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An analysis of oasis evolution based on land use and land cover change:

A case study in the Sangong River Basin on the northern slope of the Tianshan Mountains

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Abstract: This study investigated oasis evolution and the changes of peripheral desert in the Sangong River Basin since the 1950s by rebuilding seven land cover maps derived from black-and-white aerial photographs (1958, 1968, and 1978), a color-infrared aerial photograph (1987), Landsat Thematic Mapper (TM) imagery (1998), Satellite Pour l'Observation de la Terre (SPOT) imagery (2004), and Landsat Operational Land Imager (OLI) imagery (2014). The results showed that: (1) Since 1950, the oasis consecutively expanded more than four times from an alluvial fan to an alluvial plain, causing the shrinkage of desert landscapes that were dominated by a *Haloxylon ammodendron Bunge* community (HBC) and a *Tamarix chinensis Lour* community (TLC). Furthermore, the primary (1958–1968) and final (2004–2014) stages were the most important periods, during which agricultural land experienced the most rapid expansion during the period 1958–1968, and the built-up area showed the most rapid expansion after the 2000s. (2) Two basic management modes, a "local mode" formed by the local governments and a "farm management mode" developed by Xinjiang Production and Construction Corps, together promoted oasis evolution under various land-use and land-cover (LULC) stages. (3) The evolution of the modern oasis during the 1950s–2004 showed the general features of an arid oasis, while during the period of 2004–2014 it was characterized by a large-scale inter-basin water diversion or the import of new water sources. (4) The oasis expanded at the expense of desert vegetation, resulting in distinct variation in the structure of the desert plant community, which will make it more difficult to protect the desert ecosystem.

Keywords: oasis evolution; land-use and land-cover change; desert plant community; land management; Sangong River Basin

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1 Introduction

As one of the most important components of global change, land-use and cover change (LUCC) has received worldwide attention (Turner II, 1994; Pascual, 2003; Foley, 2005; Gao, 2015). However, the evaluation of LUCC in arid regions was scarcely quantified before the 1980s due to the unavailability of satellite data (Liu, 2009; Ma, 2013; Yang, 2013; Huang, 2015; Luo, 2015). There were many uncertainties in previous studies caused by the use of low-resolution images, short data series, and scattered historical data, resulting in a lack of knowledge regarding the effects of LUCC on climate change and the carbon/water cycle (Ge, 2008; Ye, 2009; Li, 2010; Liu, 2011).

LUCCs in China, especially in the arid areas of northwest China, including Xinjiang, have been significant since the 1950s. Due to massive exploitation at the watershed level from troops stationed in Xinjiang from the 1950s to the 1960s (Chen, 2008; Chen, 2008; Liu, 2014), land-use and land-cover (LULC) in arid watersheds has changed remarkably, with a transfer from desert to artificial oasis, and a replacement of river runoff by reservoirs and irrigation canals. However, LULC information is scarce, and some is based only on qualitative descriptions, and it is therefore difficult to assess the impact of human activity on the desert ecosystem. The northern slope of the Tianshan Mountains is an area of Xinjiang that has been heavily exploited. Studies of LUCC and its drivers have been conducted based on remote sensing images, mainly after the 1970s (Luo, 2006; Tang, 2006; Luo, 2008). We acquired aerial photographs of the Sangong River Basin for 1958 and 1968, which enabled an LUCC analysis to be conducted. As a typical case study at the watershed scale, the reconstruction of the LUCC process during the 1950s and 1960s enabled an evaluation of oasis evolution in Xinjiang.

The continuous expansion of the oasis occurred through the shrinkage of peripheral desert landscapes or a desert–oasis transition zone that was constantly transferred into artificial oasis. In previous studies, the shrinking of peripheral desert landscapes has been generally described as a change between desert and artificial oasis (agricultural land), with a lack of detailed information about how oasis expansion impacts on desert ecology (Cheng, 2005; Tang *et al*., 2006), and especially on desert plant communities. Nevertheless, vegetation plays a crucial role in desert landscapes, especially in energy transformation and material circulation. Hence, it is necessary to analyze the variation of vegetation in oasis–desert ecosystems to comprehensively understand the ecological response.

Therefore, this study analyzed oasis evolution based on LUCC, as a case study in the Sangong River Basin. Our major objectives were as follows. (1) To rebuild an LULC dataset from the 1950s based on black-and-white aerial photographs (1958, 1968, and 1978), a color-infrared aerial photograph (1987), Landsat Thematic Mapping (TM) imagery (1998), Satellite Pour l'Observation de la Terre (SPOT) imagery (2004), and Landsat Operational Land Imager (OLI) imagery (2014). (2) To analyze variation in LULC in an oasis and plant communities in a desert based on a statistical model. (3) To reveal the extent of the socio-economic background and different land management regimes as drivers of change, and conduct a preliminary discussion on the ecological effects of oasis expansion.

2 Materials and methods

2.1 Study area and environmental conditions

The Sangong River drains from the Tianshan Mountains and flows northward into the southern Junggar Basin in Xinjiang (Figure 1). The basin is lower lying in the south than in the north, and is a typical mountain–oasis–desert ecosystem. The study area was the plain in the Sangong River Basin, which consists of two physiographical units: an oasis in the middle and a peripheral desert (Figure 1). The oasis in this study was specified as an artificial oasis, and developed from natural land-cover into a highly artificial ecosystem due to human development and management activities (Chen *et al.*, 2008). The oasis evolution started in 1949, which marked the peaceful liberation of Xinjiang. Due to different modes of zonal management, the study area could be divided into a "farm management mode (FMM)" developed by the Xinjiang Production and Construction Corps (XPCC) and composed of the Fubei and Liuyunhu farms, and a "local mode (LM)" formed by the local governments and composed of Fukang city and bearby towns including Jiuyunjie.

