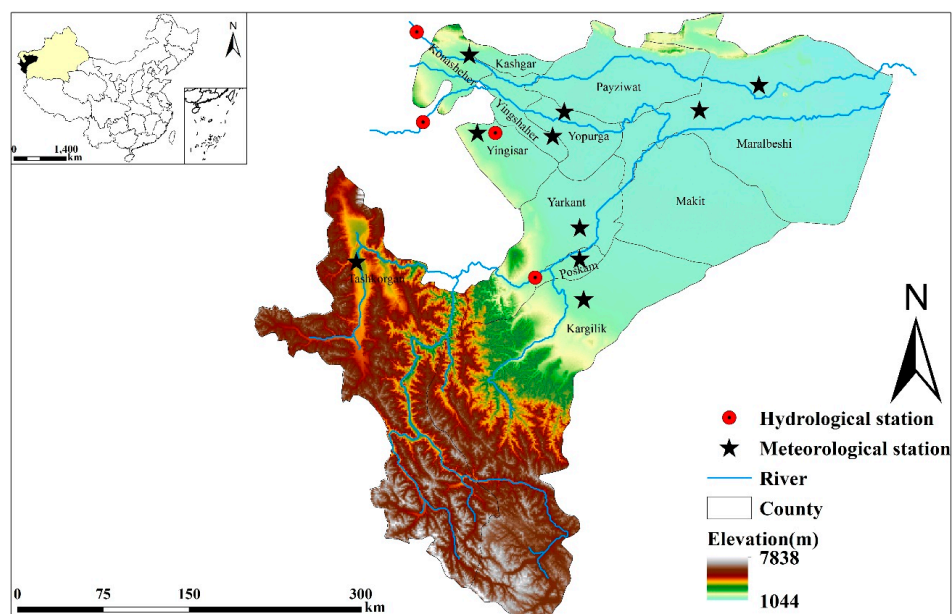


Figure 1. Location map of study area.

### 2.2. Data

In this study, we integrated the following different multi-spectral satellite images for LUCC analysis: Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), Operation Land Imagery (OLI), and VGTATION images on board the SPOT-4. We further used natural and social statistical datasets to identify LUCCs' driving forces. Table 1 summarizes the characteristics of these datasets.

**Table 1.** Datasets used in this study.

| Data Category  | Sensor       | Date   | Resolution      | Path/Row                           | Sources of Data                                  |
|--|--------------|--|-----------------|------------------------------------|--|
| Remote sensing data  | MSS          | 1972 (From June to October)  | 60 m            | P147R32~P149/35                    | USGS   |
|  | TM           | 1990 (From June to September)  | 30 m            | P147R32~P149/35                    |  |
|  | ETM+         | 2000 (From June to September)  | 30 m            | P147R32~P149/35                    |  |
|  | OLI          | 2014 (From June to September)  | 30 m            | P147R32~P149/35                    |  |
|  | SPOT-4       | 1 January 1999–30 May 2014   | 1 km            | 71°39′~79°52′ E<br>35°28′~40°18′ N | VITO   |
| Hydrological data (annual runoff)                                    | -            | 1964–2014  | Station data    | -                                  | Karbal, Kirik, Kaqung Stations                   |
| Meteorological data (annual temperature, precipitation, evaporation) | -            | 1964–2014  | Station data    | -                                  | Kashgar, Yarkant, Maralbeshi Tashkorgan stations |
| Statistical data   | -            | 1984–2014  | -               | -                                  | Xinjiang Statistical Year Book                   |
| Reference data   | Google Earth | 11 August 1972 Landsat<br>29 June 1973 Landsat<br>31 August 1990 Landsat<br>31 December 2000 Landsat<br>31 July 2013 Airbus<br>6 August 2013 Airbus<br>25 May 2014 Airbus<br>10 June 2014 Digital Globe<br>19 September 2014 Digital Globe |                 | P147R32~P149/35                    |  |
|  |              | GDEM   | 17 October 2011 | 30 m                               | P147R32~P149/35<br>USGS                          |

