

# Processes and trends of the land use change in Aksu watershed in the central Asia from 1960 to 2008

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**Abstract:** Land use change (LUC) in trans-boundary watersheds is of great importance to environmental assessment. The Aksu River is the largest trans-boundary river crossing Kyrgyzstan and China, but there was little information on the LUC of the watershed. We quantitatively investigated the processes and trends of its LUC by using analytic models based on the land use data derived from the remote sensing images and topographic maps. The LUC was in the quasi-balanced status with a slight difference between the loss and the gain of the area for most land use types during the period of 1960–1990, whereas transferred to the unbalanced status with significant difference between the loss and gain of the area during the period of 1990–2008. At the same time, land conversion direction changed from two-way transition to one-way transition for the most land use types. The integrated rate of net change of land use during the period of 1990–2008 is 2.1 times of that during the period of 1960–1990. Information on the processes and trends of LUC is valuable for better understanding the environmental changes across the whole trans-boundary watershed, and helpful to decision-making management for Kyrgyzstan and China.

**Keywords:** land use change (LUC); trans-boundary river; Aksu River; remote sensing

## 1 Introduction

Land use change (LUC) has been identified as one of the primary causes of global change including impacts on ecosystems, global biogeochemistry, climate change, and human vulnerability (Foley *et al.*, 2005). This has taken place since the beginning of environmental management by human being, whereas the change is especially significant and intense during the last 50 years (Metzger *et al.*, 2006). Remote sensing combined with land inventory techniques facilitates scientists to make assessment of current land resources, identify ongoing LUC processes and hot-spots of change (Herold, 2006). Consequently, many studies had been conducted on the spatial-temporal dynamics in land use (Lambin, 2001, 2002; Parker *et al.*, 2003; Gutman *et al.*, 2004; Turner 2004; Bender *et al.*, 2005; Luo *et al.*, 2008; Bayarsaikhan *et al.*, 2009). However, our knowledge about LUC is still limited, due to the unbalanced efforts in the different research areas and the scales and deficiency in accessing distinctive underlying driving factors of LUC (Foody, 2002). In watershed level, researchers generally extract the

boundary of a watershed with reference to the local administration boundaries (Verbunt *et al.*, 2005; Qi *et al.*, 2006; Luo *et al.*, 2008; Liu *et al.*, 2009), since it is easy to acquire the social-economic data which are necessary for evaluating the LUC. For the trans-boundary watershed, scientists usually divide the whole watershed into several parts based on their borders to study the LUC process of every part (Reenberg, 1994; McIver and Starr, 2001; Verbunt *et al.*, 2005). However, these researches seldom investigate the LUC of the trans-boundary river watershed as a whole, which is unfavorable for objective assessment of environmental change.

The Aksu River is a typical trans-boundary river in the inland arid region, where several projects have been carried out to study the climate and runoff changes as well as the water resources securities in the background of environmental changes (Liu *et al.*, 2005; Liu *et al.*, 2006; Wang *et al.*, 2008). However little information was about its LUC, particularly the

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integrated assessment of the whole watershed, which would alter hydrological processes and impact water resource supply (Lin *et al.*, 2007). Shi *et al.* (2006) analyzed the LUC processes and its ecological effects in the ecotone of oasis and desert of the Aksu watershed based on the administration boundaries from 1995 to 2003. Obviously, the information about the LUC and its ecological effects can not meet the requirements of the assessment on the long-term environmental changes, especially the shortage of information about entire watershed in the past 50 years.

The objectives of this study are to (1) improve formerly proposed models of the rate in net change of land use and validate them together with other proposed models by remote sensing data; (2) investigate the processes and trends of the LUC in Aksu watershed during the period of 1960–2008, and (3) analyze its primary driving forces.

## 2 Study area and methods

### 2.1 Study area

The Aksu watershed is located at the west of the central part of Tianshan Mountains, and lies to the north-west of the Tarim basin of China ( $40^{\circ}14'11''\text{N}$  to  $42^{\circ}27'42''\text{N}$ ,  $75^{\circ}33'16''\text{E}$  to  $80^{\circ}59'7''\text{E}$ ). It covers the area in the west of Aksu Prefecture in China and the

area in the east of Kyrgyzstan. The vertical zonation of the landscape in this watershed is marked, including alpine snow zone, sub-alpine zone, middle mountains, low mountains, hills, piedmont alluvial-pluvial fan, alluvial-diluvial clinoplain and piedmont alluvial plain. The climate belongs to the type of temperate continent-draught climate, with the annual mean temperature ranging from  $9.2^{\circ}\text{C}$  to  $11.5^{\circ}\text{C}$  and the mean annual precipitation and annual potential evaporation are 64 mm and 1,890 mm respectively. The Aksu River consists of two main branches originating from Kyrgyzstan named Kunmarik River and Taushkan River (Fig. 1). The runoff of the Aksu River is mainly yielded at the mountains in the upstream and is primarily consumed by irrigation of the oasis in downstream and ecosystem.

