Oasis evolution in response to human induced water resources reallocation in South Xinjiang during past four decades

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Abstract: Vegetation in drylands is sensitive to climatic changes and human activities. Remote sensing and spatial analyses provide us useful tools for monitoring long-term vegetation dynamics over large regional scale. In this study, we analyzed the oasis vegetation cover change of the Tarim Basin using Landsat data sets from six epochs, 1975s, 1990s, 2000s, 2005s, 2010s and 2014. The results show that vegetation cover of oases increases from 34600 km^2 in 1975s to 101000 km^2 in 2014, though there was a vegetation coverage decrease from 77600 km^2 in 2000s to 42680 km^2 in 2010s. The percentage of annul water consumption has increased from 34% in 1970s to 52% in 2010s in the upper Tarim River, and decreased from 15% in 1970s to 9% in 2010s in the lower Tarim River. The decrease of oases area from 2000s to 2010s probably resulted from the rapid urbanization and large scale land reclamation. Although there is an increasing trend for oases coverage, local degradation of oases especially in the northern part occurred. This may be caused by inadequate water supply of the Tarim River. The results of multiple regression show that human activities contribute 70% of oases area change. Human induced water resources reallocation and heat energy balance is the primary cause of total oasis change.

Keywords: Oasis; Climatic change; Human activities; Water resources; Remote Sensing; Tarim River basin

1. Introduction

Dryland is characterized by high climate variability (low precipitation, long dry seasons, high wind speed, and frequent dust storms), and are quite sensitive to land use practice [1,2]. Drylands totally cover about 40% of terrestrial land surface and occupy 38% of living places of the global population [1-3]. Drylands can account for approximately 40% of global net primary productivity [2,4,5], which made nearly equal proportion compared with the other land types. With rapid population growth, intensive human activities have resulted in land degradation and desertification [2], which bring great challenge to environmental sustainability in drylands.

Oasis represent a unique ecosystem in arid and semi-arid regions [6-9]. An oasis is ecologically defined as an ecosystem that has higher vegetation cover and primary productivity than surrounding desert and significantly depends on external water supply [9]. The origination and evolution of oases are significantly dependent on specific hydrologic, topographic and geologic settings [10,11]. A systematic mapping from remote sensing data shows that oases are geographically distributed on alluvial fans and along the rivers channels [12]. Precipitation is an important input of water sources to oases, however snow and glacier melting water from surrounding high mountains provide a more significant source. The oases naturally oppose the encroachment of desert by staying moist in the soil [8,11]. Some investigations have attempted to manifest how to maintain sustainable development of oases by controlling the local circulation of hydrothermal environment [13,14]. In the context of global change and human modification, large-scale hydrological cycling and spatial configuration of water resources has been changed substantially [7,15], which potentially affect the development and

self-regulation of oases [6,8].

The condition of vegetation growth and cover plays an important role in terrestrial ecosystem and hydrological cycle, especially in drylands with limited water input [1,16]. Although filed investigation could provide more accurate information about vegetation condition, it's laborious and time-consuming. The integrations of approaches from remote sensing, spatial statistics, and geo-informatics provide powerful tools to monitor large scale vegetation encroachment and desertification in drylands over multiple decades [1]. The consistency and repeatability of satellite data allow to compare the regional change through image-to-image measurement at the same thematic scale [17]. All various spectral vegetation indices, the Normalized Difference Vegetation Index (NDVI) is the most widely used one [18], which serves as a good indicator of vegetation productivity [19]. On this basis, NDVI can be employed to the long-term monitoring of oases dynamics.

In china, oases are mainly distributed along the pediments of surrounding mountains in northwestern dryland regions [20,21]. In these regions oases account for only about 5% of the total land surface area, but feed more than 90% the local growing population and social wealth [8,13,14,22]. It has been observed that desertification is happening and causes the environmental deterioration of oases [23,24] because of unsustainable economic development [25]. Large part of South Xinjiang has an arid climate, and is prone to change as a result of highly variable climate and intensifying human activities. As the primary living places of dryland population, oases are theoretically and practically fundamental to the social and economic developments in this region. Long-term monitoring is essential to our explicit understanding of the oases dynamic. Hence, the objective of this study is to map the spatial and temporal changes of oases vegetation using long time series of remote sensing datasets and identify the major factors affecting oases change.

2. Study Area

The study area is located in the Tarim Basin in South Xinjiang, which includes five sub-provisional prefectures (Figure 1). The Tarim Basin is enclosed by Tien Shan to the North, the Pamir Plateau to the West, and the Kunlun Mountain to the South. In the central part of the basin is the Taklimakan Desert, which covers 85% of the whole basin (Sun and Liu, 2006). The Tarim River originates from the Pamir Plateau and then fed by a series of rivers from the surrounding high mountains flowing from the southern-southwestern part to the northeastern part of the basin (Figure 1). The total catchment area is about 1.02×10^6 km^2 [26]. Historically, nine headwater drainage systems were hydrologically connected to the main stream of the Tarim River, however, currently only three major headwaters (the Aksu River, Yarkant River, and Hotan River) flow into the mainstream. The mean annual runoff in the Tarim basin is about 39.8 km^3, 40% of which comes from glacial and snowmelt water [27,28]. The Aksu River, Hotan River, and Yarkand River contribute 73.2%, 23.2% and 3.6% of the total runoff, respectively [28]. The Tarim River basin covers 42 counties, and 55 Production and Construction Units of Xinjiang. During the last 50 years, the ecosystems and environments of the Tarim River have been changed significantly due to extensive agricultural exploitation in the area [29]. Recent investigations showed that annual runoff in the middle and lower reaches of the Tarim River reduced significantly. It is argued that human activities (irrigation and domestic water use) has led to a decrease of the water into the main stream of the Tarim River Basin since 1970s, which was aggravated in the 2000s [26,30,31].
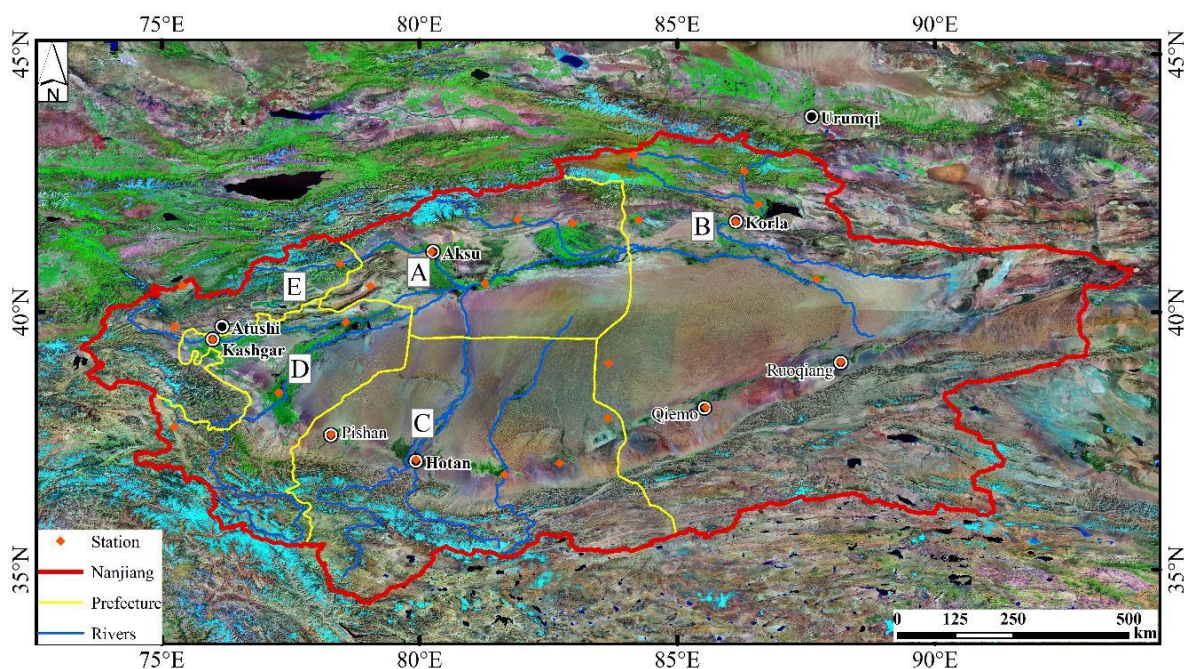
Figure 1. Landsat mosaic image showing location map of the study area and spatial distribution of meteorological stations in South Xinjiang. The five prefectures labeled in figure are: A. Aksu, B. Bayinguole, C. Hotan, D. Kashgar, and E. Kizilsu. In this study five stations (Aksu, Korla, Kashi, Hotan, and Ruoqiang) were selected to show the climate characteristics in different regions.