### 2.3. Methodology

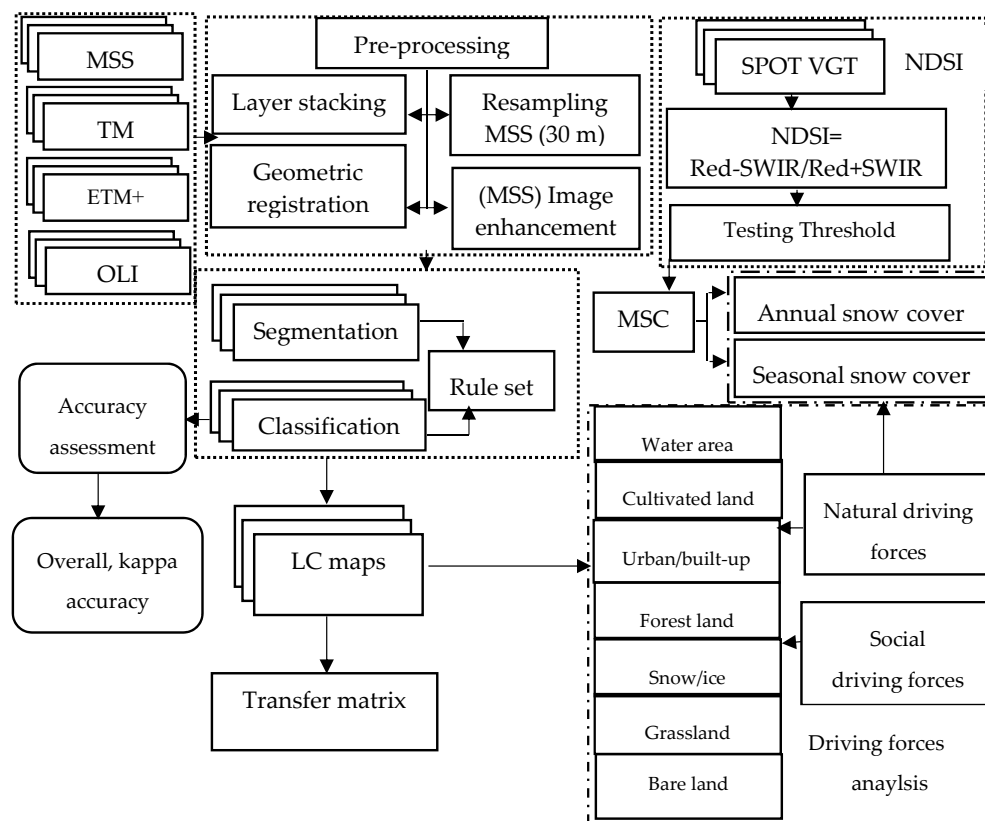
#### 2.3.1. Land Cover Mapping

Based on the study area's morphology and landscape, the possible appearance of LC types was considered to be 21 classes, and a hierarchical classification system of 21 classes was grouped into seven aggregated classes of LC: urban/built-up area, water area, grassland, cultivated land, forestland, snow/ice (considered only in summertime), and bare land. Table 2 provides detailed descriptions of each class. These classes' information was extracted using the maximum likelihood classification method combined with image segmentation (Figure 2). During summer seasons with cloud-free conditions, 48 Landsat images were acquired to map snow/ice and major LC types in the study area. Geometric correction was conducted by collecting for each image 40 well-conditioned ground control points, determined from topographic maps using ArcGIS. Root mean square (RMS) errors were less than 0.5 pixels for MSS (60 m), TM, ETM+, and OLI (30 m) images. MSS images were resampled to a 30 m cell size using the nearest-neighbor method. All images were geometrically corrected, with a reference system of a UTM map projection Zone 44 North on a WGS 1984 datum. In the initial step, we segmented band-stacked images into groups of pixels as objects. Homogenous pixel groups were created, which are called image objects, based on size, shape, and area. The multi-segmentation method utilized object-based classification because it generates objects very closely resembling ground features [24]. We implemented image segmentation using eCognition 9.0 to create objects that delineated LC classes. We applied two levels for the segmentation and classification process based on LC classes. Level 1 was applied for small and spread LC classes, such as grassland. The scale parameter was set at 5 [25]. Level 2 was applied for large LC classes, such as cultivated land, water, and bare land. The scale parameter was set at 10. Color and shape parameters were adjusted to 0.9 and 0.1, respectively [26]. After segmentation was completed, LC information was extracted with the maximum likelihood classification method [27]. Training sites were collected from original Landsat

data based on segmentation results, their different spectral features, Google Earth high-resolution images, and topographic maps, respectively. Because of the study area's high mountains' cloudy conditions during wintertime, collecting cloud-free Landsat images was difficult. Therefore, SPOT VGT imagery, chosen for mapping snow/ice cover due to its high temporal resolution and its maximum value composite (MVC) approach, helped minimized the effect of cloud cover [28]. The next section provides a detailed description of the snow/ice cover mapping process.

**Table 2.** Classification of land types in this study.

| Classes             | Definition  |
|---------------------|---|
| Urban/build-up area | Urban area, villages, industrial and commercial areas, transportation, communication and utilities    |
| Cultivated land     | Crop fields, cotton fields, vegetable lands, irrigated land, non-irrigated vegetation                 |
| Water               | All areas of open water, rivers, streams, channels, lakes, reservoir and ponds, bottomland, swampland |
| Grassland           | Dense grass, moderate grass, sparse grass,  |
| Forest              | Dense forest, scrubland, Sparse forest, orchards, groves, shrubland                                   |
| Snow/ice            | Glacier, snow, ice  |
| Bare land           | Desert, Gobi, salinized land, area of thin soil, rock, almost no vegetation cover                     |



**Figure 2.** Flow chart of methodology.

### 2.3.2. Snow Cover Changes

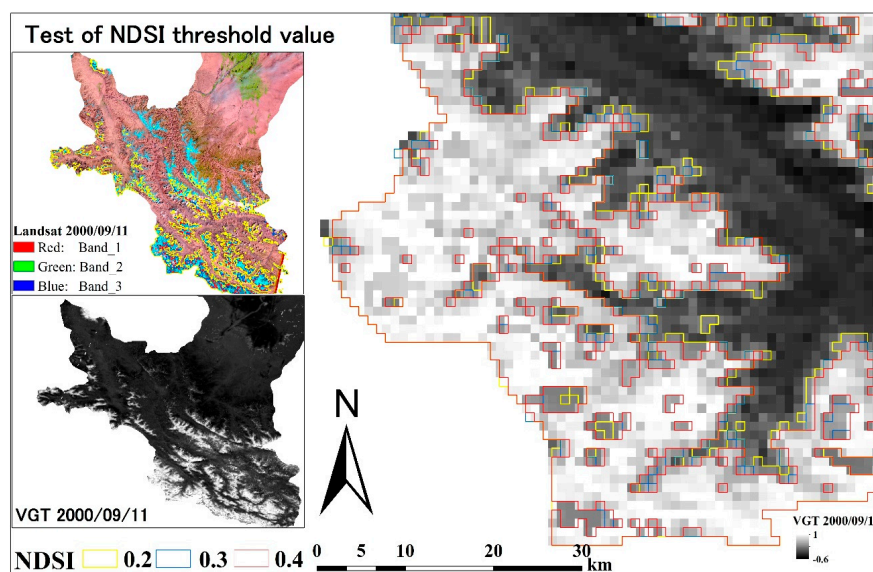
Investigation of snow cover changes was completed in two steps, including the selection of critical threshold values for Normalized Difference Snow Index (NDSI) and threshold values from the NDSI index for extracting snow and ice information. VGT data have four spectral bands: B0 (blue, 430–470 nm), B2 (red, 610–680 nm), B3 (near infrared, 780–890 nm), and SWIR (short-wave infrared, 1580–1750 nm). Three standard VGT available products are VGT-P, VGT-S1, and VGT-S10. We applied the VGT-S10 (10-day synthesis product) data for snow cover mapping in this study. There are three 10-day composites for 1 month: days 1–10, 11–20, and day 21 to the last day of the month by



MVC [29]. The NDSI takes advantage of difference in reflectance of snow-covered and snow-free areas in near infrared and short-wave infrared bands [30,31]. The NDSI was calculated as follows:

$$\text{NDSI} = (\text{Red} - \text{SWIR}) / (\text{Red} + \text{SWIR}), \quad (1)$$

where Red and SWIR are band 2 and band 4 of digital numbers of SPOT VGT, respectively [32]. To determine whether a pixel is covered by snow or not, an observed pixel must meet a certain NDSI threshold value. A threshold value of 0.4 has been used to distinguish snow from bright soils, rocks, and clouds [32]. Kondoh and Suzuki [33] in 2005 modified the 0.4 of NDSI threshold using an NDVI adjustment to take into account forest effects on snow detection in Northern Eurasia. In this study, the original threshold value of 0.4 underestimated snow-covered areas. Therefore, several threshold values of 0.4, 0.3, and 0.2 were tested for NDSI, and the best agreement was found with a slightly lower threshold value of 0.2 (Figure 3). The best agreement for snow and ice pixels extraction using VGT data should correspond to broad snow-cover characteristics of the local area. Thus, a lower threshold value of 0.2 was adopted for VGT snow and ice detection in this study area. Then, 567 stages for the entire duration of time-series VGT data were collected to investigate snow cover changes from 1 January 1999 to 30 May 2014. From first year of September to the next year of August, 36 images were composited, representing the annual maximum snow cover area. Then, we averaged the annual areas to determine the annual average extent of snow cover in square kilometers. Seasonal snow cover variation was calculated quarterly: spring (March, April, May), summer (June, July, August), fall (September, October, November), and winter (December, January, November).