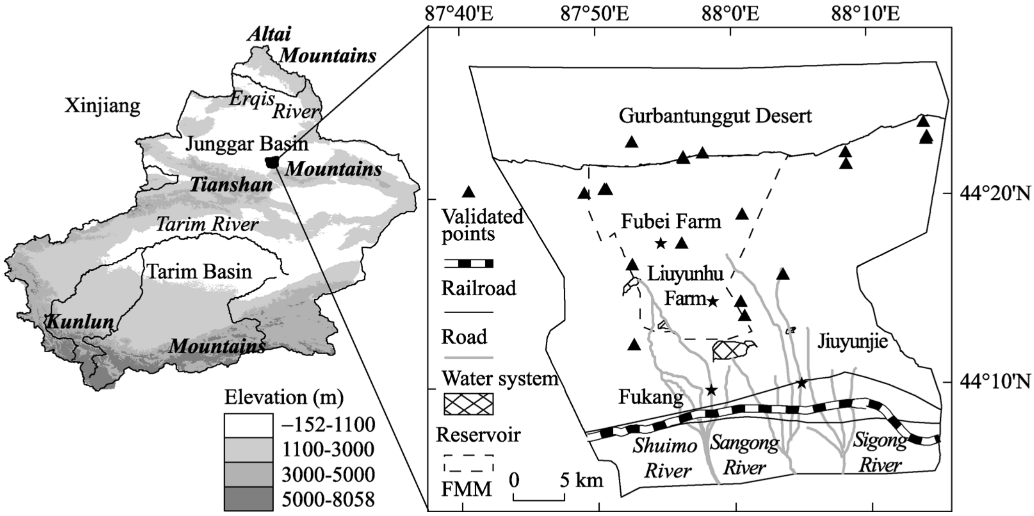

Figure 1 Location of the Sangong River Basin on the northern slope of the Tianshan Mountains

2.2 Data source

Several data sources were used in this study. (1) Black-and-white aerial photographs (1958, 1968, and 1978), a color-infrared aerial photograph (1987), Landsat TM imagery (1998), SPOT5 imagery (2004), and Landsat OLI imagery (2014) that were used to obtain LUCC data (Table 1). (2) High-resolution Google Earth images for 2002, 2006, and 2014 that were used to validate the LULC types. (3) *The Annals of Fukang County* and the survey data and interviews, which were used by a researcher to verify LUCC. (4) LULC and plant community distribution data obtained by a field investigation in 2014, which determined the LULC in 2014. (5) Documented data that validated LULC in 1978, 1987, and 1998, and desert plant communities in 2004. (6) Topographical maps and a digital elevation model (DEM), to determine the boundary of the study area.

Table 1 Remote sensing images used in the study

Year	Data type	Image acquisition date	Resolution or scale
1958	Black-and-white aerial photographs	1958	1:35,000
1968	Black-and-white aerial photographs	1968	1:35,000
1978	Black-and-white aerial photographs	August 1978	1:35,000
1987	Color-infrared aerial photograph	June 1987	1:70,000
1998	Landsat TM imagery	August 1998	30 m
2004	SPOT5 imagery	June 2004	10 m
2014	Landsat OLI imagery	August 2014	15 m

Aerial photogrammetry professionals processed two digital orthophoto maps from aerial photographs taken in 1958 and 1968. All remote sensing images were converted into the World-Geodetic-System-84 (WGS-84) geographical coordinate system and Universal Transverse Mercator (UTM) (45°N) projection coordinate system and then geometrically corrected. Aerial photographs taken in 1978 and color infrared photographs taken in 1987 were geometrically corrected based on topographic maps from the 1980s. SPOT5 imagery from 2004 and Landsat OLI imagery from 2014 were geometrically corrected by Google Earth imagery in 2004 and 2014, with the root mean square error (RMSE) within 0.5 pixels. All images were cross corrected to conduct the LUCC analysis.

The LULC classification referred to the national standards of land-use classification (GB/T21010-2007) (MLR, 2007), oasis LULC classifications, and plant community classifications used in previous studies (Luo, 2003; Lv, 2007; Chen, 2008; Luo *et al*., 2015). Plant communities were named after the dominant species, based on the principles of plant community classification, and their spatial distribution was classified by combining the survey data with remote sensing images. LULC classification was divided into three levels. The first grade contained oasis, desert, and mountain; the second grade included agricultural land, built-up area, water, soil-desert, and sandy-desert; and the third grade was a finer classification of soil-desert and sandy-desert (Table 2). Some linear features, such as rural roads, ditches, and shelterbelts, which could not be classified for technical reasons, were regarded as agricultural land, built-up areas, or other classifications and were not listed separately.

A natural oasis was situated in the alluvial plain before 1949, but did not develop further due to the lack of water facilities. Based on this knowledge, we referred to *The Annals of Fukang County* and socioeconomic statistics (1949–1992) to roughly determine the scope of the oasis in 1949. In addition, due to the relatively low levels of human activity from 1949 to the 1960s, the LULC in the oasis remained unchanged between 1949 and 1958, with the LULC and plant community distribution of 1949 remaining largely intact.

LULC classification was evaluated by the overall accuracy and Kappa coefficient (Giles, 2002) (Table 3). Overall accuracy represents the degree of consistency in LULC between random samples and the actual land cover type. Kappa coefficients represent the consistency of two images (between classification maps and Google Earth images, field data, or credible classification maps), determined by not only the proportion of correct classifications, but also the errors in classification (Donker, 1993). It is generally accepted that the Kappa coefficient represents the classification accuracy. When the Kappa coefficient is greater than

Table 2 Classification of land use and land cover (LULC)

Grade I	Grade II	Grade III (abbreviation)
Oasis	Agricultural land: includes irrigated lands, and other cultivated lands equipped with irrigation facilities Built-up area: includes cities (Fukang City and the South Junggar oil-based towns), land used for townships and settlements, and industrial and mining land (rural villages, industrial enterprises, mining areas, stone pits, and brickyard fields). Water: includes reservoirs and ponds.	
Desert	Soil-desert	*Haloxylon ammodendron* Bunge Community (HBC), *Tamarix chinensis* Lour Community (TLC), *Reaumuria songarica* (Pall.) Maxim Community (RMC), *Tamarix chinensis* Lour – *Reaumuria songarica* Maxim Community (TL-RMC), Grass (G)
	Sandy-desert	*Haloxylon ammodendron* Bunge Community (HBC), *Reaumuria songarica* Maxim Community (RMC)
Mountain	Mountain (only low mountains and hills existed in the study area)	

0.75, it is considered that there is good consistency between two images.

LULC in 2014 was assessed using random samples of Google Earth high-resolution satellite images from July 14, 2014 and survey data collected on August 9, 2014. LULC in 2004 was validated by random samples of Google Earth high-resolution satellite imagery data from June 16, 2004, and plant community distribution data (Lv *et al.*, 2007). LULC in 1998, 1987, and 1978 was validated by stratified random sampling with reference to the LULC map of the oasis (agricultural land, built-up, water, etc.) (Luo *et al.*, 2003; Luo *et al.*, 2008), with each layer containing 30 random points (Table 3).