The climate in the Tarim River catchment is extremely dry with high temperature and low precipitation. The mean annual temperature varies from 10.6 ℃ to 11.5℃, with the mean monthly temperature between 20℃-30℃ in July and 10 ℃-20℃ in January [26]. The mean annual precipitation is about 116.8 mm, but the annual potential evaporation is as high as 2500-3000 mm [26]. The annual precipitation exhibits an elevation-dependent decreasing gradient, from 200-500 mm in the mountainous area, to 50-80 mm in the pediments of the mountain or alluvial fans, and then to less than 10 mm in desert of the central basin [32]. The interannual distribution of precipitation is significantly heterogeneous. More than 80% of the total annual precipitation falls within the period from May to October, and less than 20% falls between November and April [26].

3. Data and methods

3.1. Data

All datasets used in this study were retrieved from Global Land Cover Facility (GLCF) of Maryland University (http://glcf.umd.edu/) and Geospatial Data Cloud of Chinese Academy (http://www.gscloud.cn/). The Landsat MSS/TM/ETM+ datasets was from the Global Land Survey (GLS) collection, which is designed to meet a need from scientists to use a carefully coordinated collection of high resolution imagery for global modeling, including for the climate and carbon cycles (http://glcf.umd.edu/data/gls/). Based on the existing GeoCover dataset, the GLS provides wall-to-wall, georeferenced and orthorectified, cloud free Landsat coverage of Earth's land area at 30-meter resolution in nominal "epochs" of 1975s, 1990s, 2000s, 2005s, and 2010s (Franks et al., 2009; Gutman et al., 2008). The GLS is intended to provide clear-view images acquired during the peak growing season of each epoch [17]. However, when high quality images were not available due to lack of cloud-free images during the growing season (Franks et al., 2009; Gutman et al., 2008), images had to be selected with a date outside this range [17]. This may cause certain derivation when change detection during two different periods is performed. The images from 1975s and 1990s are originally

orthorectified data which was not calibrated by atmospheric correction and transformed into surface reflectance (Tucker et al., 2004). The data from 2000s, 2005s, and 2010s were surface reflectance production after atmospheric correction using Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS). The datasets for each epoch were acquired from the primary Landsat sensor in use at the time. The image datasets used for the year of 2014 was Landsat 8 OLI_TRIS retrieved from Geospatial Data Cloud of Chinese Academy (http://www.gscloud.cn/). For each epoch, totally 26 scenes of images are chosen to cover the extent of oases in South Xinjiang (Tables S1 and S2).

In addition, SRTM DEM (http://www.gscloud.cn/) was used to extract the contour line for delineating the extent of oases. In this study, the area below 2000 m above sea level is determined as the habitat place of oases.

Precipitation and temperature datasets from five stations (Figure 1) were used to investigate the relationship between oases changes and climatic variables. The time span of meteorological data used here range from 1971 to 2012.

3.2 Methods

Because of the datasets of 1975s, 1990s and 2014 were just georeferenced and orthorectified, they need to be corrected and transformed into surface reflectance before they are used to calculate NDVI. The atmospheric correction method adopted here is FLAASH. The digital number (DN) values of the data were converted into at-satellite radiance, and then the at-satellite radiances were converted to surface reflectance by correcting for both solar and atmospheric effects [33].

NDVI was used to map the spatiotemporal changes of vegetation cover of oases. It was suggested that the value of 0.1 was appropriate to discriminate the vegetation from other land cover types [34]. The values of large than 0.1 was defined as vegetation. It was cross checked through comparison of NDVI results and the atmospherically corrected images. Because the oases are geographically distributed in the places below 2000 m above sea level, the area below 2000 m and with NDVI values of large than 0.1 was regarded as oases.