### 2.2 Methods

#### 2.2.1 Data and processing

To extract the boundary of Aksu watershed, we generated the boundary by a distributed hydrological model—SWAT (Soil and Water Assessment Tool) (Neitsch *et al.*, 2000) based on STRM (Shuttle Radar Topography Mission) data (Jarvis *et al.*, 2008), with the resolution of  $90\text{ m} \times 90\text{ m}$ , and then modified the boundary of the plain with reference to the scope of Aksu River's irrigation area. Then we selected three

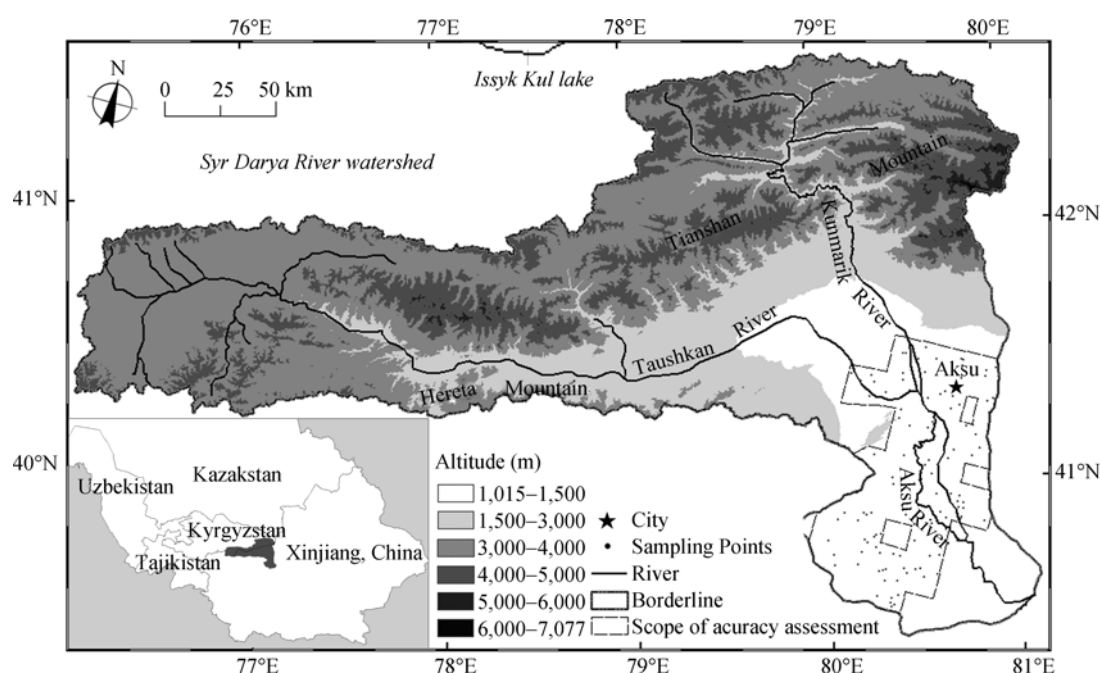


Fig. 1 Sketch map of the Aksu watershed

representative years of 1960, 1990 and 2008 to investigate the long-term LUC in this area. The data sources used to acquire LUC information are listed in Table 1, including topographic maps, Landsat MSS, TM and ETM+ image data. Due to no topographic data in Kyrgyzstan, we utilized the Landsat MSS images instead.

The data were preprocessed including geometric precision correction, mosaic of images and re-projection. With reference to topographic data, geometric correction and mosaic of the satellite images were implemented by using ERDAS software. Albers Conical Equal Area was selected as their re-projection system.

At present there is no an internationally accepted land use classification system in use (GLCN, 2005). This study categorized the land into ten types according to the characteristics of the land sources and the precision requirement of the analysis (Table 2), including cropland, woodland, grassland, built-up, per-

manent glacier and snow (PGS), water body, sand land, saline land, wetland and other unused land. For linear surface features, such as rural highways, irrigation canals and shelter-forest belts, could not be individually categorized due to the limitation of spatial resolution of the images, thus, they are included into above ten categories.