**Figure 3.** Test results of different threshold value for the Normalized Difference Snow Index (NDSI).

### 2.3.3. Accuracy Assessment

In this study, the accuracy assessment of image classification used the stratified random sampling design. Reference points were created randomly from classified maps of the study area for 1972, 1990, 2000, and 2014. A total of 700 points were selected randomly (100 points for each class). The original Landsat and Google Earth images were used as reference sources to classify the selected points. The reference points were confirmed by visual interpretation of the reference source, which were the only available reference data for evaluating the accuracy assessment. Overall accuracy, user accuracy, and the Kappa coefficient were computed from error matrices.

### 2.3.4. Trend Analysis with the Mann-Kendall Test for Hydro-Climate Variables

Characteristics of hydro-climatic changes in the Kashgar Region were analyzed based on data collected at four meteorological stations and three hydrological stations for the period of 1964–2014. The Mann-Kendall (MK) test can assess trends in a time series without requiring normality or linearity [34,35]; it is highly recommended for use by the World Meteorological Organization [36]. Therefore, the MK trend test has been widely used to test for randomness against trends in hydrology and climatology [37]. This study also used the MK trend test method, adapted by Xu et al. (2013) [38] to analyze trends in precipitation, temperature, evaporation, and annual runoff.

## 3. Results

### 3.1. Land Cover Mapping

Results of overall accuracy ranged from 88% to 91% (Table 3), and standard overall accuracy for LC maps has been established at 85% [39]. Kappa coefficient values ranged from 0.86 to 0.90; users and producers' accuracy for individual classes ranged from 100% to 65%. The grassland and forest's lowest accuracy could be explained by the area's aridity and sparse vegetation, which led to confusion between these LC types. However, the visual comparison method between the original satellite images and LC maps showed robust classification accuracy.

**Table 3.** Accuracy assessment of land cover (LC) map for 1972, 1990, 2000, and 2014.

| Land Cover Classes | 1972            |                     | 1990            |                     | 2000            |                     | 2014            |                     |
|--------------------|-----------------|---------------------|-----------------|---------------------|-----------------|---------------------|-----------------|---------------------|
|                    | Users' Accuracy | Producers' Accuracy | Users' Accuracy | Producers' Accuracy | Users' Accuracy | Producers' Accuracy | Users' Accuracy | Producers' Accuracy |
| Urban              | 86%             | 67%                 | 100%            | 95%                 | 100%            | 91%                 | 100%            | 68%                 |
| Water              | 100%            | 78%                 | 97%             | 97%                 | 100%            | 88%                 | 100%            | 90%                 |
| Grassland          | 91%             | 91%                 | 88%             | 65%                 | 100%            | 69%                 | 100%            | 96%                 |
| Cultivated land    | 80%             | 97%                 | 89%             | 97%                 | 94%             | 100%                | 91%             | 100%                |
| Forestland         | 90%             | 60%                 | 76%             | 73%                 | 98%             | 91%                 | 87%             | 81%                 |
| Snow/ice           | 100%            | 100%                | 100%            | 100%                | 100%            | 94%                 | 100%            | 97%                 |
| Bare land          | 87%             | 100%                | 92%             | 100%                | 68%             | 100%                | 73%             | 100%                |
| Overall accuracy   | 88%             |                     | 93%             |                     | 93%             |                     | 91%             |                     |
| Kappa statistic    | 0.86            |                     | 0.92            |                     | 0.91            |                     | 0.90            |                     |

Each LC type's area changed significantly during the 42-year study period, as shown in Figure 4 and Table 4. Results indicate that cultivated land increased remarkably from 1972 to 2014, with its area reaching 11,677.5 km<sup>2</sup>. This cultivated area results were compared with the sown area of XJSYB of Kashgar Region—as Figure 5 showed, the correlation was 0.9. Increased cultivated land led to increased water consumption and utilization of water resources. Water area has consistently decreased from 2762.9 km<sup>2</sup> (2.4%) in 1972 to 1062.4 km<sup>2</sup> (0.9%) in 2014. The urban/built-up area increased from 40.2 km<sup>2</sup> (0.4%) in 1972 to 392.8 km<sup>2</sup> (3%) in 2014. Increased population is associated with urban and built-up land expansion. The urbanization level (as the proportion of total population residing in the state's urban areas) increased from 19.63% in 2000 to 22.76% in 2014 [22].

Mainly distributed from the southern mountain to the northern plain in the study area, grasslands decreased from 4779.1 km<sup>2</sup> (4.1%) in 1972 to 2680.6 km<sup>2</sup> (2.3%) in 2000. In general, rainfall variability is a key driver of grassland changes in arid regions. Therefore, monthly precipitation data was observed in 2000 and 2014, respectively (Figure 6). In contrast, conversion of grassland to cultivated land and over-grazing are other reasons for grasslands' decreasing on the plain (Table 5; [40]). However, by 2014, grassland had increased to 3302.5 km<sup>2</sup> (2.9%). This trend was related to increasing precipitation in 2014 and the grassland restoration program launched in 2003. Figure 6 showed high precipitation in 2014, compared with 2000. In addition, the grassland restoration program mainly focused on improving the richness of local plant species in grasslands and controlling the stock density. Therefore, grasslands increased after in 2000.

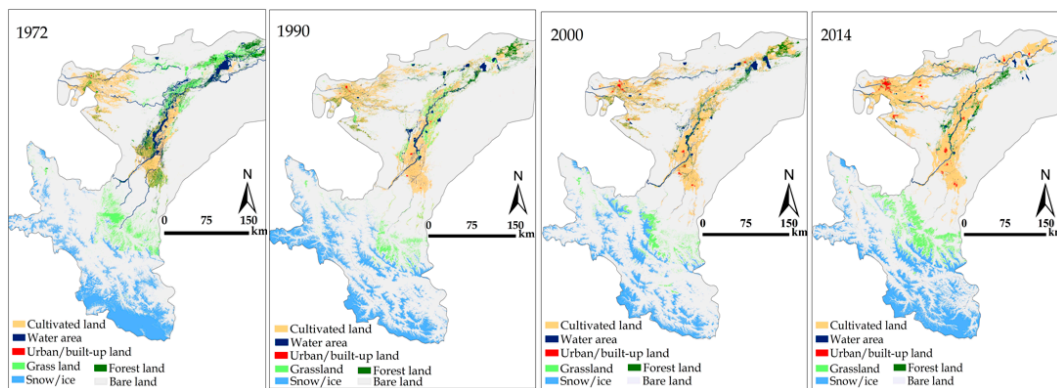


Figure 4. LC map of study area in 1972, 1990, 2000 and 2014.