Table 3 Accuracy assessments of classifications of land use and land cover (LULC) in the oasis

Year	Method	Validation data	Overall accuracy (%)	Kappa coefficient
1978	Stratified random sampling	LULC in oasis (Luo *et al.*, 2003; Luo *et al.*, 2008)	87.50	0.84
1987	Stratified random sampling	LULC in oasis (Luo *et al.*, 2003; Luo *et al.*, 2008)	90.00	0.88
1998	Stratified random sampling	LULC in oasis (Luo *et al.*, 2003; Luo *et al.*, 2008)	92.00	0.89
2004	Random sampling	Google images with high-resolution and plant community distribution (Lv *et al.*, 2007)	90.67	0.89
2014	Random sampling and field investigation	Google images with high-resolution survey data	87.97	0.86

Due to the insufficient amount of data for sampling, the classification accuracy of LULC in 1958 and 1968 could not be verified. However, because the aerial photographs in 1958 and 1968 had a scale of 1:35000, higher than the other images, the LULC accuracy in the oasis would be similar to or even higher than for 1978. There was no obvious variation in desert plant communities, except for the area influenced by human activities. In addition, desert plant communities in 1958 and 1968 were interpreted by the same researchers who participated in the field investigation of vegetation communities; thus, the interpretation accuracy of desert plant communities was similar to that in 2014. Moreover, auxiliary information such as crop area and yield data from *The Annals of Fukang County* and socioeconomic statistics were used to verify the oasis area in 1950. The classification accuracy in different periods satisfied the requirements of LUCC research (Janssen, 1994).

2.3 Methods

LUCC processes can be described by variations in LULC (Luo *et al.*, 2003; Pontius, 2004; Luo *et al.*, 2008; Feng, 2011), which directly reflect the changing extent of each land type during a given period. Quantitative parameters based on variations in the area of land type include the net change (ΔU), the relative change (ΔS), the status and trend of individual land types (Ps), and the total status and trend of the whole area (Pt) (Table 4).

Table 4 Statistical models for the quantitative analysis of land use and cover change (LUCC)

	Parameter	Meaning	Expression
Individual land types	Net change (ΔU)	The areal change of a land type over a period	$\Delta U = (U_b - U_a) / U_a \times 100\%$
	Relative change (ΔS)	Sum of the loss and gain (i.e., the overall change) of a land type over a period	$\Delta S = (\Delta U_a + \Delta U_b) / U_a \times 100\%$
	Status and trend (Ps)	Describes the strength of a contraction or expansion in a land type, and describes whether or not a particular LULC type is in a stable state	$Ps = \frac{\Delta U_{in} - \Delta U_{out}}{\Delta U_{in} + \Delta U_{out}}$ $-1 \leqslant Ps \leqslant 1$ and $\Delta U_{in} + \Delta U_{out} \neq 0$
Whole area	Total status and trend (Pt)	Describes the state of LUCC in the whole study area	$Pt = \frac{\sum_{i-1}^{n} \lvert \Delta U_{in} - \Delta U_{out} \rvert}{\sum_{i-1}^{n} \Delta U_{in} + \Delta U_{out}}, 0 \leqslant Pt \leqslant 1$

Notes: U_a represents the area of a LULC type at the beginning of a period; U_b represents the area of a land type at the end of a period; ΔU_{out} ($\geqslant$0) represents the area of a land type lost or converted to other land types over a period; ΔU_{in} ($\geqslant$0) denotes the total area gained by or converted from other land types. Ps (> 0) reflects the expansion of a land type, Ps (< 0) reflects the contraction of a land type, and Ps (= 0) indicates that losses and gains for a land type are balanced. Pt is the total status and trend of the whole area. To better determine the influence of LUCC on Pt, it can be divided into four levels: (1) Balanced status (0–0.25), where there is equality between the losses and gains of a particular land type in a given area; (2) Quasi-balanced status (0.25–0.50), where there is a slight inequality between losses and gains; (3) Unbalanced status (0.50–0.75), where there is a significant difference between losses and gains; (4) Extremely unbalanced status (0.75–1), which indicates an extremely significant difference between the losses and the gains.

3 Results and discussion

3.1 The process of oasis evolution based on LUCC

Figure 2 shows the position of the oasis in the Sangong River Basin in eight years (1949, 1958, 1968, 1978, 1987, 1998, 2004, and 2014). Although the scale and status of oasis expansion were significantly different during these periods (Figures 2 and 3, Tables 5 and 6), expansion was the main feature throughout its evolution. Based on the size and status of the oasis, the expansion process could be divided into four stages: (1) expansion along a river (from 1949 to 1968), (2) abandonment (from 1968 to 1978), (3) intensive conversion and extensive expansion (from 1978 to 2004), and (4) urbanization (from 2004 to 2014) (Figure 3).

The oasis in 1950 was located in the alluvial fan and its edge in Sangong River, extending northward to the groundwater overflow zone (Figure 2a), where abundant water resources, a deep soil layer, and fertile soil were present. This location was ideal for the development of traditional agriculture, and therefore the location of the oasis remained relatively stable (Luo et al. 2004). The plain beyond the groundwater overflow zone mainly consisted of desert