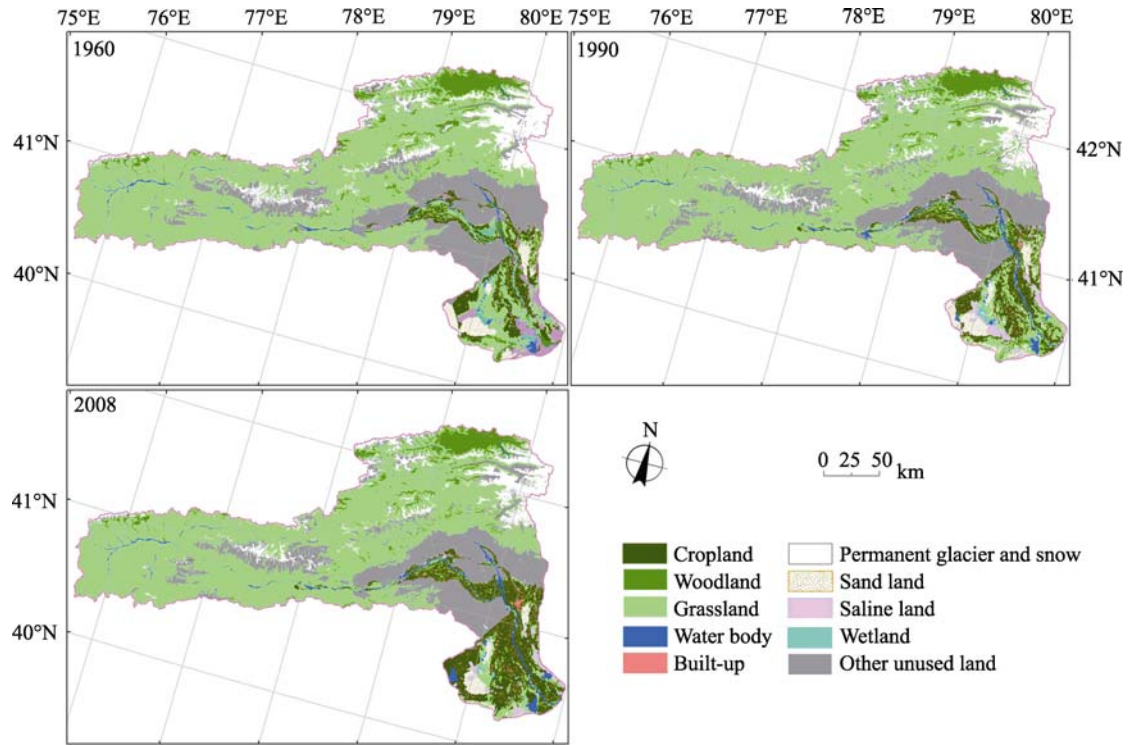
As to the different data sources, we developed different interpretation marks according to above classification system. A GIS database of land use classification developed by manually classification together with topological relationships were built by using ArcGIS software. Attributes related to land changes were derived from the images. Lacking of topographic maps of Kyrgyzstan, we interpreted MSS images (acquired in 1970s) to extract the land use information (in 1960) of Aksu watershed in Kyrgyzstan. The visual map of the three-stage land use classification data is shown in Fig. 2.

**Table 1** Data sources for land classification

Stage	Data types	Time of drawing topographic maps/remote sensing images (path/row, collection time)
1960	Topographic data	Topographic data with scale of 1:100,000 derived from aerial images (1 m × 1 m) collected in 1960 (in China)
	Landsat MSS (79 m × 79 m)	158/31, 1976-10-16; 159/31, 1973-09-18; 160/31, 1975-08-13; 162/31, 160/32, 1975-08-13; 1977-05-23 (in Kyrgyzstan)
1990	Landsat TM (30 m × 30 m)	146/32, 1990-10-05; 147/31, 1990-09-10; 147/32, 1989-10-25; 148/31, 1990-07-31; 148/32, 1990-07-31; 149/31, 1991-10-29; 149/32, 1992-06-09
2008	Landsat ETM+ (30 m × 30 m)	146/32, 2008-08-27; 147/31, 2007-09-01; 147/32, 2008-05-14; 148/31, 2007-06-20; 148/32, 2007-06-20; 149/31, 2007-07-29; 149/32, 2007-07-29