In order to achieve a quantitative understanding of the contribution of climatic changes and human activities to oases area change, we performed a multiple regression analysis. We chose 18 counties with enough data sets from the years 1990, 2000, and 2005 for experimental samples. These 18 counties are distributed in different region of the Tarim basin, which is representative for this analysis (Figure 2). Because of the limited data of water consumption, here population and farmland were considered as the two primary variable accounting for human activities, and annual precipitation and mean annual temperature as the primary variables for climatic changes. The oasis area is considered as independent variable, and the four influencing variables as dependent variables. All the data are normalized before multiple regression, and the derived coefficients of the corresponding variables represent their relative contribution to the variation of oasis.
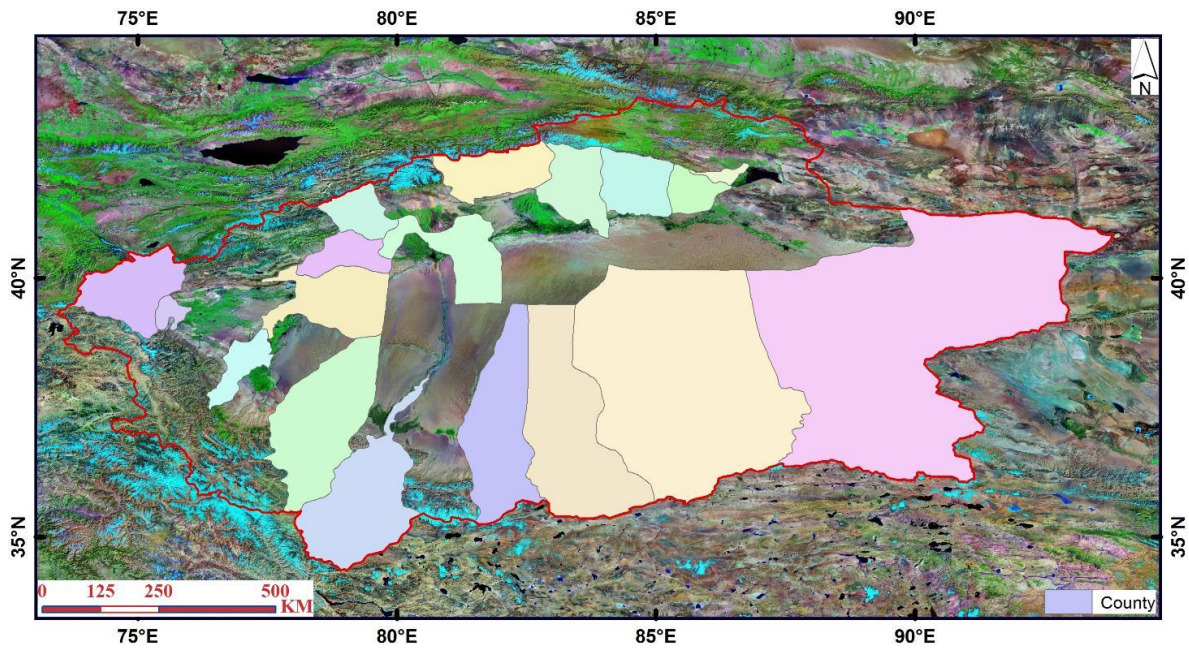
Figure 2. The eighteen counties selected for quantifying the contribution of varying variables to oasis area change using multiple regression.

4. Results and Discussion

4.1. Spatiotemporal changes of oases

As mentioned in the section of 'method', the spatial patterns of oases were mapped using NDVI with value of large than 0.1 (Figure 3). This value may introduce some error because of the image quality and temporal and spatial differences of surface reflectance (see some sparse patches around the Hotan oases in 1975s). However, the results is still considered to be reliable in that the oases has a significant expansion with the population growth and the cropland increase [6] (Figure 9). The spatial patterns of vegetation cover during different periods are shown in Figures 4 and 5. And the oases area in the whole region and five sub-provisional prefectures are calculated, respectively (Figure 6). For the whole study region, the vegetation cover in the oases increases from in 34600 km² in 1975s to 10100 km² in 2014, with a decrease from 77600 km² in 2000s to 42680 km² in 2010s (Figure 6). There is no significant change between 2005s and 2010s, despite of some sparse increase or decrease within the study area. Except Hotan, the temporal changes of oases area in other four prefecture have the same increasing-decreasing-increasing changing trends with the whole study region. The area of oases in Hotan shows no significant change from 1975s to 2010s. However, from 2010s to 2014, there is an obvious increase.

