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Oasis dynamics change and its influence on landscape pattern on Jinta oasis in arid China from 1963a to 2010a: Integration of multi-source satellite images

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ABSTRACT

As one of the vital research highlights of global land use and cover change, oasis change and its interaction with landscape pattern have been regarded as an important content of regional environmental change research in arid areas. Jinta oasis, a typical agricultural oasis characterized by its dramatic exploitation and use of water and land resources in Hexi corridor, northwest arid region in China, was selected as a case to study the spatiotemporal oasis change and its effects on oasis landscape pattern. Based on integration of Keyhole satellite photographs, KATE-200 photographs, Landsat MSS, TM and ETM+ images, we evaluated and analyzed the status, trend and spatial pattern change of Jinta oasis and the characteristics of landscape pattern change by a set of mathematical models and combined this information with landscape metrics and community surveys. During the period of 1963a–2010a, Jinta oasis expanded gradually with an area increase of 219.15 km^2, and the conversion between oasis and desert was frequent with a state of "imbalance–balance–extreme imbalance conditions". Moreover, most of the changes took place in the ecotone between oasis and desert and the interior of oasis due to the reclamation of abandoned land, such as Yangjingziwan and Xiba townships. Furthermore, the area, size and spatial distribution of oasis were influenced by human activities and resulted in fundamental changes of oasis landscape pattern. The fractal characteristics, dispersion degree and fragmentation of Jinta oasis decreased and the oasis landscape tended to be simple and uniform. Oasis change trajectories and its landscape pattern were mainly influenced by water resource utilization, policies (especially land policies), demographic factors, technological advancements, as well as regional economic development. We found that time series analysis of multi-source remote sensing images and the application of an oasis change model provided a useful approach to monitor oasis change over a long-term period in arid area. It is recommended that the government and farmers should pay more attention to the fragility of the natural system and the government should enhance the leading role of environmental considerations in the development process of oasis change, particularly with respect to the utilization of the limited water and land resources in arid China.

1. Introduction

Human-induced land use and land cover change (LUCC) is one sentinels of research on socioeconomic development and global environmental change (Turner, 1997). LUCC has profoundly influenced natural landscapes via a combination of physical, ecological and socio-cultural factors (Verburg et al., 2002; Nagendra et al., 2004), and this issue has received worldwide attention since the mid-1990s (Turner, 1997). The context, direction, and rate of landscape change have increasingly attracted the planners and researchers' interest recently. In arid areas, oasis change and its implications for landscape structure are not only the most visible type of LUCC, but also fundamental for developing a better understanding of the relationships and interactions between human activity and environmental change (Lambin and Geist, 2006; Gong et al., 2013), especially at the regional scale.

Oasis change can be observed as the sprawling and shrinking of the oasis boundary over time, namely, oasification and desertification. Oasification and desertification are the two basic but

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opposite geographic processes in arid area (Shen et al., 2000). Oasification (the antonym of desertification) has often been defined as the conversion process of desert to oasis, corresponding to the expansion in oasis area and scale, a process affected by human activities and human-nature interactions (Wang, 2009). And then, oasification has impacted on human well-being and social development directly (Jia et al., 2004; Luo et al., 2010) through a series of measures, such as expanding cultivated land, land consolidation and dam construction on inland rivers. Hence, understanding and analyzing the processes, status and trends of oasification procession, especially in the long-term oasis landscape change dynamics were urgently needed for the control and governance of human activities and protection of natural systems in arid China.

Spatially explicit time-series studies represent an important starting point to improve understanding of oasis change and its effect on landscape pattern. Historical insights on LUCC processes, actors, driving forces and resulting changes could provide a valuable basis to efficiently control or direct future changes (Brink et al., 2014). The scientific interest of satellite observations of oasis change over long periods of time has been recognized. However, there is a lack of longer time scale satellite data available from the same source, especially for more than 40 years. Lack or inaccessibility of appropriate data sets across multiple time scales may be a great challenge for the study of long-term oasis changes. In addition, oasis land use patterns have also created dynamic, short-term land cover transitions that are difficult to capture with available data. Hence, to monitor the complexities of oasis change of long duration effectively, multi-type, time-serial remote sensing data are needed (Luo et al., 2008; Ruelland et al., 2010). For instance, Zhou et al. (2010) quantitatively investigated the processes and trends of land use change in Aksu watershed in arid China based on topographic data, Landsat MSS, TM and ETM+ images. Ruelland et al. (2010, 2011) used Corona, Landsat and SPOT satellite images to contrast land-cover changes in Mali. Brinkmann et al. (2012) used multi-source satellite images to analyze the extent of land cover changes and major landscape transformation processes of four West African cities over the latest 50 years.