**Table 2** Classification of land use types in Aksu watershed

Land use types	Codes	Description
Cropland	1	Including newly reclaimed lands for cropping, fallowing for over 3 years, and grass-crop rotation lands. All the cultivated lands are equipped with irrigation facilities, thus belonging to irrigated lands. The irrigation ditches, farm-machine roads and other service lands are also included in this group
Woodland	2	Including woodlands (lands where natural or planted forests with a canopy density >30%, including Orchards), shrub lands (woodlands with >40% coverage by woody vegetation) and shelterforest lands (including shelter-forest zones, located mostly in the lower part of oasis)
Grassland	3	Lands covered by grass, and ranching lands
Built-up	5	Consisted of cities, towns (lands used for townships and settlement), thorps, industrial and mining lands (including rural thorps, industrial enterprises, mining areas, stone pits, and brickyard fields)
Permanent glacier and snow	41	Lands covered by glaciers or snow permanently
Water body	42	Including reservoirs and ponds, rivers and flood lands
Sand land	61	Lands covered by aeolian sand
Saline land	63	Including lands where only natural salt-tolerant plants can grow, and salt or alkali minerals often accumulate in the topsoil
Wetland	64	Including wetlands and swamps with vegetation
Other unused land	65	Including Gobi, bare land, gravel deserts, alpine deserts, tundra



**Fig. 2** The distribution of the ten land use types in the study area: the data of the year 1960 derived from topographic map and Landsat MSS images; the data of the years 1990 and 2008 derived from Landsat TM and ETM+ images, respectively.

Different methods had been used for accuracy assessment of land use classification. The land use data in 1960 were mainly converted from topographic maps, thus its accuracy is viewed reliable; for the data in 1990, we utilized the land use map of Xinjiang, China in 1990, which is considered as accurate in land use classification, as reference data; for the land use classification data in 2008, we selected the images on Google earth with high spatial resolution as reference data, and then 200 points were generated randomly (the least distance is one kilometer) within the scope of these images, then the land use types of each points in land use data were compared with that of the images in Google earth. Then the Kappa Coefficients were calculated, which were 0.812 and 0.842 in the years of 1990 and 2008 respectively.

### 2.2.2 Processes and trends of LUC

The processes and trends of LUC can be characterized by quantified elements or values such as net change, total change, rate of net change, status, direction and trend. Net change is defined as the difference between the gain and loss of land use type, and the total change is the sum of the loss and gain of each land use type (Pontius *et al.*, 2004). The rate of net change will be

discussed in detail in the next section. Assuming that the amount of land use type A has changed from  $U_a$  to  $U_b$  in areas over a time period, the net change and total change  $N_c$  and  $T_c$  are defined as:

$$N_c = \frac{U_b - U_a}{U_a} \times 100\% = \frac{\Delta U_{in} - \Delta U_{out}}{U_a} \times 100\%, \quad (1)$$

$$T_c = \frac{\Delta U_{in} + \Delta U_{out}}{U_a} \times 100\%, \quad (2)$$

where  $\Delta U_{out}$  and  $\Delta U_{in}$  represent the land loss and gain respectively.

The analytic models developed by Luo *et al.* (2008) were applied to analyze the status, trend and direction of the LUC in the study area. The mathematical expressions for above models are as follows:

$$P_s = \frac{N_c}{T_c} = \frac{\Delta U_{in} - \Delta U_{out}}{\Delta U_{in} + \Delta U_{out}} \quad (\Delta U_{out} + \Delta U_{in} \neq 0, -1 \leq P_s \leq 1), \quad (3)$$

$$S_a = \frac{1}{2} \sum_{i=1}^n (|U_{bi} - U_{ai}|) / \left( \sum_{i=1}^n U_{ai} \right) \times 100\% \\ = \frac{1}{2} \sum_{i=1}^n (|\Delta U_{in-i} - \Delta U_{out-i}|) / \left( \sum_{i=1}^n U_{ai} \right) \times 100\%, \quad (4)$$

$$S_s = \frac{1}{2} \sum_{i=1}^n (\Delta U_{in-i} + \Delta U_{out-i}) / \left( \sum_{i=1}^n U_{ai} \right) \times 100\%$$

$$= \sum_{i=1}^n \Delta U_{out-i} / \left( \sum_{i=1}^n U_{ai} \right) \times 100\%$$

$$\left( \sum_{i=1}^n \Delta U_{out-i} = \sum_{i=1}^n \Delta U_{in-i} \right), \quad (5)$$

$$P_t = \frac{S_a}{S_s} = \frac{\sum_{i=1}^n (|\Delta U_{in-i} - \Delta U_{out-i}|)}{\sum_{i=1}^n (\Delta U_{in-i} + \Delta U_{out-i})} \quad (S_s \neq 0 \text{ and } 0 \leq P_t \leq 1). \quad (6)$$

Where  $P_s$  is defined to characterize the status and trend for a particular land use type;  $S_a$  and  $S_s$  are the net and total change of the total land use types used to explore the overall status and trend of all land use types;  $U_{ai}$  and  $U_{bi}$  represents the area of land use type  $i$  at the initial and the last stage of a time period respectively;  $n$  is the number of land use types of the study area;  $\Delta U_{out-i}$  is the sum of the area converted from land use type  $i$  into other land use types and  $\Delta U_{in-i}$  is the total area converted from other land use types into land use type  $i$ ;  $P_t$  is defined to characterize the overall status and trend in LUC of the study area. Information about these indices can be found in Luo *et al.* (2008).