The results from the comparison between 2014 and 1990s (Figure 5) show that vegetation cover increases in most parts of the headwaters in the upper reach from Aksu and decreases over large spatial scale along the middle and lower reaches of the Tarim River from 1990s to 2014. The construction of reservoirs in the headwaters to great extent accounted for the expansion of oases (Figure 5B), and then the shrinkage of the Tarim River accounted for the degradation of oases in the lower reach (Figure 5C).
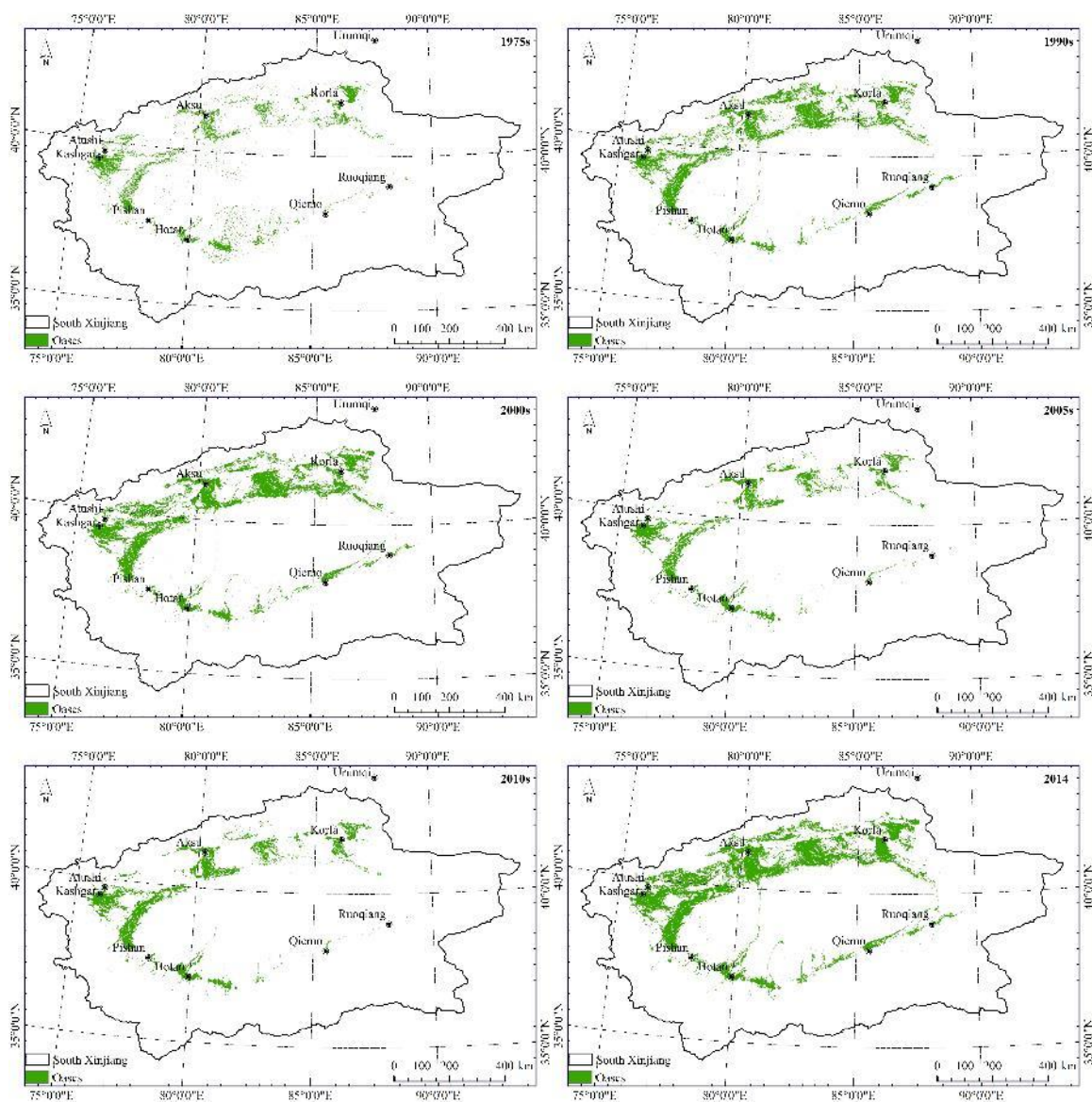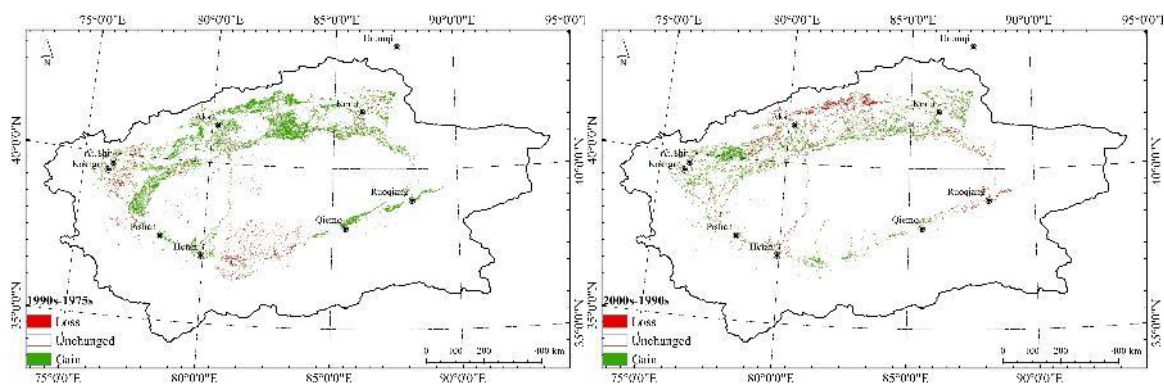