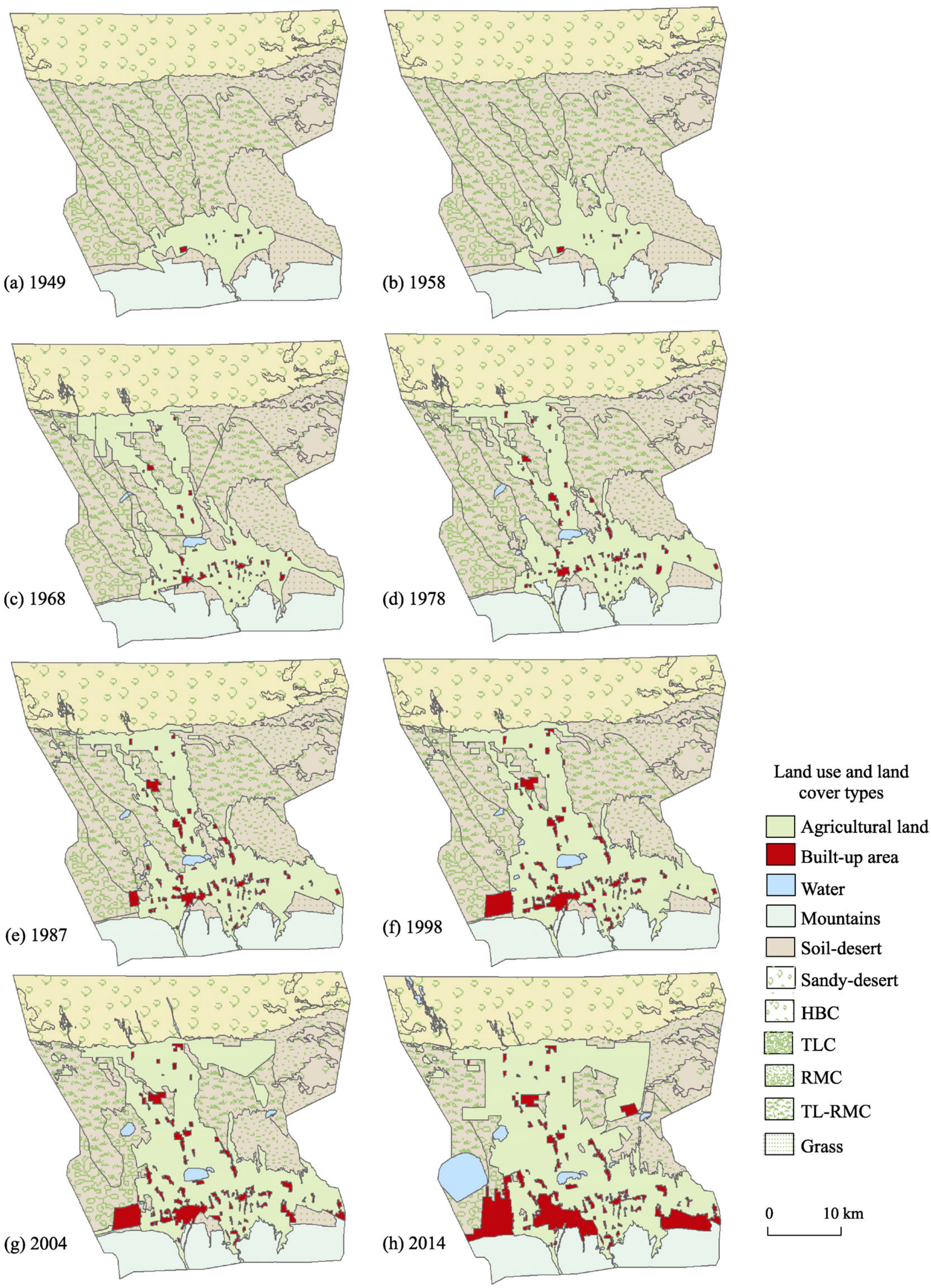

Figure 2 The spatial patterns of land-use and land-cover (LULC) in the Sangong River Basin from 1949 to 2014. (HBC, TLC, RMC, and TL-RMC are abbreviations of *Haloxylon ammodendron Bunge* Community, *Tamarix chinensis* Lour Community, *Reaumuria songarica* Maxim Community, and *Tamarix chinensis* Lour-*Reaumuria songarica* Maxim Community, respectively.)

landscape, which was unused by the local people who were unable to develop an artificial oasis, resulting from constraints in production techniques and water availability before 1950. After the peaceful liberation of Xinjiang in 1949, troops collectively undertook an oasis development project in 1954, forming the XPCC. The XPCC performed the historical mission of "reclaiming land and guarding the border areas", which led to the large-scale exploitation of land, and began the massive expansion of the oasis. This period was the early stage of the modern oasis evolution (1949–1958), with the main task being the expansion of the old oasis along with a simple diversion of groundwater along the river (Figure 2b). Compared with 1949, the oasis area in the Sangong River Basin had increased by 29.06 km^2 (i.e., a 30% increase) by 1958.

From 1958 to 1968, water reservoirs were built in the Sangong River Basin, and a large-scale expansion of the oasis occurred, with a significant transformation from soil-desert to oasis (Figure 2b-c and Figure 3a-b). Fubei and Liuyunhu farms were established by the XPCC in the Sangong River Basin in 1959, and the plain reservoir was built in the groundwater overflow zone for flood storage. This resulted in a massive reclamation in the soil-desert and the establishment of agricultural irrigation and forest protection (Figure 2b-c and Figure 3a-b). At the same time, as water moved from the piedmont and productivity improved, the oasis in the alluvial fan expanded upstream; thus, this period of oasis expansion is also referred to as "tracing and migrating towards the origin". During this period, the oasis expanded significantly, experiencing its fastest rate of expansion over the whole period of the evolution of the modern oasis. The oasis area increased by 123.48% from 1958 to 1968, and the extent of agricultural land and the built-up area increased by 115% and 502%, respectively, based on the analysis of ΔU and ΔS (Table 6).

During the period of 1968–1978, the LUCC of the oasis in the Sangong River Basin was in a balanced state (Pt = 0.34) with the outward expansion of agricultural land gradually slowing (Figure 2c-d and Figure 3c-d). Compared with the previous period, only 10% of the increased extent of the oasis was influenced by the Cultural Revolution in China. The Cultural Revolution was a special period in Chinese history, during which there was falling productivity and a stagnant economy, resulting in a relatively slower expansion of the oasis. In addition, there had been a massive exploitation of land in the previous period, with a limited awareness of oasis development and poor drainage in the new oasis. This resulted in secondary salinization of the soil and a dereliction of irrigation land in the oasis that was not suitable for cultivation.

From 1978 to 2004, LULC was mutually transformed in the oasis and expanded outward in a relatively unstable state (Figure 2d-g), i.e., from a quasi-balanced to unbalanced state (the oasis Pt values were 0.45, 0.75, and 0.69 in the three periods from 1978 to 1987, 1987 to 1998, and 1998 to 2004, respectively). And unstable state is a normal state in oasis evolution. In total, the extent of agricultural land and the built-up area increased by 120.26 and 37 km^2, respectively, during this period. The built-up area was 2.5 times larger than in 1978, with most of the increase occurring from 1987 to 1998. Most of the LUCC occurred through the "household contract responsibility system" after the "reform and opening-up" period.

From 2004 to 2014, many water reservoirs was established (the area was three times larger than before) and the drip irrigation technique became popular, improving agricultural water use efficiency and contributing to a further large-scale expansion of the oasis (Figure 2g-h

Figure 3 Maps showing the land-use and land-cover change (LUCC) in the Sangong River Basin in the period 1958–2014

Table 5 The areal structure of land-use and land-cover (LULC) in the Sangong River Basin in the period 1958–2014

Year	Parameter	Oasis				Desert		
		Water	Agricultural land	Built-up area	Total	Sandy-desert	Soil-desert	Total
1958	Area (km^2)	0.00	127.50	1.73	129.23	380.46	828.56	1209.02
	Proportion of Grade I land	0.00	0.99	0.01	1	0.31	0.69	1
	Proportion of study area	0.00	0.08	0.00	0.09	0.25	0.55	0.80
1968	Area (km^2)	4.49	273.89	10.42	288.81	376.08	672.67	1048.75
	Proportion of Grade I land	0.02	0.95	0.04	1	0.36	0.64	1
	Proportion of study area	0.00	0.18	0.01	0.19	0.25	0.45	0.70
1978	Area (km^2)	7.09	298.43	15.64	321.16	374.81	646.11	1020.93
	Proportion of Grade I land	0.02	0.93	0.05	1	0.37	0.63	1
	Proportion of study area	0.00	0.20	0.01	0.21	0.25	0.43	0.68
1987	Area (km^2)	6.45	305.81	26.07	338.34	374.11	635.07	1009.18
	Proportion of Grade I land	0.02	0.90	0.08	1	0.37	0.63	1
	Proportion of study area	0.00	0.20	0.02	0.22	0.25	0.42	0.67
1998	Area (km^2)	8.11	356.69	43.45	408.25	373.54	565.83	939.37
	Proportion of Grade I land	0.02	0.87	0.24	1	0.40	0.60	1
	Proportion of study area	0.01	0.24	0.03	0.27	0.25	0.38	0.62
2004	Area (km^2)	10.70	418.68	52.56	481.94	372.39	494.05	866.44
	Proportion of Grade I land	0.02	0.87	0.11	1	0.43	0.57	1
	Proportion of study area	0.01	0.28	0.03	0.32	0.25	0.33	0.58
2014	Area (km^2)	42.95	500.97	100.94	644.86	370.68	333.14	703.82
	Proportion of Grade I land	0.07	0.78	0.16	1	0.53	0.47	1
	Proportion of study area	0.03	0.33	0.07	0.43	0.25	0.22	0.47