Generally, oasis change has been studied through analysis of changes in land use type of the oasis, such as, farmland, forestry, water area, and grassland. However, at the scale of the entire arid region, an oasis could be considered as a single landscape patch. But, till now, few studies have taken the oasis as a single geographical landscape unit that without consideration of the internal structure change in oasis to quantitatively analysis oasis change and its effect on landscape pattern. In addition, landscape features are sensitive to the spatiotemporal processes involved in LUCC (Nagendra et al., 2004; Luo et al., 2010) due to the fact that most landscape features are scale dependent and have self-similar, fractal structures (Alhamad et al., 2011). Thus, case studies are needed to ascertain and study the relationship of oasis dynamics change and its effects on oasis landscape pattern without consideration of the internal structure change in oases, especially under the influence of increasing human activity and global climate change (Qi et al., 2012).

In China oases are mainly distributed in temperate and warm temperate desert and gobies areas surrounding mountains. Although oases took up only 4–5% of the total area of arid China, more than 90% of the population and 95% of social wealth were concentrated within these oases (Jia et al., 2004; Wang, 2009). Here, an oasis is defined as a unique geographical landscape that has allowed flourishing vegetation and human settlements due to a stable water supply in an arid region (Ling et al., 2013). On the geographical pattern of the arid land, the mountainous forest grassland – plain oasis in basins and watersheds which is co-existed with desert is the most obvious characters. On the watershed scale, fresh groundwater and surface runoff from the nearby mountains had profoundly influenced the location and the size of an oasis (Wang et al., 2011; Ling et al., 2013). Furthermore, the abundance or shortage of water resources is relation to landscape pattern change of the oases located in the upper, middle and lower watershed, respectively (Zhang et al., 2012), evenly determines the stability of the oasis ecosystem. Especially, the temporal-spatial pattern of lower oasis landscape is more sensitive than others.

In this paper, Jinta oasis, a typical artificial and agricultural oasis in the lower reaches of Beida River Basin (the largest anabranch of Heihe River) of arid China, was selected as a case to study the oasis dynamics. We used multi-source satellite images to ascertain the change of the oasis over a long-term time scale and to apply landscape metrics to analyze its effects on the landscape pattern. The analysis was performed in the context of the background of the social factors associated with oasis change between 1963a and 2010a. Our specific objectives were to: (i) detect and explore the dynamics of oasis change over a 47 year period by developing quantitative models for characterizing status, directions, and trends of oasis change; and (ii) reveal the relationship between oasis change and landscape metrics. We concluded with a short discussion on the driving forces of oasis change and landscape pattern of Jinta oasis in arid China.

2. Study area

Jinta oasis (98°39′–99°08′ E, 39°48′–40°17′ N), located in the middle of the Heihe River Basin in Northwest China (Fig. 1), with a total area of 1652 km^2, a population of 124,032 people residing in eight townships in 2010a. It is not only an alluvial fan in the desert-oasis ecotone, but also is a typical agricultural oasis, a representative of the non-homogeneous oases in arid China. There were various soil types including mud soil, meadow soil, aeolian sandy soil and typical gray-brown soil (Ma et al., 2003; Qi et al., 2007). The total annual average precipitation is about 59.5 mm which mainly stretches from July to September, and annual potential evaporation is about 2567 mm. The main vegetation types included crops, such as cotton, hops, wheat, fennel and corn, and the desert vegetation and saline vegetation included Persican Saxoul (*Haloxylon persicum Bunge ex Boiss*. et), Tamarix chinensis, Calligonum (*Calligonum leucocladum*), and salt-living Anabasis (*A. salsa Benthex Volkens*).