Figure 3. Spatial pattern of oases in South Xinjiang during six different periods.
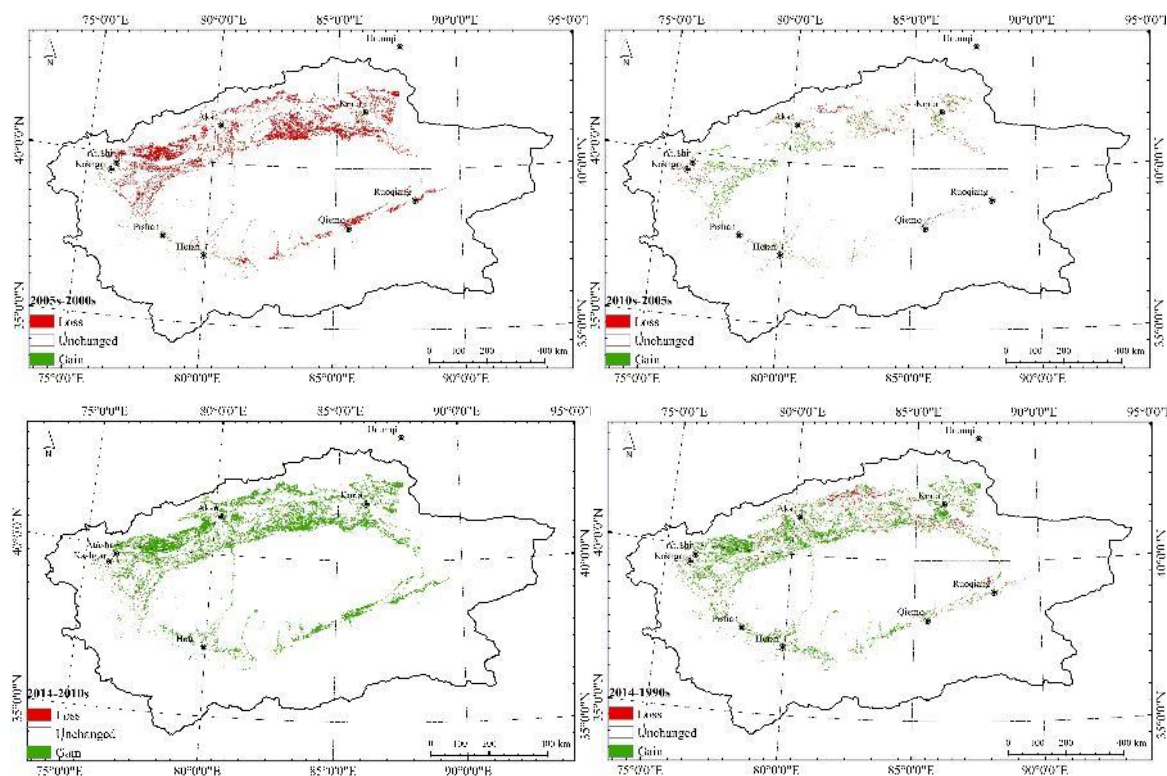
Figure 4. Spatial changes of vegetation cover in oases between different periods. The green area means increasing vegetation cover and red area means decreasing vegetation cover.
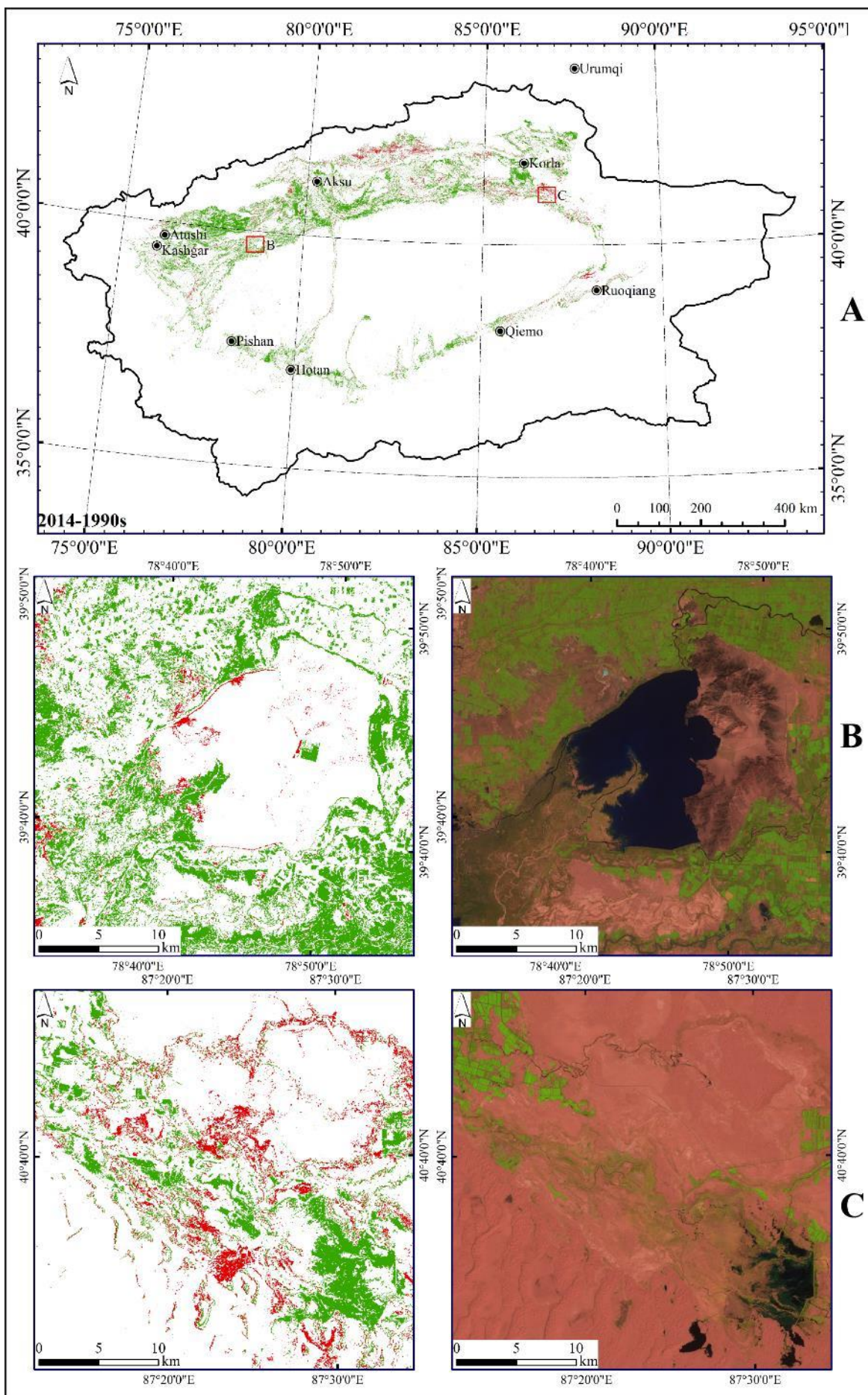
Figure 5. The representative areas are chosen to show the spatiotemporal changes of oases in the Tarim River basin. A. South Xinjiang; B. Xiaohaizi Reservoir surrounding area; C. the lower Tarim River.
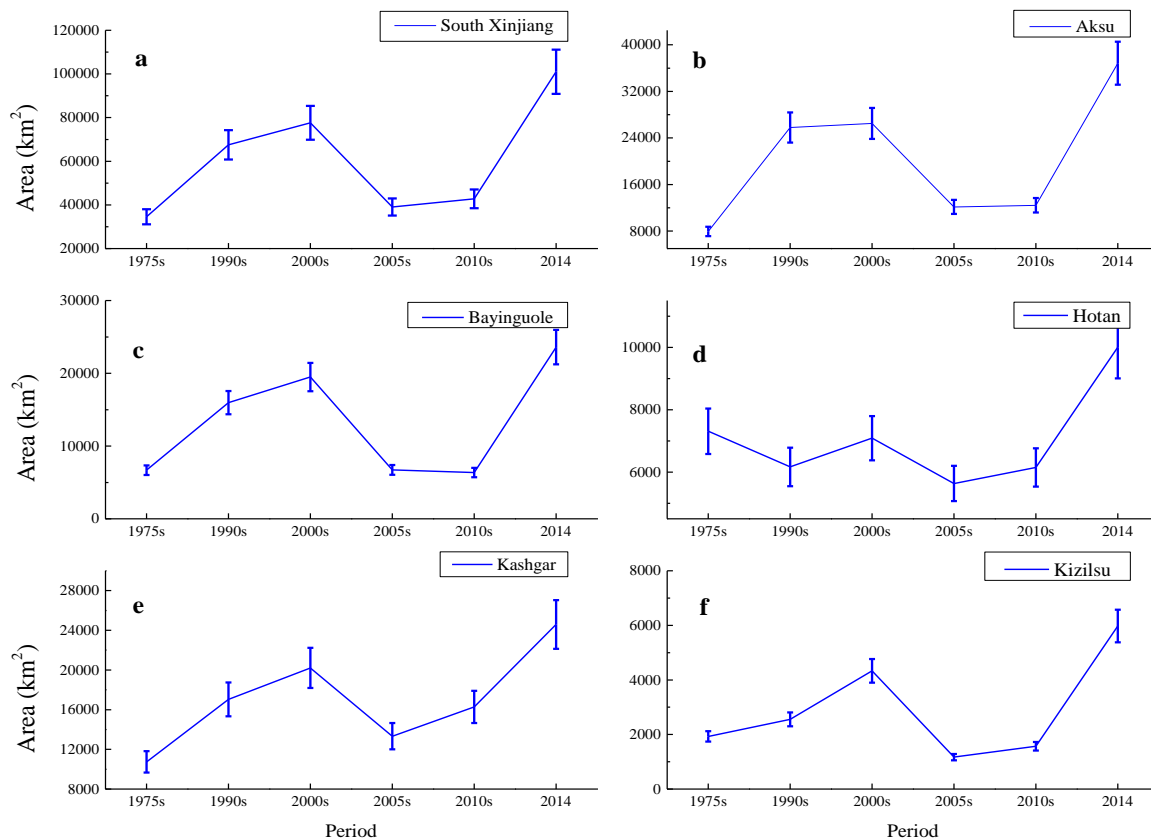