### 2.2.3 The rate of net change in LUC

The rate of net change is another efficient quantitative element to characterize the LUC process. It was mainly calculated by arithmetic mean algorithm (Xu *et al.*, 2005; Hao and Ren, 2009) with the hypothesis of independence in different periods of the LUC processes. However, the LUC is a cumulative process, suggesting that the land area will increase exponentially at the rate of net change. Thus, we defined the rate of net change as follows:

$$R_s = (T \sqrt{\frac{U_b}{U_a}} - 1) \times 100\%$$

$$= (T \sqrt{\frac{U_a + (\Delta U_{in} - \Delta U_{out})}{U_a}} - 1) \times 100\%, \quad (7)$$

where  $T$  is the length of study period.

Similarly, the integrated rate of net change  $R_t$ , representing the integrated rate of the net change in total land use types, can be defined as:

$$R_t = \left( T \sqrt{\frac{\sum_{i=1}^n U_{ai} + \frac{1}{2} \sum_{i=1}^n (|U_{bi} - U_{ai}|)}{\sum_{i=1}^n U_{ai}}} - 1 \right) \times 100\%$$

$$= \left( T \sqrt{\frac{\sum_{i=1}^n U_{ai} + \frac{1}{2} \sum_{i=1}^n (|\Delta U_{in-i} - \Delta U_{out-i}|)}{\sum_{i=1}^n U_{ai}}} - 1 \right) \times 100\%. \quad (8)$$

## 3 Results

### 3.1 Processes and trends of LUC

Based on the land use classification data, the spatial analysis and statistics were performed using Eqs (1)–(6), by which we acquired the area of every categories of land use of the three stages, the changes in the area, statuses, and trends during the periods of 1960–1990, 1990–2008, and 1960–2008 (Table 3). The rates of net changes in these three periods were calculated according to Eqs. (7) and (8), and the results were shown in Table 4.

Table 3 revealed that the grassland, other unused land, PGS and together with cropland are the four dominant land use types in Aksu watershed. During the period of 1960–2008, the status and trend index  $P_t$  was 0.44, which means that the land use in the study area was in quasi-balanced status and the change was controlled by two-way transition. The  $P_t$  during the period of 1960–1990 was three-fifth of that 1990–2008, suggesting that the land use changed from quasi-balanced status to unbalanced status together with the prime change direction varying from two-way transition to one-way transition. The quasi-balanced status during 1960–1990 was mainly caused by lands abandonment (the cultivated land was converted into other land use types) during the reclamation (the other land use types were converted into cultivated land), which may exert negative influence on ecosystem. During the period of 1990–2008, the abandonment is less than reclamation and a large area of the other unused land was reclaimed (including some lands that were abandoned during the period of 1960–1990), which would be beneficial to ecological restoration and sustainable development of environment. The

**Table 3** The area status and trend for individual land use types and total land use types in Aksu watershed

Land use types	1960	1990	2008	1960–1990			1990–2008			1960–2008		
	Area (km <sup>2</sup> )			$N_C$	$T_C$	$P_S$	$N_C$	$T_C$	$P_S$	$N_C$	$T_C$	$P_S$
Cropland	2,919.8	3,729.4	5,453.8	27.7	61.5	0.45	46.2	59.6	0.78	86.8	114.8	0.76
Woodland	2,625.3	2,313.4	2,179.0	−11.9	19.8	−0.60	−5.8	7.5	−0.78	−17.0	26.2	−0.65
Grassland	28,146.6	28,672.2	27,652.2	1.9	10.0	0.19	−3.6	8.0	−0.45	−1.8	10.6	−0.17
Built-up	143.3	235.1	364.5	64.0	130.8	0.49	55.1	77.1	0.71	154.3	243.5	0.63
PGS	4,323.7	3,545.7	3,412.7	−18.0	18.2	−0.99	−3.8	4.9	−0.77	−21.1	23.1	−0.91
Water body	710.4	779.1	870.1	9.7	53.0	0.18	11.7	41.0	0.28	22.5	91.1	0.25
Sand land	969.0	900.8	579.3	−7.0	62.6	−0.11	−35.7	45.2	−0.79	−40.2	75.7	−0.53
Saline land	972.7	738.6	532.1	−24.1	114.7	−0.21	−28.0	83.1	−0.34	−45.3	102.1	−0.44
Wet land	293.3	123.9	66.7	−57.7	90.8	−0.64	−46.2	85.0	−0.54	−77.2	101.6	−0.76
Other unused land	9,991.7	10,057.6	9,985.5	0.7	12.2	0.05	−0.7	7.3	−0.10	−0.1	22.0	0.00
Total area	51095.8	51095.8	51095.8	—	—	—	—	—	—	—	—	—
Integrated change	—	—	—	3.06( $S_a$ )	9.47( $S_s$ )	0.32( $P_t$ )	3.81( $S_a$ )	7.22( $S_s$ )	0.53( $P_t$ )	5.70( $S_a$ )	12.95( $S_s$ )	0.44( $P_t$ )