3. Materials and methods

3.1. Remote sensing and data processing

Nine time periods of multi-source images were acquired to detect the spatiotemporal change of Jinta oasis from 1963a to 2010a. They were Keyhole photographs (nominal resolution is 2.7 m × 2.7 m) of 1963a and 1968a, Landsat MSS of 1973a (nominal resolution is 79 m × 79 m), KATE-200 photographs of 1980a (nominal resolution is 8.9 m × 8.9 m), Landsat TM images from 1986a, 1993a, 2005a, 2010a and ETM+ from 1999a (nominal resolution is 30 m × 30 m). These data were selected in either summer and/or autumn for it is the best time to study the oasis. Other map data included a topographic map of 1:50 000 made in 1960a and 1972a, a topographic map of 1:100 000 made in 1984a, and a land use map at a scale of 1:100 000 of 1990a, 2007a, all the maps came from Gansu Department of Land and Resources.

The images were geo-referenced to obtain optimal superimposition and minimize geographical deviation (Ruelland et al., 2010). With reference to topographic data, geometric correction and mosaic of the satellite images were implemented using ERDAS version 9.3 (Zhou et al., 2010). The ETM+ image (1999) was geo-referenced using ground control points with a root mean square error (RMSE) of two pixels (Table 1). The KATE-200 photographs, Keyhole photographs, MSS and TM images were geo-referenced

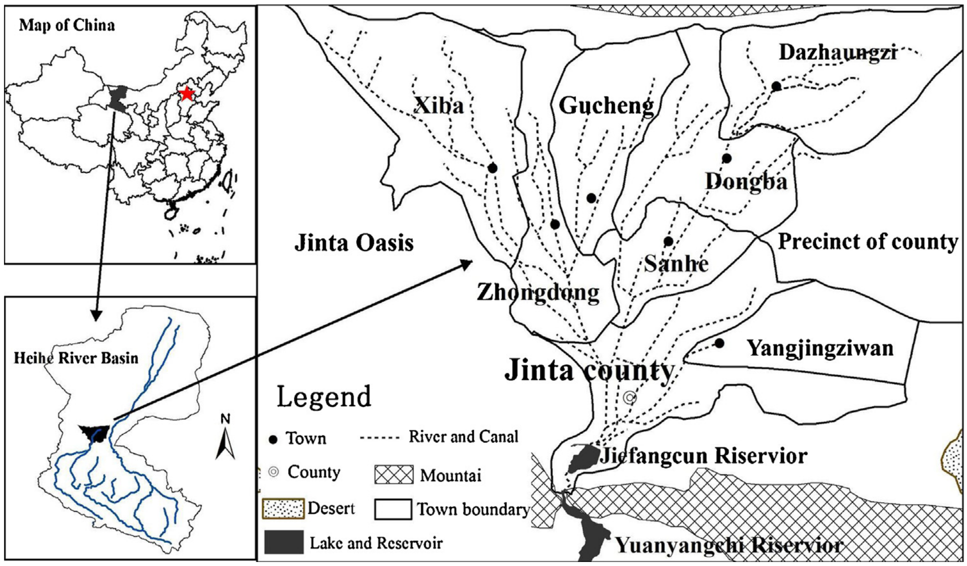

Fig. 1. Location of Jinta oasis in the Heihe River Basin of China.

using ETM (1999) as a master image. To make these images compatible (Lillesand and Kiefer, 2000), all the Keyhole photographs, KATE-200 photographs, TM and ETM+ images were re-sampled to a 79 m × 79 m pixel size, same as the nominal resolution as Landsat MSS, using the Bilinear Interpolation and nearest-neighbor re-sampling technique, respectively (Ruelland et al., 2011).

3.2. Oasis landscape types classification and accuracy assessment

In this study, land use and land cover was divided into two categories: oasis and desert. Oasis included the land use/cover types of farmland, grassland, forestland, water area and residential area, while the desert included the land use/cover types of salinized land, bare land, desert, and Gobi and low coverage grassland with the vegetation cover of ≤15%. We used spatial information with field-based data (perceptional) derived from workshops to revise and improve the distribution of historical oasis maps which had errors or omitted portions, and analyzed the oasis change by post-classification change detection (Coppin et al., 2004). Specifically, all the images were therefore manually classified using a geographical information system through grid-based visual interpretation (Ruelland et al., 2010, 2011). After that, the post-classification comparison approach and the field observations were used to assess the oasis change detection. Based on land use map and the images on Google earth with high spatial resolution, the corresponding training samples were detected for the oasis in 2005a, 2010a. We also identified oasis training samples of 1980a, 1986a and 1999a due to no geographical information on past land cover of these two years. Then, the Kappa coefficients 1980a, 1986a, 1999a, 2005a, 2010a were 83.56%, 84.70%, 87.38%, 90.2% and 89.26%, respectively, all were good enough to contrast with others. The land use data in the 1960s and the year of 1973 were mainly converted from topographic maps, thus their accuracy were viewed reliable. In the meantime, we interviewed with many local residents about the history of land use and analyzed the land transformation information provided by the local government and residents to understand and explain the factors responsible for triggering landscape changes (Hersperger et al., 2010). Three field visits to the study area were carried out in September 2009, August 2010, and July 2011, respectively.