Figure 6. Temporal changes of oases area during past decades.

4.2 Temporal changes of hydrometerological conditions

Figure 7 indicates that precipitation and temperature have increased slightly during past four decades. Results derived from data sets collected from 39 weather stations and 29 hydrological stations indicate that precipitation, relative humidity, vapor pressure, and the aridity increased since 1986 and surface temperature began to increase in 1996. However, the time of sunshine started to decrease from 1990, and the potential evapotranspiration (ET) began to descend since 1985 due to the decreasing wind speed rather than the increasing temperature [30,35]. Because of the intensive evapotranspiration, the relatively less precipitation would contribute less to vegetation growth. The seasonal and phonological change of oasis vegetation are significantly dependent on the water allocation of river runoff. The streamflow in Aksu River, Yarkand River and Kaidu-Kongque River (near Korla) (Figure 1) shows an increasing trend, while the streamflow in Hotan River is of significant fluctuation (Figure 8a-d). The annual runoff in the mainstream of Tarim River has decreased significantly since 1950s over decadal timescale. The decrease in streamflow of the mainstream of the Tarim River results from anthropogenic activities (such as irrigation and domestic water use) and climatic changes [30,31] in the upper headwater areas and oases.

Although precipitation and the streamflow from the headwater of the Tarim River exhibited significant increase, decreasing trend has been detected in the streamflow along the mainstream of the river. This suggested that anthropogenic activities instead of the climate change dominated the streamflow cessation and the drying-up of the river [15,31].
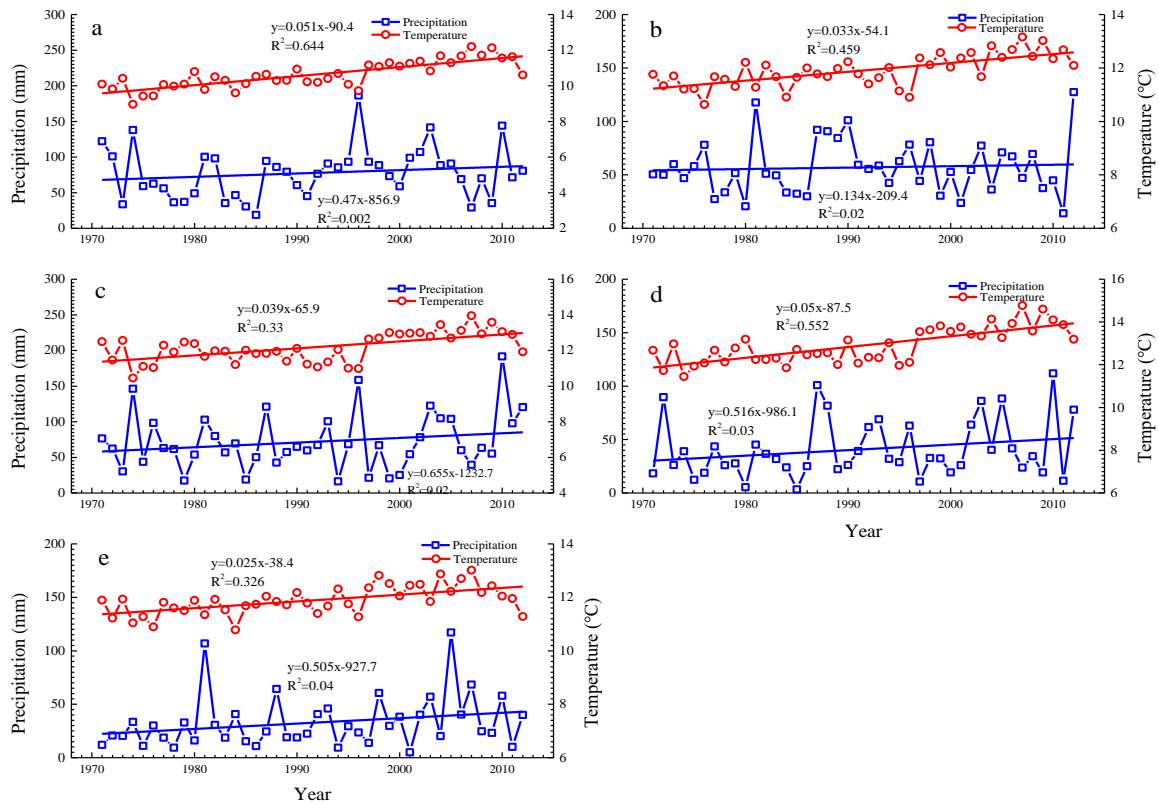
Figure 7. Temporal changes of precipitation and temperature in South Xinjiang. a. Aksu; b. Korla; c. Kashgar; d. Hotan; e. Ruoqiang.
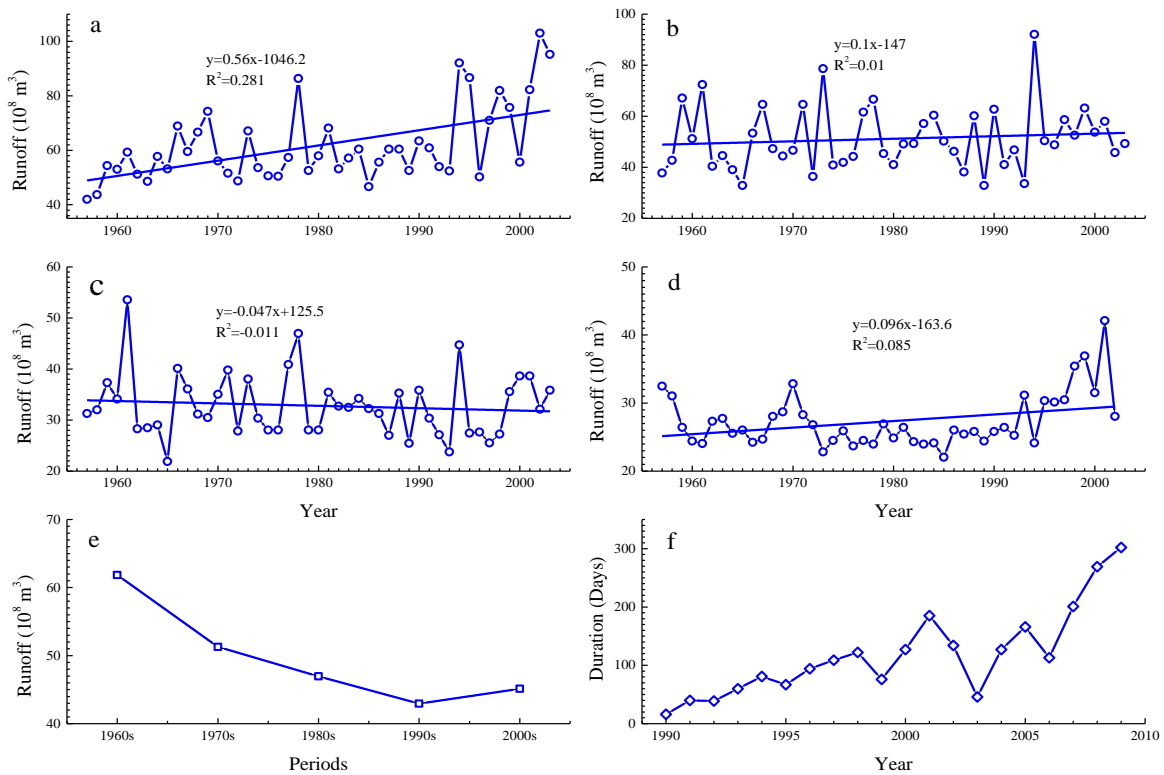

Figure 8. The temporal change of annual runoff between 1957-2010 in Aksu River, Yarkant River, Hotan River, Kaidu-Kongque River and the mainstream of Tarim River. a. Aksu River; b. Yarkant River; C. Hotan River; d. Kaidu-Kongque River; e. Decades-average annual runoff in the mainstream of Tarim River during 1950s-2000s; f. The dry-ups in the mainstream of the Tarim River. The data was retrieved from Chen et al. (2009), Chen et al. (2011) and Tao et al. (2011).