and Figure 3g-h). Peripheral desert was further developed into agricultural land and the built-up area increased significantly, and thus LUCC was significant and remained in an unbalanced stage during this period. The oasis also experienced a fast rate of urbanization during this period, with the built-up area expanding by 48.38 km^2. LUCC in the whole study area was still in an unbalanced state (Pt = 0.83), with a similar extent of change to that in 1958 and 1968. During this period, the LUCC features of the oasis were similar to other oases in which water facilities had been improved (inter-basin water transfer and drip irrigation).

Although there have been significant differences in the speed, size, and status of the various stages of oasis expansion under different socioeconomic conditions, the oasis has clearly expanded over time. The area of oasis in the Sangong River Basin has increased by 544.7 km^2, which is 4.44 times larger than in 1949. By considering the uncertainties in the 1949 boundary described in *The Annals of Fukang County*, historical documents, and LULC types in 1958, the current oasis area was more accurately compared with that of 1958, and was found to have increased 3.99-fold. The primary (1958–1968) and final (2004–2014) stages were the most remarkable periods of oasis expansion, and were the most important stages in the development of the modern oasis. The oasis evolution in the Sangong River Basin during the period 1950–2004 was similar to the oasis development reported in the

Table 6 Land-use and cover (LUCC) change in the oasis–desert system of the Sangong River Basin in the period 1958–2014

Period	Parameter	Oasis				Desert			Whole area
		Agricultural land	Built-up area	Water	Total	Soil-desert	Sandy-desert	Total	
1958–1968	Δ*U* (%)	114.82	501.75	–	123.48	–17.96	–1.15	–12.43	
	Δ*S* (%)	134.44	501.75	–		24.62	1.15		
	Ps	0.85	1	1		–0.83	–1		
	Pt				0.86			0.84	0.85
1968–1978	Δ*U* (%)	8.96	50.13	57.9	11.20	–3	0.19	–1.81	
	Δ*S* (%)	31.57	53.92	60.42		11.35	1.27		
	Ps	0.28	0.93	0.96		–0.21	0.15		
	Pt				0.34			0.52	0.43
1978–1987	Δ*U* (%)	2.47	66.65	–8.99	5.35	–1.52	0.08	–0.91	
	Δ*S* (%)	9.43	76.01	13.12		12.53	1.65		
	Ps	0.26	0.88	–0.69		–0.01	0.05		
	Pt				0.45			0.45	0.45
1987–1998	Δ*U* (%)	16.64	66.67	0.45	20.66	–11.19	0.11	–6.86	
	Δ*S* (%)	23.92	68.28	36.08		27.7	0.7		
	Ps	0.7	0.98	0.71		–0.37	0.16		
	Pt				0.75			0.59	0.65
1998–2004	Δ*U* (%)	17.38	20.97	31.87	18.05	–13.13	–0.3	–7.85	
	Δ*S* (%)	25.82	22.49	54.65		36.35	0.99		
	Ps	0.67	0.93	0.58		–0.37	–0.31		
	Pt				0.69			0.83	0.78
2004–2014	Δ*U* (%)	19.65	92.03	301.54	33.80	–29.53	–0.85	–16.76	
	Δ*S* (%)	26.28	92.45	350.70		37.82	1.90		
	Ps	0.75	1	0.86		–0.8	–0.45		
	Pt				0.83			0.79	0.81
1958–2014	Δ*U* (%)	292.92	5728.99	–	399.00	–57.39	–1.91	–39.14	
	Δ*S* (%)	334.45	5728.99	–		71.44	1.99		
	Ps	0.88	1	1		–0.81	–0.96		
	Pt				0.91			0.84	0.88

Notes: Δ*U*: the net change; Δ*S*: the relative change; *Ps*: the status and trend of individual land types; *Pt*: and total status and trend of the whole area

Manas River and Heihe River basins (Cheng *et al.*, 2005; Liao, 2012), both of which show the general features of oasis evolution in arid areas. During the period 2004–2014, LUCC was the result of large-scale inter-basin water diversion or the development of new water sources.

At the regional level, LUCC differed in the two zones of LM (formed by the local governments) and FMM (developed by the XPCC).

During the period of 1958–1968, the oasis area increased 9.48-fold, with the majority of the expansion occurring in the FMM. The area of increase was only 0.46 times in the LM (Table 7). During the "Great Leap Forward" phase of Chinese economic development and the early period of the Cultural Revolution, poor productivity and a lack of understanding of

Table 7 Comparisons of land-use and cover change (LUCC) between the farm management mode (FMM) and the local mode (LM) in the oasis in the Sangong River Basin in the period of 1958–2014

Period	Parameter	FMM			LM		
		Agricultural land	Built-up area	Total	Agricultural land	Built-up area	Total
1958–1968	Δ*U* (%)	945.49	–	9.48	42.32	376.33	0.46
	Δ*S* (%)	950.01	–		63.27	376.34	
	Ps	1.00	1.00		0.67	1.00	
	Pt			1.00			0.70
1968–1978	Δ*U* (%)	–5.64	0.57	–0.05	18.31	37.12	0.19
	Δ*S* (%)	28.01	99.52		33.99	41.91	
	Ps	–0.20	1.00		0.54	0.89	
	Pt			0.26			0.56
1978–1987	Δ*U* (%)	0.35	0.33	0.00	3.56	70.69	0.03
	Δ*S* (%)	6.80	56.87		10.80	83.35	
	Ps	0.05	0.99		0.33	0.85	
	Pt			0.30			0.49
1987–1998	Δ*U* (%)	24.14	0.12	0.24	12.92	78.53	0.13
	Δ*S* (%)	26.18	33.34		22.81	80.53	
	Ps	0.92	0.98		0.57	0.98	
	Pt			0.93			0.67
1998–2004	Δ*U* (%)	28.64	0.13	0.29	11.25	23.32	0.12
	Δ*S* (%)	33.67	11.96		21.55	25.23	
	Ps	0.85	1.00		0.52	0.92	
	Pt			0.85			0.58
2004–2014	Δ*U* (%)	18.18	1.00	0.18	20.58	110.73	0.32
	Δ*S* (%)	18.97	13.03		30.94	111.29	
	Ps	0.96	1.00		0.67	0.99	
	Pt			0.96			0.79
1958–2014	Δ*U* (%)	1768.29	–	17.77	164.15	5072.49	2.00
	Δ*S* (%)	1779.61	111.08		208.33	74.90	
	Ps	0.99	1.00		0.79	1.00	
	Pt			0.99			0.84