$N_C$  and  $S_a$  mean the net change in single land use type and total land use types respectively;  $T_C$  and  $S_s$  are the total change in single land use type and total land use types;  $P_S$  and  $P_t$  denote the index of the status and trend in certain land use type and total land use types respectively. PGS represent permanent glacier and snow.

**Table 4** The rate of net change for individual land use types and total land use types in Aksu watershed

Period (year)	The rate of net change (%)										$R_t$
	Cropland	Woodland	Grassland	Built-up	PGS	Water body	Sand land	Saline land	Wetland	Other unused land	
1960–1990	0.82	−0.42	0.06	1.66	−0.66	0.31	−0.24	−0.91	−2.83	0.02	0.10
1990–2008	2.13	−0.33	−0.20	2.47	−0.21	0.62	−2.42	−1.81	−3.38	−0.04	0.21
1960–2008	1.31	−0.39	−0.04	1.96	−0.49	0.42	−1.07	−1.25	−3.04	0.80	0.12

$R_t$  is the integrated rate of net change in the total land use types; PGS represent permanent glacier and snow.

economic and ecological effects caused by LUC will be discussed in another article thoroughly.

During the period of 1960–1990, the total change of all land use types  $S_s$  was 9.47%, which resulted in the decrease of all land use types  $S_a$  to 3.06%. Built-up, cropland and water body were in rising trends, while the wetland, saline land, PGS, and woodland were in significant falling trends. The other unused land and grassland grew slightly during this period. In view of the status and trend index  $P_s$ , PGS primarily converted into other land use types with small gain ( $P_s=0.99$ ), and it was in extremely unbalanced status. The wetland, woodland, cropland and built-up were in unbalanced status, and the other land use types were in balanced status.

By comparison, during the period of 1990–2008, the value of  $S_s$  is 7.22%, while  $S_a$  is 3.81% which is minimally larger than that of the period 1960–1990. The built-up, cropland, and water body kept on increasing; wetland, saline land and woodland continued to shrink, and the sand land decreased dramatically in

the present stage; whereas the grassland and other unused land diminished minimally. As to the status, all land use types during the period of 1990–2008 presented the same status as that of the first stage, except the sand, which converted from quasi-balanced to unbalanced status.

Table 4 shows that the integrated rate of net change in all land use types ( $R_t$ ) increased from 0.1% to 0.21% from the periods of 1960–1990 to 1990–2008 and the rate of net change ( $R_s$ ) varied with large amplitude in different land use, types, and stages. In general, the  $R_s$  of all land use types during the period of 1990–2008 is larger than that of 1960–1990 except woodland and PGS; the cropland and built-up increased faster compared to the grassland and other unused land, and the wetland, saline land, sand land shrunk at a larger rate compared to the decreased PGS, woodland and grassland. Viewing from the whole study period, the integrated rate of net change is comparatively low (0.12%), which may be beneficial to the ecological improvements of the watershed, par-

ticularly to the downstream that mainly covered by oasis.

### 3.2 Driving forces underlying LUC

The research results indicate that Aksu watershed changed significantly in the study period, especially the oasis in the downstream, and the driving forces consisted of both human-induced and natural factors. Luo *et al.* (2008) revealed that the policy shifts are the primary human factors driving LUC, which is also true in the present study. In late 1978, the Chinese government adopted a new policy, the Household Responsibility System, launching a nationwide land reform campaign. Under the new system, land-use rights were granted to individuals in the rural areas, creating tremendous economic incentives. In the study area, the farmers were allowed to reclaim some croplands abandoned before, grasslands, sand lands, saline lands and wetlands for agricultural use, which lead to a significant increase in cropland together with the dramatic decrease in wetlands, saline lands, and sand lands.