3.3. Oasis change detection methods

3.3.1. Dynamic change, status and trends of change of oasis

Oasis dynamic change was characterized by the rate of net change (Pontius et al., 2004; Luo et al., 2008; Zhou et al., 2010) and bidirectional dynamic degree of the oasis (Seto and Fragkia, 2005), and the status, trend and direction of oasis were analyzed using LUCC models (Luo et al., 2008), these mathematical expressions were as follows:

$$\bar{x} = \left(\sqrt[T]{\frac{U_b}{U_a}} - 1 \right) \times 100\% \quad (1)$$

$$K = \left(\left(\left(\frac{\Delta U_{in} + \Delta U_{out}}{U_a} + 1 \right)^{1/T} \right) - 1 \right) \times 100\% \quad (2)$$

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

where $\bar{x}$ and K were defined as the rate of net change and bidirectional dynamic degree of the oasis; U_a and U_b represented the oasis area at the initial and the last stage of a time period, respectively, while ΔU_{in} and ΔU_{out} represented the oasis gain and loss, respectively; T was the length of study period. P_s was defined to characterize the overall status and trend in oasis and information about P_s could be found in Luo et al. (2008).

3.3.2. Analysis of oasis distribution pattern

A transition matrix model was used to describe the reciprocal relationship between oases and desert. And the model expression was as follows:

$$S_{kj} = \begin{vmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{vmatrix} \quad (4)$$

where k and j were land cover types at the initial and the last stage of a time period, k (or j) = 1 and k (or j) = 2 represented the oasis and desert, respectively.

Based on the constraint function there were a number of oases occurrences (c), occurring in successive sampling years (r) continuously over the time period (t), we coded the oasis spatial data using multiple coding by Matlab 7.10 (2010beta) to evaluate the stability of oases space change. The degrees of oases change from 1963a to

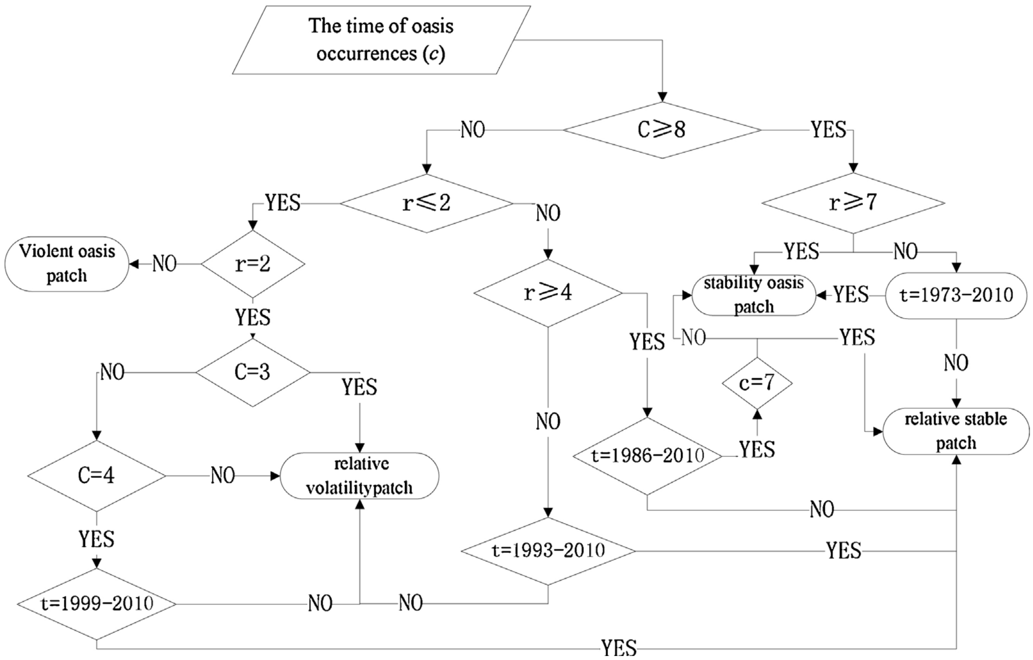

Fig. 2. The technology roadmap of oasis stability zoning.