Notes: Δ*U*: the net change; Δ*S*: the relative change; *Ps*: the status and trend of individual land types; *Pt*: total status and trend of the whole area

oasis evolution, together with the extensive and rapid land reclamation resulted in ecological degradation. Poor drainage in the new oasis area, a falling underground water level, and soil salinization resulted in the abandonment of the oasis. In the process of developing the new oasis, much of the TL-RMC communities disappeared, and peripheral HBC, RMC, and other natural vegetation was cut for firewood. The vegetation in the area suffered unprecedented levels of damage.

In addition, some of the LUCC in the LM and FMM regions also resulted from the differences in land management, especially after 1978 due to the Chinese reform and opening-up policy. Land-management differences resulted in zonal LUCC discrepancies. During the initial stage of reform and opening-up (from 1978 to 1987), the LM experienced a conversion from a "collective ownership land system" to the "household contract responsibility system", separating ownership and usage rights of farmers and requiring family units to undertake irrigation. This reformation led to remarkable changes in LULC types in the LM, especially in agricultural land. Nevertheless, agricultural land expanded little (only by 0.35%) in the FMM. During the later stage of reform and opening-up (from 1987 to 2004), the booming productivity resulted in the irrigation of abandoned farmland in the inner oasis area in the FMM. This occurred under a new policy that promoted uniform sowing and fertilizer application, as well as more efficient irrigation methods, which benefited both the economy and the local ecology. LULC conversion inside and outside the oasis was significant in the FMM and was much greater than in the LM during this period (Table 7).

Throughout the entire process of oasis evolution, the different land management regimes in the FMM and LM resulted in increasing discrepancies of LUCC. The land in the FMM was "state-owned", while it was "collectively-owned" in the LM. The two completely different models of land ownership resulted in significant differences in the land management modes throughout the various historical stages of development, with their different economic systems, causing LUCC to take different forms in the different areas during these periods. For example, after the reform and opening-up period, the LM was uniformly sowed and irrigated by small family units, while the FMM was uniformly sowed and fertilized, with more efficient irrigation methods applied, resulting in differences in land reclamation, fertilization, irrigation management, prevention of soil salinization and desertification, defense against natural disasters, agricultural development, and even socioeconomic benefits. This contributed to huge diversities in LUCC between the LM and FMM during the evolution of the modern oasis (Table 7). The entire process of the evolution of the modern oasis has been promoted by practices in the LM and FMM, together with the various LUCC stages.

3.2 The variation of peripheral desert plant communities during oasis expansion

Consecutive expansion was a characteristic of the oasis evolution, which resulted in deforestation and the destruction of desert vegetation. RMC, TL-RMC, HBC, and other natural plant communities in the area where the oasis developed were degraded or even disappeared, which resulted in a significant variation of the area and structure of plant communities as the oasis expanded (Table 8 and Figure 2).

At the beginning of oasis evolution, the area of soil-desert was larger than the area of sandy-desert. However, as the oasis expanded, the area of soil-desert decreased, becoming smaller than the area of sandy-desert in the final stage of oasis expansion (Table 8). The oasis expansion in the soil-desert was accompanied by a decline in the plant communities in the same areas. The most significant decrease was for HMC, with a reduction in area of 192.06 km^2 over the 65-year study period, followed by TLC, with a decrease of 154.47 km^2. The area of sandy-desert decreased only by 9.78 km^2, and was less influenced by the distance to water than soil-desert. The area of HBC declined only by 7.28 km^2. Although much of the HBC in soil-desert was destroyed in the early period of oasis evolution, the native HMC was not visible (Sun, 2010). Only the secondary HMC was apparent, having benefited from protection and enclosure, as well as the increase in precipitation after 1980 (Liu, 2005). The increase in precipitation led to a trend for desert vegetation cover to increase, with the shallow roots of shrubs and herbs being more sensitive to precipitation (Wang, 2011).

Table 8 The land use and cover change (LUCC) in deserts in the Sangong River Basin in the period of 1958–2014

Year	Parameter	Soil-desert						Sandy-desert			Total
		TL-RMC	RMC	TLC	HBC	G	Total	RMC	HBC	Total	
1958	*S*	324.07	221.24	193.78	36.85	52.62	828.56	22.62	357.84	380.46	1209.02
	*Pct*1	0.39	0.27	0.23	0.04	0.06		0.06	0.94		
	*Pct*2	0.27	0.18	0.16	0.03	0.04	0.69	0.02	0.30	0.31	
1968	*S*	265.57	196.03	119.79	36.81	54.46	672.67	22.62	353.46	376.08	1048.75
	*Pct*1	0.39	0.29	0.18	0.05	0.08		0.06	0.94		
	*Pct*2	0.25	0.19	0.11	0.04	0.05	0.64	0.02	0.34	0.36	
1978	*S*	264.22	170.18	129.21	36.76	45.75	646.11	21.69	353.13	374.81	1020.93
	*Pct*1	0.41	0.26	0.20	0.06	0.07		0.06	0.94		
	*Pct*2	0.26	0.17	0.13	0.04	0.04	0.63	0.02	0.35	0.37	
1987	*S*	259.37	174.21	115.62	36.23	49.64	635.07	21.60	352.51	374.11	1009.18
	*Pct*1	0.41	0.27	0.18	0.06	0.08		0.06	0.94		
	*Pct*2	0.26	0.17	0.11	0.04	0.05	0.63	0.02	0.35	0.37	
1998	*S*	247.26	157.62	103.07	36.02	21.86	565.83	21.34	352.20	373.54	939.37
	*Pct*1	0.44	0.28	0.18	0.06	0.04		0.06	0.94		
	*Pct*2	0.26	0.17	0.11	0.04	0.02	0.60	0.02	0.37	0.40	
2004	*S*	203.86	135.09	97.07	35.05	22.97	494.05	20.60	351.79	372.39	866.44
	*Pct*1	0.41	0.27	0.20	0.07	0.05		0.06	0.94		
	*Pct*2	0.24	0.16	0.11	0.04	0.03	0.57	0.02	0.41	0.43	
2014	*S*	132.01	120.57	39.31	35.05	6.20	333.14	20.12	350.56	370.68	703.82
	*Pct*1	0.40	0.36	0.12	0.11	0.02		0.05	0.05		
	*Pct*2	0.19	0.17	0.06	0.05	0.01	0.47	0.03	0.50	0.53	

Notes: *S*: area (km^2); *Pct*1: proportion of Grade II land; *Pct*2: proportion of desert land. (HBC, TCL, RMC, TL-RMC, and G are abbreviations of *Haloxylon ammodendron* Bunge Community, *Tamarix chinensis* Lour Community, *Reaumuria songarica* Maxim Community, *Tamarix chinensis* Lour – *Reaumuria songarica* Maxim Community, and Grass, respectively.)