In 1992, China begun to adopt market economy, which brought a rapid development period in the fields of technology and economy, causing great improvements in techniques of fertilization, irrigation, and management together with a sharp growth in economic strength. Thus, the activities of human beings to disturb the land system were strengthened considerably. For instance, many lands (such as sand and saline lands) difficult to use in the past, were reclaimed under the present conditions, which resulted in the great land changes during the period of 1990–2008. Meanwhile, farmers could maintain the reclaimed lands more efficiently than ever before, especially the abilities to utilize the water sources and to solve the salinization problems. All these factors contributed to the change of land use from the quasi-balanced status (dominated by two-way transition) during the period of 1960–1990 to the unbalanced status (controlled by one-way transition) during the period of 1990–2008.

Human activity, closely related to governmental policies, is another critical human-induced factor driving LUC. Many studies have found that human activities have become a dominant factor shaping most cultivated landscapes of the Earth (Goudie and Viles, 1997). After 1949, farmers, graduates and retired soldiers immigrated into the study area, due to the gov-

ernmental preferential policies to development together with the construction of border areas, which lead to the rapid increase of the population in this watershed. Lambin *et al.* (2001, 2002) suggested that the increasing urban population concentration leads to increased demand for resources in rural regions, such as built-up and cropland. Taking the oasis city named Aksu city, located in the downstream, as an example, the population increased from 255,971 in 1960 to 599,496 in 2007, which inevitably lead to the extensive reclamation to support the increased population (Fig. 3). Furthermore, in order to meet the irrigation requirement, four large reservoirs (the total capacity is  $3.9 \times 10^8 \text{ m}^3$ ) around Aksu watershed were built, which changed the consumption process of the river water source and subsequently increased the water bodies (Liu *et al.*, 2006).

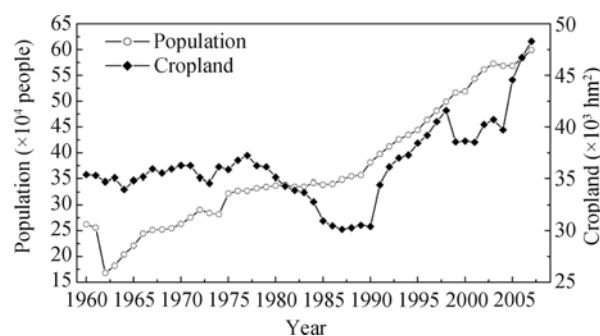


Fig. 3 Changes of the population and the cropland area in Aksu city from 1960 to 2007

The natural factors, linking climate and runoff changes, also posed substantial effects to the LUC in the study area. From 1956 to 2000, the temperature increased steadily with the tendency rate of  $0.2^\circ\text{C}/10\text{a}$  and the precipitation increased gradually at the tendency rate of  $10.8 \text{ mm}/10\text{a}$  (Liu *et al.*, 2005). The increased temperature resulted in the PGS shrinking (with mean annual decrement of  $0.44 \text{ km}^2$ ), although the loss can be offset by the increased of precipitation. The increase of both precipitation and temperature had contributed to the growth of the runoff, and Wang *et al.* (2008) found that the glacial meltwater is the primary contributor to the rising of the runoff in the Aksu River from 1956 to 2006. Subsequently, the rising runoff is another important driving factor for the water bodies' increase (with the mean annual increment of  $0.47 \text{ km}^2$ ).

The area of the Aksu watershed in Kyrgyzstan is dominated by the mountains, the LUC of which main-

mainly includes the diminished PGS and the increased grassland, and thus the natural factors are the primary driving force.

#### 4 Discussion

This study shows that remote sensing data are effective in studies on LUC at the watershed level. In many cases, remote sensing is an economically feasible way to gather regularly land-cover information within spatial, spectral, and temporal resolution over large areas (Verstraete *et al.*, 1996; Seidl and Moraes, 2000; McCallum *et al.*, 2006). The satellite-based data acquisition methods used in this study at least has two advantages over alternative data-collection methods. First, in trans-boundary river watershed, like the Aksu River, extensive field-based survey is difficult and expensive due to restricted accessibility. In such areas, a limited amount of field sampling combined with satellite data can facilitate accurate analysis at a large scale with lower cost. Second, most available land use data are based upon geopolitical boundaries and regional planning maps, neither of which relate well to the spatial arrangement changing land-use patterns, especially in trans-boundary watershed level.