Table 4. Results of land use/cover change (LUCC) statistics for 1972, 1990, 2000, and 2014.

| Year             | 1972                          |     | 1990           |     | 2000      |     | 2014      |      |
|------------------|-------------------------------|-----|----------------|-----|-----------|-----|-----------|------|
| Land Cover Class | Total Area (km <sup>2</sup> ) |     | Percentage (%) |     |           |     |           |      |
| Water area       | 2762.9                        | 2.4 | 1925.6         | 1.6 | 1291.2    | 1.1 | 1062.4    | 0.9  |
| Cultivated land  | 4148.6                        | 3.6 | 5991.4         | 5.2 | 6572.5    | 5.7 | 11,677.5  | 10.2 |
| Urban/Built up   | 40.2                          | 0.4 | 96.3           | 0.8 | 169.2     | 1.5 | 392.8     | 3    |
| Grassland        | 4779.1                        | 4.1 | 3701.3         | 3.2 | 2680.6    | 2.3 | 3302.5    | 2.9  |
| Forest land      | 3584.5                        | 3.1 | 2991.1         | 2.6 | 1545.7    | 1.3 | 1344.5    | 1.2  |
| Snow/ice         | 10,838.8                      | 10  | 10,789.5       | 9.4 | 8987.8    | 7.8 | 10,001.2  | 8.7  |
| Bare land        | 87,558.4                      | 77  | 88,417.0       | 77  | 92,665.5  | 80  | 86,131.7  | 74   |
| Total area       | 113,912.5                     | 100 | 113,912.5      | 100 | 113,912.5 | 100 | 113,912.5 | 100  |

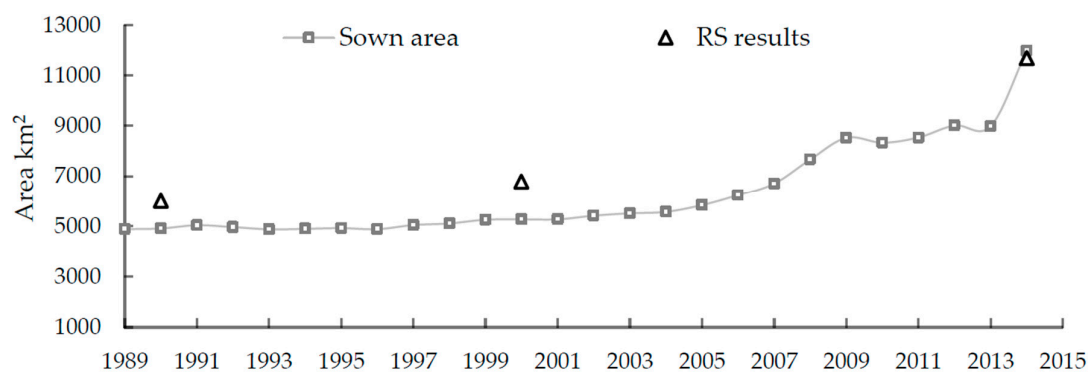


Figure 5. Sown area and remotely sensed (RS) estimated cultivated area comparison for Kashgar Region (sown area source [22]).

Conversely, from 1972 to 2014, forestland decreased from 3584.5 km<sup>2</sup> (3.1%) to 1344.5 km<sup>2</sup> (1.2%). Agricultural expansion was a key factor for forestland's reduction. Forest area has mainly been distributed around the study area's riverbanks, and it depends on groundwater resources, that is, groundwater seeping from a river. Therefore, forestland was easily converted into cultivated land due to abundant water resources for agricultural activity.

From 1972 to 2000, the area of snow/ice cover decreased slightly from 10,838.8 km<sup>2</sup> (10%) to 8987.8 km<sup>2</sup> (7.8%), but then increased to 10,001.2 km<sup>2</sup> (8.7%) in 2014. Overall, however, snow/ice cover shows a decreasing trend. Based on the First and Second Glacier Inventory of China, the glacier area in the Kashgar Region has shrunk by 927 km<sup>2</sup> due to global warming [41].



Bare land was the Kashgar Region's most dominant LC, accounting for 77%–74% of its total overall area. Due to decreased of snow/ice, bare land remained at 92,665.5 km<sup>2</sup>, or 80% of its 1990–2000 measurement. Bare land is characterized by sand, desert, and rock, so it is difficult to reclaim, as summarized in Table 2.

Furthermore, several observations can be made from time-series LC maps. Cultivated land: (i) expanded generally from west to east (the Kashgar River side); (ii) expanded along the banks of the Yarkant River; (iii) increased near the forest area; and (iv) expanded much more near the southern borders of the Yarkant River. These observations were mainly related to the study area's topography and water resources because the flat alluvial plain could sustain increasing expansion of cultivated land and had sufficient water resources for agricultural production.

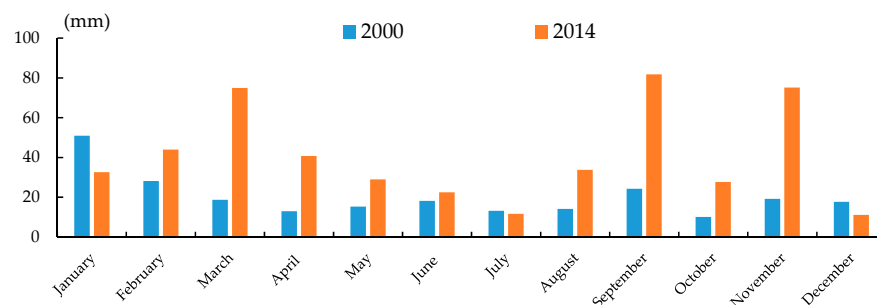


Figure 6. Monthly precipitation variation of mountain region in 2000 and 2014.

Table 5. Area transition matrix of Kashgar Region during 1972 to 2014.

| Land Cover Classes in 1972 (km <sup>2</sup> ) | Land Cover Classes in 2014 (km <sup>2</sup> ) |                 |                |           |            |          |           | Total      |
|---|---|-----------------|----------------|-----------|------------|----------|-----------|------------|
|   | Water   | Cultivated Land | Urban/Built-up | Grassland | Forestland | Snow/Ice | Bare Land |            |
| Water   | 954   | 151             | 0.01           | 157       | 70         | 456      | 974.8     | 2762.8     |
| Cultivated land                               | 27.1  | 2631            | 205.75         | 711       | 402        | 0.21     | 171.5     | 4148.5     |
| Urban/built-up                                | 0.23  | 5.9             | 28.99          | 0.1       | 0.02       | 0        | 5         | 40.2       |
| Grassland                                     | 0.12  | 1913            | 13.6           | 2196      | 29.06      | 316      | 311.9     | 4779.6     |
| Forestland                                    | 0.1   | 2328            | 10.74          | 9.4       | 843        | 52.4     | 340.8     | 3584.4     |
| Snow/ice                                      | 1.45  | 1.6             | 0.00           | 38.9      | 0.19       | 8456     | 2340.6    | 10,838.7   |
| Bare land                                     | 79.4  | 4647            | 133.4          | 189.9     | 0.01       | 720.6    | 81,987    | 87,757.4   |
| Total 2014                                    | 1062.4  | 11,677.5        | 392.4          | 3302.5    | 1344.5     | 10,001.2 | 86,131.6  | 113,911.88 |