4.3 Natural and anthropogenic controls on oases dynamics

The investigations on hydrometerological changes have shown that there is an increasing trend in precipitation and decreasing trend in potential evapotranspiration [35,36]. This indicates that the more precipitation will be supplied to vegetation and will contribute to the survival of the arid fragile ecosystems, especially for those in the margin of oases and deserts.

Although effective precipitation for vegetation growth increased during past decades, the increasing water irrigations should primarily account for the oases expansion (Figures 7e and 8). The quantitative assessment indicates that local human activities since the 1970s led to a decrease of the water volume diverted into the main stream of the Tarim River Basin, which had been aggravated in the 2000s [30]. The water consumption exhibits a complicated spatial pattern between different reaches due to the difference water resource allocation strategy in the river basin [15]. The irrigated area in the Tarim River basin has increased obviously (Figure 10), particularly after 2000 with the growing population. The actual irrigated area for the "four headstreams (Aksu River, Yarkand River, Hotan River and Kaidu-Kongque River) and one mainstream" of the Tarim River largely exceeds the originally designed irrigated area [15]. If the specific irrigation volume in the Tarim River basin is 1.2 $\times 10^4$ m^3/ha m^2, more about 5.0 $\times 10^6$ m^3 of water is required for the exceeding irrigated area [15], which need to be extracted from groundwater. Therefore, it can be inferred that the expansion of oases in South Xinjiang mainly resulted from the intensive water irrigations including both river water and underground water.
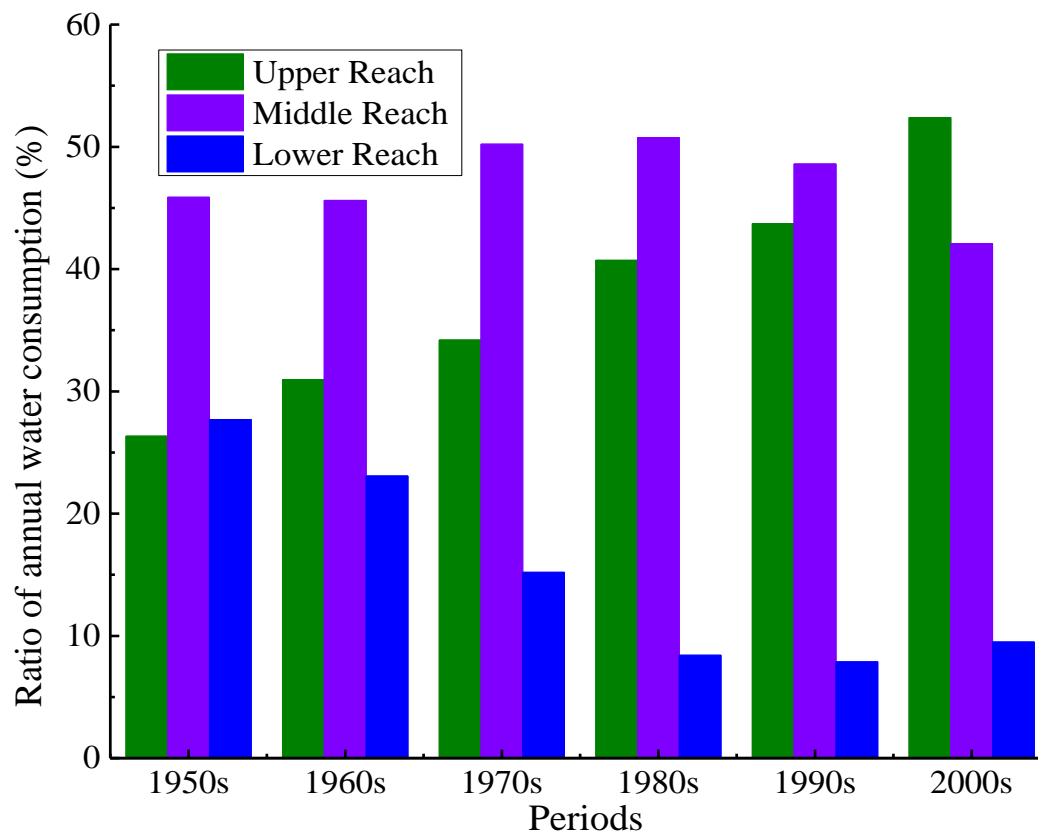