The study area experienced significant LUC between 1960 and 2008, and the changes are closely related to human-induced factors including policy shifts and technological innovations, thus it is not a stationary and random process as defined by Markov models. In other words, the LUC here is not strictly Markovian (Turner, 1988; Wood *et al.*, 1997). Although Markov models are effective in temporal processes, they are ineffective in spatial processes. A simple interpretation of the transition matrix of Markov method may induce scientists to focus only on the transitions with larger area such as grasslands to other land use types, other unused land to other land use types together with the croplands expansion. While the more critical changes are ignored such as increased built-ups and water bodies together with the dramatically decreased wetlands, sands and saline lands, which actually imply important information on the environmental changes of the study area. On the other hand, some large transitional dynamics, e.g. transition of the grasslands to other land use types, does not necessarily indicate that grasslands is losing systematically, nor does it follow that grasslands experienced substantial changes, con-

trarily, grassland changed very slightly at the smaller rate of net change in the whole study period. Therefore, the analytic models used in this paper are useful tools to study the non-Markovian process. The models developed by Pontius *et al.* (2004) and Luo *et al.* (2008) proved to be efficient in donating spatiotemporal LUC processes.

In this paper, we also developed geometric mean models for the rate of net change, which are more rational arithmetic mean algorithm models used by Xu *et al.* (2005) and Hao and Ren (2009) because the LUC is a cumulative process. For instance, the rate of the net change of the cropland during the period of 1960–2008 was 1.31% calculated by the models developed in this paper, while it equaled to 1.81% calculated by arithmetic mean algorithm, which demonstrated that arithmetic mean algorithm will overestimate the rate of the land use change.

The information implied by the indices calculated in this paper not only provides insights into the LUC processes and trends together with the underlying driving factors, but also offers important information for land use planning and decision-making. For instance, during the periods of 1960–1990 and 1990–2008, the  $P_t$  values were 0.32 and 0.53 respectively, implied that there were dramatic spatiotemporal changes of land use in the study area; the  $P_s$  values were  $-0.21$  and  $-0.34$  for saline land during the two periods, indicting that saline lands contracted and the salinization problems were controlled effectively by human beings, whereas we must be cautious of the negative effects of excessive reclamation on environment. As such, these quantitative indicators can provide land-use planners with necessary information on land change for a report area. However, the driving forces were only analyzed preliminarily, and the modeling method is needed for a further study on them in future (Verburg *et al.*, 2004).

Taking a trans-boundary river as an example, this paper not only validated the usefulness of the analytic models in LUC studies, but also accessed the LUC processes in trans-boundary river watershed which is necessary for evaluation on the environmental changes, and the methods used in this study can be extended and used in other areas where prominent change occurs. Future research should focus on the ecological effects of the LUC on trans-boundary watersheds and



modeling the LUC processes in order to explore the underlying driving factors or future trends. In this study, we only used land use observation data to analyze land use system, in order to evaluate land use system changes more efficiently, more socio-economic information should be introduced in the analysis. Moreover, the relationship between land use and land function (provide extensive products and services) is non-linear, and the analysis on the land function change may be more efficient in accessing land change (Verborg *et al.*, 2009). Thus, in the future, more attention should be paid to the land function change.

## 5 Conclusions

The remote sensing data is economic-effective in detecting and classifying the LUC in the trans-boundary river watershed, although they are ineffective in identifying the details of land use, like irrigation, crop, orchard, etc. The mathematical analytic models used in this paper are effective in revealing the processes and trends of the spatiotemporal changes in land use. These models are especially useful in analyzing land changes which are primarily triggered by human-induced factors, such as policy shifts, technology innovations, and ever-strengthening human activities, but lacking typical Markovian randomness and stationarity.

By using these methods and remote sensing data, the LUC of Aksu watershed from 1960 to 2008 was

studied. The cropland, grassland and water body were in rising trends; the reverse is true for saline land, sand land, PGS and wetland; and the other land use categories were in relative balanced status. The status in the total study area transformed from quasi-balanced into unbalanced status, and the integrated rate of net change in 1990–2008 is greater than that in 1960–1990. Shifts in policy, enhancement of human activities, changes of climate and runoff are the main driving factors underlying the LUC. However, human-induced factors exerted little influences on the LUC in the upstream which is mainly dominated by mountains, and also is the border area of China and Kyrgyzstan. Consequently, the LUC in that area was comparatively slight. Information on the process and trend of the LUC (including net change, total change, the rate of net change, status, direction and trend) is useful not only for better understanding the LUC processes and trends together with the underlying driving factors, but also for land use planning and decision-making. For the efficient evaluation on land changes, more attention should be paid to the land function change.

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