### 3.2. Snow Cover Changes

This research's second aim was to investigate snow cover changes in the Kashgar Region, and Figure 7 shows those changes from 1999 to 2014. In general, a maximum snow-covered area exists in winter and spring when most snowfall has occurred but melting has not begun. As the summer season advances, depletion of snow-covered area occurs and temperatures increase. In this study region, annual snow cover variation was complicated and fluctuated greatly. Two high snowfalls occurred in the mountains of Kashgar and Yarkant in 2005 and 2009, respectively (Figure 7), most likely caused by an accumulation of winter and spring snowfall in those years. In contrast, low snow cover was recorded in 2007, and total snow cover tended to decrease, especially in the Yarkant River Mountain area, where it decreased remarkably year by year. The Mountains of Kashgar and the Yarkant River have a mean elevation above 4000 m, and the elevation of some mountains areas reaches 5000–6000 m—the terrain's complexity results in great variations in distribution of temperature and precipitation. The mountain area has only one meteorological station (Tashkorgan, 3097.7 m). Annual mean precipitation is 450 mm in the high-elevation area (>5000 m) and 100 mm in the lower region (<3000 m). The long-term trend of temperature and precipitation increased at a rate of 0.72°C/10 year and 8.11 mm/10 year, respectively. Indeed, increasing temperature accelerated the melting and hindered the formation of glaciers, snow, and ice.

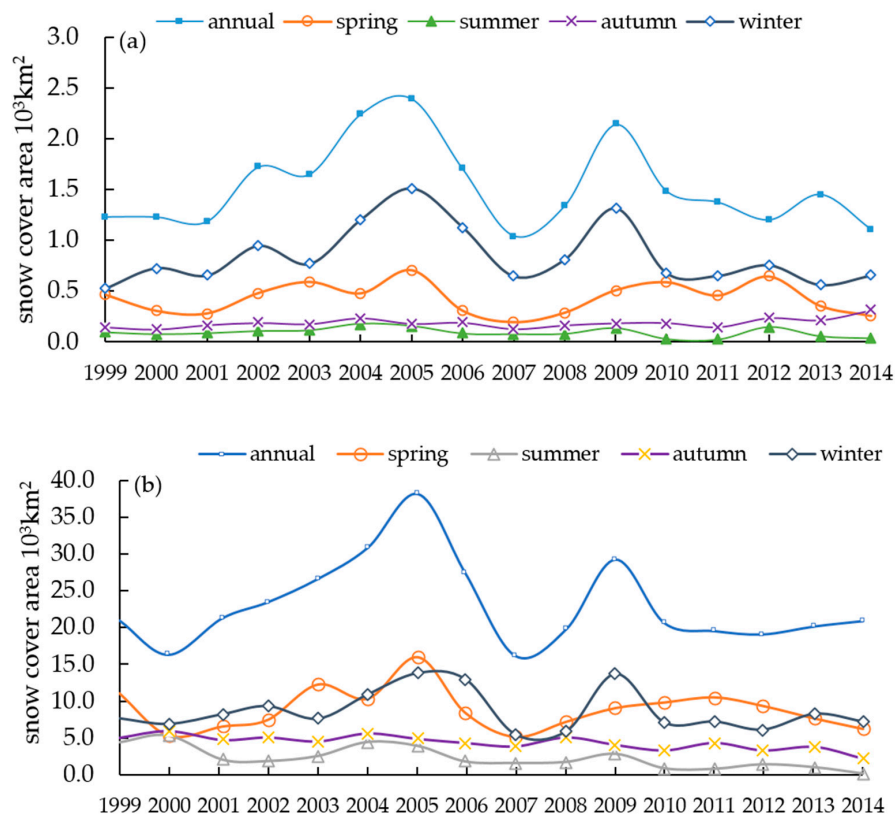


Figure 7. Annual and seasonal snow cover variation of Kashgar River (a) and Yarkant River (b).

#### 4. Discussion

On a regional scale, the LUCC of oases is key to environmental change and has a cumulative effect in this arid land. LUCC in the arid region is mainly driven by unique natural and social factors [42,43]. Therefore, research on LUCCs' driving forces in the arid region is conducted by social and natural sciences, and requires an interdisciplinary approach. In this respect, research on the driving forces in the Kashgar Region focuses mainly on natural and human factors.

##### 4.1. Natural Driving Forces of LUCC

The Kashgar Region covers a vast area; the region's southwest part is high, and its northeast part is low. Elevations in the study area divided into high and low mountains, plain, and desert areas. Due to differing characteristics of temperature and precipitation in these areas, we selected four observation stations for investigating characteristics of climate variables: Kashgar (1288.7 m, in the north), Maralbishi (1116.5 m, in the east), Yarkant (1231 m, in the south), and Tashkorgan (3093.7 m, in the mountains). As with the results of MK trend tests, all variables showed significant increasing trends, except for evaporation on the mountains (Table 6). These results indicated that during the past 50 years, the climate exhibited a warming trend. Other scholars have observed a similar trend in the northwest Xinjiang Region over the last 30 years [44].

In general, temperatures on the plain (Kashgar, Maralbeshi, and Yarkant) are higher than in the mountain ranges (Tashkorgan). On the one hand, increasing temperatures have favored agricultural production, and cotton production average yield per acre increase  $373.5 \text{ kg hm}^{-2}$  per decade from 1990 to 2013 [45]. Cultivated land increased from  $4148.6 \text{ km}^2$  in 1972 to  $11,677.5 \text{ km}^2$  in 2014 (Table 4). On the other hand, increasing temperatures enhanced transpiration and evaporation of crop and surface water. Evaporation on the plain ranged from 0.02 to 0.04 (Table 6), indicating a significant increasing trend. Expansion of cultivated land led to increased water consumption, from  $50 \times 10^8 \text{ m}^3$  to  $155 \times 10^8 \text{ m}^3$  from 1950 to 2010 [22], and increasing utilization of surface water. LUCC results

indicated that surface water decreased from 2762.9 km<sup>2</sup> to 1062.4 km<sup>2</sup> (Table 4), possibly caused by increased temperature and agricultural water consumption.