Fig. 9. Water consumption in the upper, middle and lower mainstream of the Tarim River (data retrieved from Chen et al. (2011)).
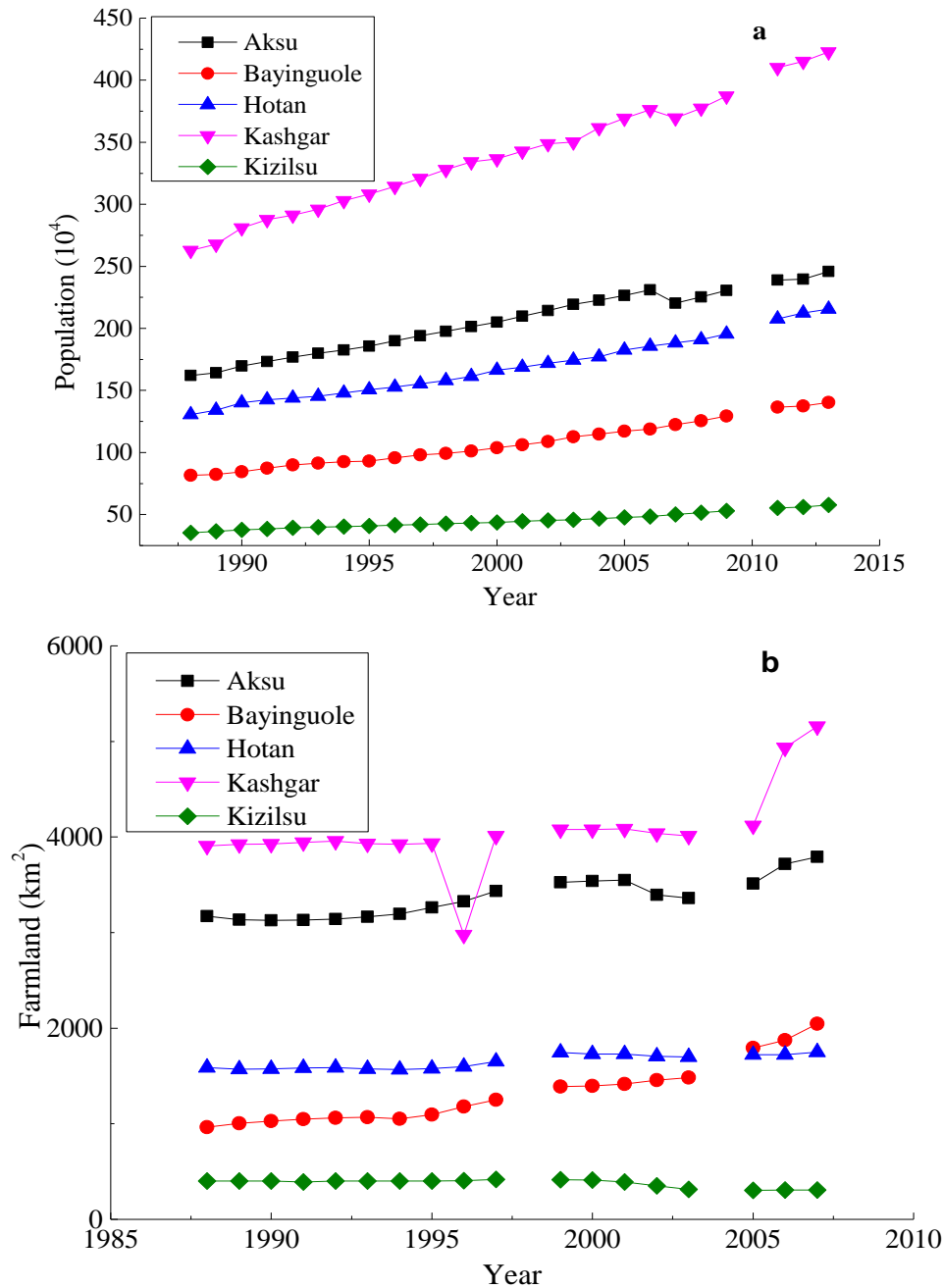
Fig. 10. Temporal changes of population and farmland area in South Xinjiang during 1988-2008.

a. Population change; b. Farmland change.

The increasing water irrigations could explain the total expansion of oases from 1975s-2014, although with a shrinkage between 2000s and 2010s (Figures 7 and 8). The shrinkage of oases between 2000s and 2010s may arise from the rapid urbanization and expansion of farmland (Figure 10b). The rapid growth of population and urbanization rate after 2000 (Figure 10a) probably led to the destruction of large-scale cropland and vegetated area. In the meantime, the land reclamation for crop planting may change the original ecosystems around the new cropland and resulted in large scale land degradation.

The spatial pattern of vegetation cover changes between 1990s and 2014s (Figures 3f and 4) could be explained by the spatial difference of water consumption and allocation along the Tarim River (Figure 9). The increasing streamflow in headwaters and decreasing streamflow in mainstream of Tarim River suggested an increasing water consumption in the upper reaches and headwaters,

which to large extent account for the expansion of oases in the south part of South Xinjiang, despite of some sparse decrease. The relatively large-scale decrease in oases vegetation cover in Northern part of South Xinjiang (Bayinguole) maybe resulted from the reducing water supply in the middle and lower Tarim River (Figure 9). Following the frequent dry-ups in the middle and lower Tarim River (Figure 8f), water supply for irrigation and crop production reduced, resulting in land degradation and bare lands.

The multiple regression equation derived from the data of 18 sample counties are given as follow:

$$A = 0.148R + 0.089T + 0.064P + 0.496L$$

Here, R means rainfall or precipitation (mm); T means temperature (℃); P means population (person); and L means arable land area (km²). The relative contribution of each variables was derived by dividing their coefficient by the sum of all the coefficients [37]. The results show that annual precipitation, mean annual temperature, population, and farmland have 18.5%, 11.2%, 8%, and 62.3% contribution to oases area change, respectively. Collectively, human activities contribute 70% of oases area change. Farmland reclamation and subsequent spatial change of water-heat flux primarily account for the oases expansion, which has more than 60% contribution. This suggests that the large scale water diversion and transformation for irrigation has to great extent change the water-heat flux and vegetation growth within the oasis [15,30,31,36].

5. Conclusions

Dryland vegetation responds sensitively to climate change and human activities. The vegetation change has changed the ecological environment and exerted great pressure on social-economic development. Remote sensing provides a useful tool to monitor long-term vegetation dynamics, especially in drylands with less gauging data. In this study, the vegetation cover change of the Tarim Basin was using Landsat data set of six epochs, 1975s, 1990s, 2000s, 2005s, 2010s and 2014. The originally orthorectified datasets were converted from DN raw products to usable surface reflectance products through atmospheric correction. The NDVI maps were produced to show the spatiotemporal changes of oases. We have the following conclusions.

(1) The vegetation coverage of oases increased from 34600 km² in 1975s to 101000 km² in 2014. However, vegetation coverage decreases from 77600 km² in 2000s to 42680 km² in 2010s. At prefecture scale, the temporal changes of oases area in other four prefectures have the same increasing-decreasing-increasing changing trends with the whole study region except Hotan.

(2) The increasing precipitation and decreasing potential evapotranspiration would improve the vegetation growth and expansion of oases, particularly along the margin of the desert. However, large scale expansion of oases mainly resulted from increased water irrigations. The percentage of annul water irrigations increased from 26% in 1950s to 52% in 2000s in the upper Tarim River, and decreased from 27% in 1950s to 9% in 2000s in the lower Tarim River. The decrease of oases area from 2000s to 2010s probably resulted from the rapid urbanization and intensive land reclamation.

(3) The spatial pattern of vegetation cover changes between 1990s and 2014s could be explained by the spatial difference of water irrigations and allocation along the Tarim River. The increasing streamflow in headwaters and decreasing streamflow in mainstream of Tarim River suggested an increasing water consumption in the upper reaches and headwaters, which to large extent account for the expansion of oases in the south part of South Xinjiang. The large-scale local decrease in oases vegetation cover in Northern part of South Xinjiang (Aksu and Bayinguole) maybe resulted from the reducing water supply and intensive land reclamation in the middle and lower Tarim River.

(4) The results of multiple regression show that human activities contribute 70% of oases area change. Farmland reclamation is the primary determinant for the oases expansion, which has more than 60% contribution. Human induced water resources reallocation and heat energy balance is the primary cause of total oasis change.

Author Contributions: Y.M conceived and designed the experiments; A. M., F. Y., J. W and Y.M. performed the experiments; Y.M. analyzed the data; Y.M. wrote the paper.

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