3.3 Analysis of the ecological effects of oasis evolution

There is a lack of inter-basin water transfer, although annual runoff (water) from mountainous area is relatively stable. The more it was consumed in the oasis, the less it was available for desert ecosystems. It is apparent from the oasis evolution in the Sangong River Basin that the continuous expansion of an oasis in an arid area leads to a continuous increase in water demand in the oasis (Yan, 2006). Oasis expansion causes a series of social disputes and ecological problems (such as intensified competition for limited and precious water resources in arid areas, the drying up of rivers, lake shrinkage or disappearance, reduction of biodiversity, desertification, and sandstorms), resulting in the protection of the ecosystem in the oasis periphery becoming more difficult (Saiko, 2000; Liu, 2014). With intensive oasis expansion and urbanization in arid areas, more studies are needed to fully reveal the oasis evolution process, its ecological response mechanism, and its environmental effects, which will then contribute to ecological protection, sustainable development, and socioeconomic stability.

In the later stage of development of the modern oasis, booming productivity resulted in the full utilization of various resources in the surrounding arid area. Some resources have been overexploited. The most notable example is water resources, which is the most fundamental aspect of oasis development. With the establishment of an anti-seepage water conservancy, and the promotion and popularity of advanced drip irrigation under mulch, both the consumption of water resources and water use efficiency in the oasis have been increasing. This has resulted in the reduction of groundwater recharge and lowering of groundwater levels in the desert area (Yan, 2005; Wang, 2015). Faced with the decline of groundwater levels, desert vegetation relying on groundwater can acquire water by increasing root length or depth, by allocating assimilation products to the roots as much as possible. Once the root is unable to obtain the water needed for survival, vegetation will degrade (Zhao, 2006).

In these later stages of oasis development, little irrigation water is available to infiltrate and recharge groundwater, because most of it is consumed by evapotranspiration, following the popularization of drip irrigation technology and improvements in water use efficiency. Thus, salt carried by the irrigation water was readily accumulated in the soil, especially in the root layer, negatively affecting crop yield (Su, 2011; Luo, 2014). Hence, irrigation water not only meets the demand of crop consumption, but also provides water to remove salt from the root layer soil (Sun, 2012; Sun, 2013). Consideration needs to be given to how sufficient water can be provided for this leaching process by making full use of winter fallow water for continuous irrigation. This is necessary for the long-term application of drip irrigation technology, and is also an objective of agricultural irrigation management in an oasis environment (Luo, 2014).

4 Conclusions

This study analyzed the evolution of the oasis in the Sangong River Basin by rebuilding a LUCC process using seven land cover maps derived from black-and-white aerial photographs (1958, 1968, and 1978), a color-infrared aerial photograph (1987), Landsat TM imagery (1998), SPOT imagery (2004), and Landsat OLI imagery (2014). This revealed the characteristics and ecological effects of the evolution of the modern oasis.

(1) During the period studied the oasis expanded overall, but there were significant differences in the speed, size, and status of the oasis expansion in the different stages of development and under different socioeconomic systems. The primary (1958–1968) and final (2004–2014) stages were the fastest and most important periods of oasis evolution. The oasis in the Sangong River Basin during the period of 1950–2004 displayed the general features of most arid oases, while during the period of 2004–2014 the area was characterized by large-scale inter-basin water diversions or new water sources.

(2) Two basic management modes were identified: the LM (formed by the local governments) and the FMM (developed by the XPCC). The formulation and development of these two modes resulted in significantly different land management regimes. The land under the FMM was "state-owned" while it was "collectively-owned" under the LM. Following the reform and opening-up period, the LM was irrigated by family units, while in the FMM there was uniform sowing and fertilizer application, with the use of more efficient irrigation methods, resulting in a diversity in irrigation management. This led to two different kinds of human-driven LUCC in each of the LM and FMM. The evolution of the modern oasis was

driven by a combination of the LM and FMM across the whole area.

(3) Over the period studied the oasis expanded at the expense of desert vegetation. Natural communities of HBC and TLC were destroyed and cut down, resulting in a distinct variation in the structure of desert plant communities, which has made it more difficult to protect the ecosystem of the desert–oasis. Furthermore, the expansion of the arid area surrounding the oasis has led to a continuous increase in water consumption, resulting in a series of social disputes, as well as economic and ecological problems.

References

Chen X, 2008. Land Use/Cover Change in Arid Areas in China. Beijing: Science Press, 29-30. (in Chinese)

Chen X, Luo G, 2008. Researches and progress of oasis ecology in arid areas. *Arid Land Geography*, 31(4): 487–495. (in Chinese)

Cheng W, Zhou C, Liu H *et al*., 2005. The oasis expansion and eco-environment change over the last 50 years in Manas River. *Science China: Earth Sciences*, 35(11): 1074–1086. (in Chinese)

Donker D K, Hasman A, Van Geijn H P, 1993. Interpretation of low kappa values. *International Journal of Bio-Medical Computing*, 33(1): 55–64.

Feng Y, Luo G, Lu L *et al*., 2011. Effects of land use change on landscape pattern of the Manas River watershed in Xinjiang, China. *Environmental Earth Sciences*, 64(8): 2067–2077.

Foley J A, De Fries R, Asner G P *et al*., 2005. Global consequences of land use. *Science*, 309(5734): 570–574.

Gao P, Niu X, Wang B *et al*., 2015. Land use changes and its driving forces in hilly ecological restoration area based on gis and RS of northern China. *Sci. Rep.*, 5: 11038.

Ge Q, Dai J, He N *et al.*, 2008. Land use, land cover change and carbon cycle research of China over the past 300 years. *Science China*: *Earth Sciences*, 38(2): 197–220. (in Chinese)

Giles M F, 2002. Status of land cover classification accuracy assessment. *Remote Sensing of Environment*, 80: 185–201.

Huang C, Zhang M, Zou J *et al.*, 2015. Changes in land use, climate and the environment during a period of rapid economic development in Jiangsu Province, China. *Science of the Total Environment*, 536: 173–181.