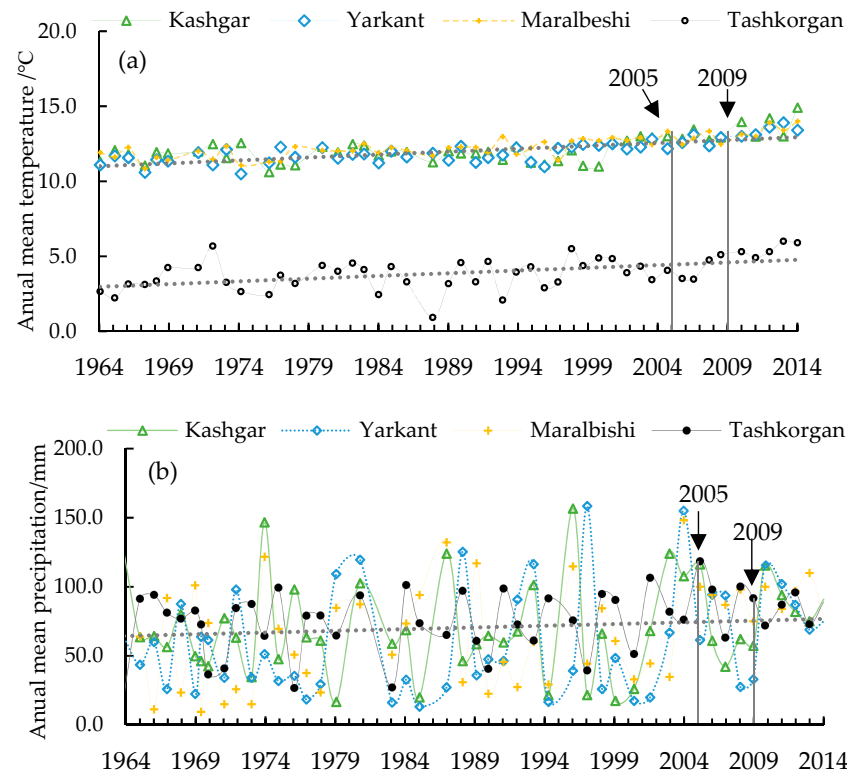
**Table 6.** The results of the Mann-Kendall test for climatic-hydro variables.

|          | Kashgar * |      | Maralbishi * |      | Yarkant * |      | Tashkorgan * |       | Kaqun + |      | Karbel + |     | Kirik + |      |
|----------|-----------|------|--------------|------|-----------|------|--------------|-------|---------|------|----------|-----|---------|------|
|          | Zc        | β    | Zc           | β    | Zc        | β    | Zc           | β     | Zc      | β    | Zc       | β   | Zc      | β    |
| <b>T</b> | 5.01      | 0.11 | 3.14         | 0.02 | 4.13      | 0.03 | 2.09         | 0.04  | -       | -    | -        | -   | -       | -    |
| <b>P</b> | 2.59      | 0.57 | 3.05         | 0.12 | 3.19      | 0.46 | 4.15         | 0.23  | -       | -    | -        | -   | -       | -    |
| <b>E</b> | 3.10      | 0.02 | 3.15         | 0.04 | 2.04      | 0.04 | −0.54        | −0.04 | -       | -    | -        | -   | -       | -    |
| <b>R</b> | -         | -    | -            | -    | -         | -    | -            | -     | 0.64    | 0.11 | 1.2      | 0.1 | 1.19    | 0.36 |

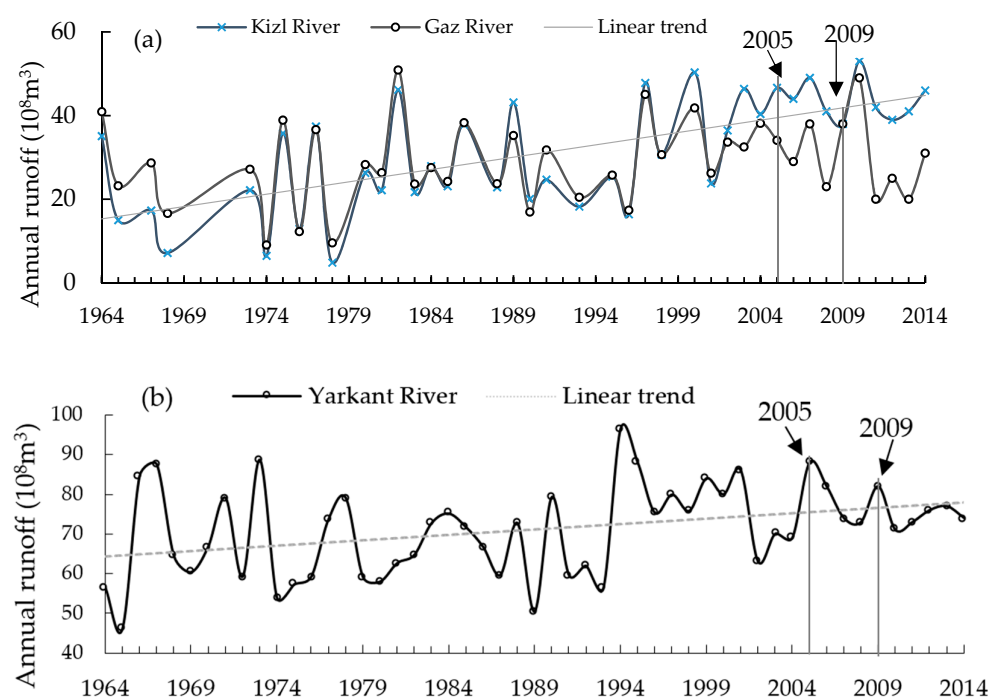
Note: \* meteorological station; + hydrological station; T-temperature, P-precipitation, E-evaporation, and R-runoff; Zc-standard normal random variable. β-Kendall slope, a positive β is rising trend, while a negative β means a decreasing trend.

In the mountainous areas, high-elevation glaciers and snow cover provide annual runoff and groundwater in the Kashgar Region. Seasonal runoff patterns were heavily dominated by winter snow accumulation and spring melt. Generally, snow cover is a seasonal phenomenon, and its variability is higher than that of glaciers. The air temperature is a major index for the snow and ice melt process, due to snow's particular sensitivity to climate changes. An increase of 2 °C in air temperature had a much more important effect on snow cover than doubling the precipitation during the snowmelt period [46]. Figure 8a displays the increased mountain temperatures over time. As temperatures rise, more precipitation falls as rain instead of snow, leading to smaller snowpack, decreased proportion of solid precipitation, and enhanced snowmelt. Figure 7 displays the slightly decreasing trend in annual snow cover. Then, rising temperatures have caused changes in snow cover that contributed to increased natural runoff of the Kashgar and Yarkant Rivers. The MK test results in Table 6 and Figure 9 indicate that runoff has increased. Particularly during the observation period from 1999 to 2014, snow cover changes have had strong effects on runoff discharge, and runoff displays an increasing trend, with pronounced peaks having occurred in 2005 and 2009. The relationship among snow cover, runoff, precipitation, and temperature on short- and long-term scales have been analyzed based on the only available annual data (snow cover, precipitation, temperature, and runoff). The high snow cover accumulations recorded in 2005 and 2009 (Figure 7) was attributed to annual precipitation in the mountain range in the same years (Figure 8b). During the same time, temperatures of the study area recorded their higher peak in mountain (Figure 8a). Increased temperatures might have accelerated snowmelt and contributed to the increased runoff in 2005 and 2009 (Figure 9) on the short-term scale. Yan et al. (2007) [47] showed that regional runoff increased by 10–16% when temperature rose by 1 °C, based on the correlation between temperature and the Yarkant River's monthly mean discharge. The magnitude of glacier contribution to natural runoff is much less than snow melt runoff in the short-term. However, Dong et al. (2009) [48] addressed the long-term effect of temperature and precipitation changes on physical characteristics of the area's glaciers. With an increase in air temperature during the study period (1960–2000), glaciers in the Yarkant River basin retreated by 6.1% and overcame effects of increased precipitation on the glacier mass balance due to regional climate changes that enhanced glacier ablation, which provided melt water for a longer time. In addition, Chen et al. (2006) [49], Xu et al. (2009) [50], and Qiang et al. (2010) [51] have addressed hydro-meteorological processes by investigating changing characteristics of precipitation, temperature, and runoff. Their results indicated significant runoff increases due to climate changes of the Yarkant and Kashgar Rivers. As discussed above, snow and glacier contributions form a major part of total runoff in the Kashgar Region, and therefore changes in snow and glacier melt runoff due to climate change are reflected in changes of the total stream flow of those rivers. Natural runoff from melting snow and ice has played an important role in the recharge of groundwater infiltration and storage. The total natural recharge of groundwater is  $89.3 \times 10^8$  m<sup>3</sup>/year in the Kashgar Region [52].

Replenishment by precipitation is not very significant to groundwater in this study area's arid climate. The geographical distribution of runoff has changed due to increased human activities, which may have affected replenishment of groundwater and changes to the changes of total stream flow of those rivers.



**Figure 8.** Annual mean temperature (a); and precipitation (b) trend of Kashgar Region.



**Figure 9.** Runoff variation of Kashgar River (a); and Yarkant River (b).

## 4.2. Social Driving Forces of LUCC

### 4.2.1. Impact of increasing of population on LUCCs

Population growth has been identified as a major driving force for agricultural expansion and water consumption by Zhou et al. (2003) [53], Zhang et al. (2003) [54], Wang et al. (2008) [55], and Til et al. (2015) [56] for different areas in arid Northwest China. The population of the Kashgar Region rose from 2,745,362 in 1988 to 4,683,114 in 2014 [22], an increase of approximately 70%. Generally, the growing population has requested more land for basic needs of living, such as food and housing. More than 78% of households in rural areas depend largely on land resources, and agriculture contributes a large share of the gross domestic product (GDP). Crop and cotton production has increased, and the total agricultural area has expanded. Figure 10 shows the population increase in the Kashgar Region. A high positive correlation was found between population and sown area. The majority of grassland and forestland was occupied by cultivated land to satisfy people's demand for food (Table 6). As a result, grassland decreased from 4779.1 km<sup>2</sup> in 1972 to 2680.6 km<sup>2</sup> in 2000, and forest decreased from 3584.5 km<sup>2</sup> in 1972 to 1344.5 km<sup>2</sup> in 2014. Bare land and cultivated land were converted to urban/built-up land, which increased from 40.2 km<sup>2</sup> in 1972 to 392.8 km<sup>2</sup> in 2014. Population growth resulted in the expansion of cultivated land, with reclamation and evident shrinkage of grass and forest cover. Therefore, population is a major factor in LUCCs.

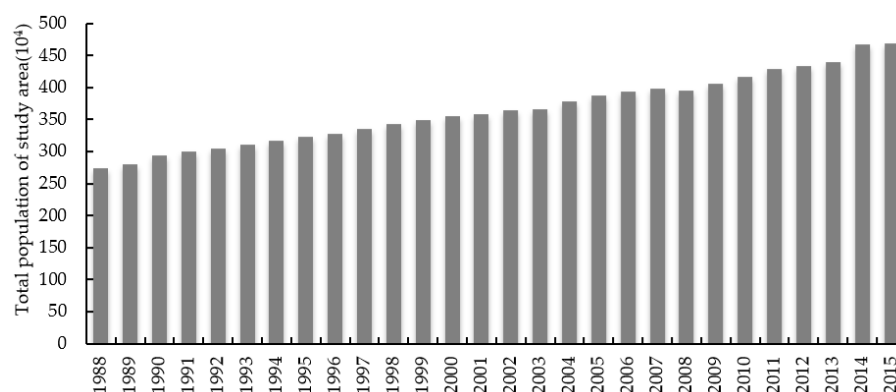


Figure 10. Total population of study area (source: [22]).

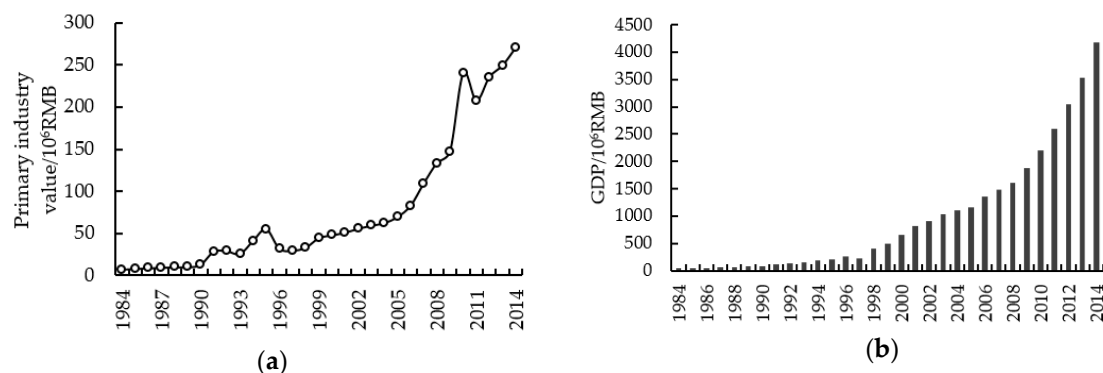
### 4.2.2. Impact of Policy-Induced Agricultural Land Development on LUCCs

Policy has contributed directly to the area's economy because political and economic activities are strongly interlinked with economic needs. Moreover, economic pressures were reflected in political programs, and economic instruments were used to implement political driving forces. Socio-economic developments of the Kashgar Region have been observed from 1984 to 2014, during which time the average annual growth rate of the GDP and primary industry increased by 138% and 35%, respectively (Figure 11). Policy influences on LUCCs in the Kashgar Region have been demonstrated based on document analysis, that is, international scientific literature, national studies, and government reports. Policy influences were closely associated with LUCC driving factors observed in the study area. For clarity, we organized these major events into the following three distinct historical periods.