Janssen L L F, van der Wel F J M, 1994. Accuracy assessment of satellite derived land cover data: A review. *Photogrammetric Engineering and Remote Sensing*, 60(4): 419–426.

Li B, Fang X, Ye Y *et al.*, 2010. Accuracy assessment of global historical cropland datasets based on regional reconstructed historical data: A case study in Northeast China. *Science China*: *Earth Sciences*, 40(8): 1689–1699. (in Chinese)

Liao J, Wang T, Xue X, 2012. Oasis evolution in the Heihe River Basin during 1956–2010. *Journal of Desert Research*, 32(5): 1426–1441. (in Chinese)

Liu J, Deng X, 2009. Development of research method of LUCC spatio-temporal process. *Chinese Science Bulletin*, 54(21): 3251–3258. (in Chinese)

Liu J, Jin T, Liu G *et al.*, 2014. Analysis of land use /cover change from 2000 to 2010 and its driving forces in Manas River Basin, Xinjiang. *Acta Ecologica Sinica*, 34(12): 3211–3223.

Liu J, Kuang W, Zhang Z *et al.*, 2014. Spatiotemporal characteristics, patterns and causes of land use changes in China since the late 1980s. *Acta Geographica Sinica*, 69(1): 1–11. (in Chinese)

Liu J, Shao Q, Yan X *et al.*, 2011. An overview of the progress and research framework on the effects of land use change upon global climate. *Advances in Earth Science*, 26(10): 1015–1022. (in Chinese)

Liu X, Yang J, Yang Q, 2005. Analysis on the variations characteristics of air temperature, precipitation in the Sangong River Basin in the past 40 years. *Research of Soil and Water Conservation*, 12(6): 54–57. (in Chinese)

Luo G, Amuti T, Zhu L *et al.*, 2015. Dynamics of landscape patterns in an inland river delta of Central Asia based on a cellular automata-Markov model. *Regional Environmental Change*, 15(2): 277–289.

Luo G, Zhou C, Chen X, 2003. Process of land use/land cover change in the oasis of arid region. *Acta*

Geographica Sinica, 58(1): 63–72. (in Chinese)

Luo G, Zhou C, Chen X, 2006. Landscape plaque stability study in the oasis of arid region: A case study of Sangong River watershed. *Chinese Science Bulletin*, 51(Suppl Ⅰ): 73–80.

Luo G, Zhou C, Chen X *et al.*, 2008. A methodology of characterizing status and trend of land changes in oases: A case study of Sangong River watershed, Xinjiang, China. *Journal of Environment Management*, 88(4): 775–783.

Luo Y, 2014. Long term effects of drip irrigation on soil salinization in arid area oasis. *Science China*: *Earth Science*, 44(8): 1679–1688. (in Chinese)

Lv G, Du X, Yang J *et al.*, 2007. Community stability of deserts vegetation at Fukang oasis-desert ecotone. *Arid Land Geography*, 30(5): 660–665. (in Chinese)

Ma C, Ren Z, Li X, 2013. Land use change flow and its spatial agglomeration in the loess platform region. *Acta Geographica Sinica*, 68(2): 257–267. (in Chinese)

Ministry of Land and Resources of the People's Republic of China (MLR, PRC). GB/T21010-2007 Classification of Land Use Status. (in Chinese)

Pascual J I, Lorente N, Song Z *et al.*, 2003. Selectivity in vibrationally mediated single-molecule chemistry. *Nature*, 423(6939): 525–528.

Pontius R G, Shusas E, McEachern M, 2004. Detecting important categorical land changes while accounting for persistence. *Agriculture*, *Ecosystems and Environment*, 101(2/3): 251–268.

Saiko T A, Zonn I S, 2000. Irrigation expansion and dynamics of desertification in the circum-Aral region of Central Asia. *Applied Geography*, 20(4): 349–367.

Su L, Abudu S, Hudan T *et al.*, 2011. Effects of under-mulch drip irrigation on soil salinity distribution and cotton yield in an arid region. *Acta Pedologica Sinica*, 48(4): 708–714. (in Chinese)

Sun L, Luo Y, 2013. Study on the evolution trends of soil salinity in cotton field under long-term drip irrigation. *Research of Soil and Water Conservation*, 20(1): 186–192. (in Chinese)

Sun L, Luo Y, Yang C J *et al.*, 2012. Salt Distribution and accumlation in soils different in rate of under-mulch drip irrigation with brackish water. *Acta Pedologica Sinica*, 49(3): 428–436. (in Chinese)

Sun P, Zhou H, Li Y *et al.*, 2010. Trunk sap flow and water consumption of Haloxylon ammodedron growing in the Gurbantunggut Desert. *Acta Ecologica Sinica*, 30(24): 6901–6909. (in Chinese)

Tang F, Chen X, Luo G *et al.*, 2006. Two typical LUCC process and driving force analysis in the oasis of arid region: A case study of Sangong River watershed in north Tianshan Mountain. *Science China: Earth Science*, 36(Suppl. II): 58–67. (in Chinese)

Turner II B, 1994. Local faces, global flows: The role of land use and land cover in global environmental change. *Land Degradation and Rehabilitation*, 5(2): 71–78.

Wang J, Bai J, Luo G *et al.*, 2015. Growth and water consumption characteristics of cotton in Manas Basin during recent 34 years. *Transactions of the Chinese Society for Agricultural Machinery*, 46(8): 83–89. (in Chinese)

Wang Z, Shi Q, Wang T *et al.*, 2011. Spatial-temporal characteristics of vegetation cover change in mountain-oasis-desert system of Xinjiang from 1982 to 2006. *Journal of Natural Resources*, 26(4): 609–618. (in Chinese)

Yan J, Chen X, Luo G *et al.*, 2005. Response of the changes of shallow groundwater level and quality to LUCC driven by artificial factors: A case study in Sangong River Watershed in Xinjiang. *Journal of Natural Resources*, 20(2): 172–180. (in Chinese)

Yan J, Chen X, Luo G *et al.*, 2006. Ground water level temporal and spatial variation in response t o the change of land cover in arid oasis region. *Chinese Science Bulletin*, 51(Suppl I): 42–48. (in Chinese)

Yang Y, Zheng D, Zhang X *et al.*, 2013. The spatial coupling of land use changes and its environmental effects on Hotan oasis during 1980–2010. *Acta Geographica Sinica*, 68(6): 813–824. (in Chinese)

Ye Y, Fang X, Ren Y *et al.*, 2009. Cropland cover change in Northeast China during the past 300 years. *Science China*: *Earth Science*, 39(3): 340–350. (in Chinese)

Zhao W, Liu H, 2006. Recent advances in desert vegetation response to groundwater table changes. *Acta Ecologica Sinica*, 26(8): 2702–2708. (in Chinese)