*First period, 1979–1984:* The land tenure system adopted an 'open-door policy'. This policy led to the distribution of land from proprietors to individual households according to land tenure [57]. Consequently, land tenure policy has impacted agricultural production's efficiency and the region's economic development. The primary change in LUCC was the expansion of cultivated land near the alluvial plain (LC map for 1972, Figure 4). Government plans supported this expansion of agriculture and provided opportunities for expansion of grain and crop cultivation, which has initially supported the population's food and economic desires.



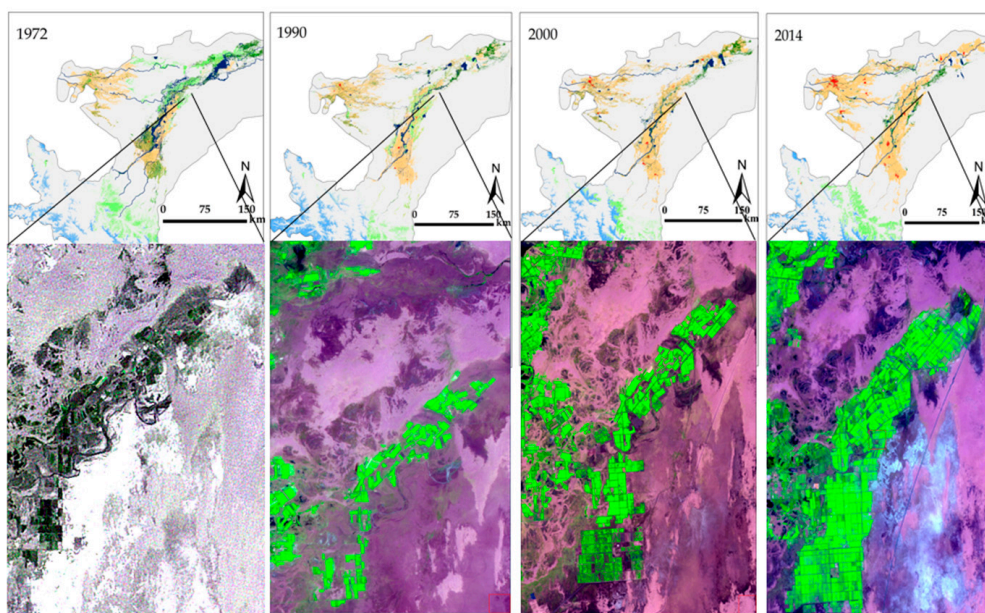
*Second period, 1984–1990s:* This period includes the most significant changes to land policy. The bureau of land administration was established and became responsible for land allocation, acquisition, monitoring, development, and for implementations of land law. Administrative law has legalized individual access to owning land in an attempt to develop the land market in Xinjiang and the inner cities of China. Individual ownership was implemented to promote socio-economic development and further improve people's living standards. Agriculture attracted the attention of land businesspeople. Because of rising market prices, cotton cultivation brought fast economic growth. China became a global leading textile and clothing exporter, with rising demand for cotton driving prices to historically high levels [58]. The Kashgar Region has accounted for 43% of Xinjiang cotton production, and responses to cotton market expansion resulted in cultivating more land there.



**Figure 11.** Primary industry (a); and gross domestic product (GDP) (b) of study area (source: [22]).

The general pattern of agricultural expansion from 1984 to 1990 in the plains and along the rivers has continued and led to intensified land use (LC map for 1990, Figure 4). The change in the distribution of land use, especially the expansion of cultivation around critical water resources, has resulted in the agricultural sector's increased demand for water. Thus, the government has increased investment to establish irrigation channels, and the pattern of expansion along irrigation channels has led to continually increasing agricultural production. The Kashgar Region's increasing agricultural output has also led to the construction of transport corridors—a long southern Xinjiang railway and a national highway from Kashgar to other domestic markets. These corridors, in turn, have led to increased economic linkages between the Kashgar Region and surrounding cities [59].

*Current period, 2000s–2014:* The government announced the abolition of the agricultural tax [60] and an adjustment of crop and cotton production structures towards market requirements. In addition, in 2001, China joined the World Trade Organization, which supports the agricultural sector [61]. Since 2002, China has implemented direct agricultural income and agricultural machinery subsidies. For these reasons, since 2005, the Kashgar Region's primary industry has undergone dramatic changes (LC map for 2000 and 2014, Figure 4). Moreover, the government launched special economic development zones along the Kashgar River to attract domestic and foreign investment. The main goal of this economic zone is to boost economic development in the Kashgar Region by providing favorable policies such as tax exemptions, energy supplies, and access to transportation in 2011 [62]. Consequently, in 2013, China and several Central Asian countries cooperated to build the 'Silk Road Economic Belt' for mutual commercial benefits [63]. These on-going political and new economic events have altered LUCCs (such as opened the new land for cultivation, Figure 12) by local- and national-level approaches to the Kashgar Region's development. These external drivers, combined with local situations, have contributed to LUCCs.



**Figure 12.** Opened new cultivated land continually from 1972 to 2014.

## 5. Conclusions

In Kashgar Region, agricultural and economic development in oasis mainly depends on melt-water from glaciers and seasonal snow in the high mountain areas. Knowledge of quantifying LUCC and its driving forces including natural and social drivers determined by anthropogenic and climate change are essential for sustainable development in this region. We combined multi-scale (Landsat) and multi-temporal (SPOT VGT) remotely sensed images to investigate spatial and temporal dynamics of LUCCs, including snow cover changes, during the last 42 years (1972–2014). The results showed that water, forest, grassland, and bare land have exhibited declining trends due to the expansion of cultivated and urban/built-up land from 3.6%, 0.4% to 10.2%, and 3%, respectively. Snow/ice covered areas have fluctuated, considering that only snow area in the summer time first decreased and then increased, according to the Landsat snapshot. However, the total snow covered slightly decreased, as confirmed by the SPOT VGT time-series data analysis.

The increasing of temperature and precipitation have different effects on plain and mountain areas. In the plain areas, increasing temperature has increased evaporation and water consumption, but inter-annual changes in precipitation had less impact on LUCCs. Meanwhile, in mountain areas, both of them especially experienced warming and decreased snow cover, which led to increased natural runoff, providing water resources in the plain.

Besides natural factors, demands from the growing population for basic needs of living and economic development were the anthropogenic drivers of LUCCs. Policy-related agricultural expansion shifted land use from small- to large-scale intensive farming. These drivers were the primary drivers of LUCCs in the Kashgar Region. At the same time, changes to the temperature, snow cover, and runoff was a facilitator of implementing anthropogenic driving forces. This study's results are valuable in the Kashgar Region and other arid regions with similar geographic conditions.

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**Conflicts of Interest:** I declare that the authors of this paper no conflict of interest.

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