2010a were divided into four types such as stable, relatively stable, relatively unstable and highly unstable status, respectively (Fig. 2). The specific technology roadmap is shown in Fig. 2.

3.4. Derivation of landscape metrics

Due to different representations of space has led to the change of spatial structure and pattern (Wu and Hobbs, 2007), the sprawling and shrinking process of oases might affect the size, shape and connection degree, and even the stability and sustainable development of the oasis. To ensure the comparability with previous studies, a set of landscape metrics and indices which reflect the shape, interspersion, fragmentation and spatial relationship of oasis were used in this study, including landscape shape index (LSI), area-weighted mean patch fractal dimension (AWMPFD), landscape division index (DIVISION) and fragmentation index (C_i). The first two metrics were the indicators of landscape shape that reflecting overall shape complexity and the effect between patch area and shape complexity across a range of spatial scales (patch sizes), respectively, and were calculated by FRAGSTATS version 3.3 (McGarigal et al., 2002). DIVISION was based on the cumulative patch area distribution and was interpreted as the probability of oasis spatial interspersion, while C_i was indicator of oasis landscape fragmentation. The latter two metrics were calculated using the following equations:

$$\mathrm{DIVISION} = 0.5\sqrt{\frac{n_i}{A}} \times \frac{A}{A_i} \tag{5}$$

$$C_i = \frac{n_i}{A_i} \tag{6}$$

where A is the study area, A_i the area of land cover type i, n_i the number of patches, i = 1 (oasis) or 2 (desert).

4. Results

4.1. Spatial and temporal change of Jinta oasis

4.1.1. Status and trends of change of Jinta oasis

The area of oasis change during the period of 1963a–2010a is shown in Fig. 3a and the trend of oasis area change is shown in Fig. 3b. Although the area change of Jinta oasis fluctuated over time, the oasis area increased rapidly with an annual rate of 1.46% from 1963a to 2010a and reached its largest in 2010a (539.47 km^2). During the period of 1963a–1968a, the area of oasis grew rapidly with a cumulative dynamic degree $\bar{x}$ of 2.96% and a status and trend index P_s of 0.24, indicating that the oasis change was controlled by unbalanced one-way transitions under a quasi-balanced status. But during the period of 1969a–1974a, the degree of oasis change was smaller although the cultivated land and desert both experienced the largest gains from other land cover types (The local history and annals editorial committee of Jinta county, 2009). From 1975a to 1980a, the oasis area continued to shrink and the desertification became more apparent. In the early 1980s, the oasis expanded apparently and its area increased as 32.96 km^2 from 1980a to 1986a. During the period of 1987a–1999a, the oasis changed similarly with the trend of 1974a–1986a. After 2000a, the oasis area grown rapidly, especially during the period of 2000a–2005a when $\bar{x}$ was at a maximum value as 4.39%.

The bidirectional dynamic degree of the oasis change and transition matrices between oasis and desert were calculated using Eqs. (2) and (4) and their long-term variations were summarized in Fig. 3c and d. During the period of 1963a–1986a, the values of K and transition matrices were consistently high, indicating that the conversions between the oasis and desert were severe and frequent. Generally, in this period, the speed of the oasification process was larger than that of the desertification process, especially during the periods of 1963a–1968a and 1980a–1986a. But, in the period of 1987a–1993a, a total of 68.90 km^2 of oasis land was converted into wasteland. Since late 1990s, oasis change was characterized by the extremely unbalanced one-way transitions. As to the whole period of 1963a–2010a, the status and trend of the oasis patch area were fluctuated and unbalanced, manifesting as sprawl–shrink–sprawl–shrink–sprawl (Fig. 4). However, the trends of area and scale in the Jinta oasis were sprawled and the speed of oasification process was larger than that of the desertification process.

4.1.2. Spatio-temporal dynamics and evolution of oasis spatial distribution

During the period of 1963a–1968a, Jinta oasis grew at a high speed due to the construction of artificial irrigation canal network

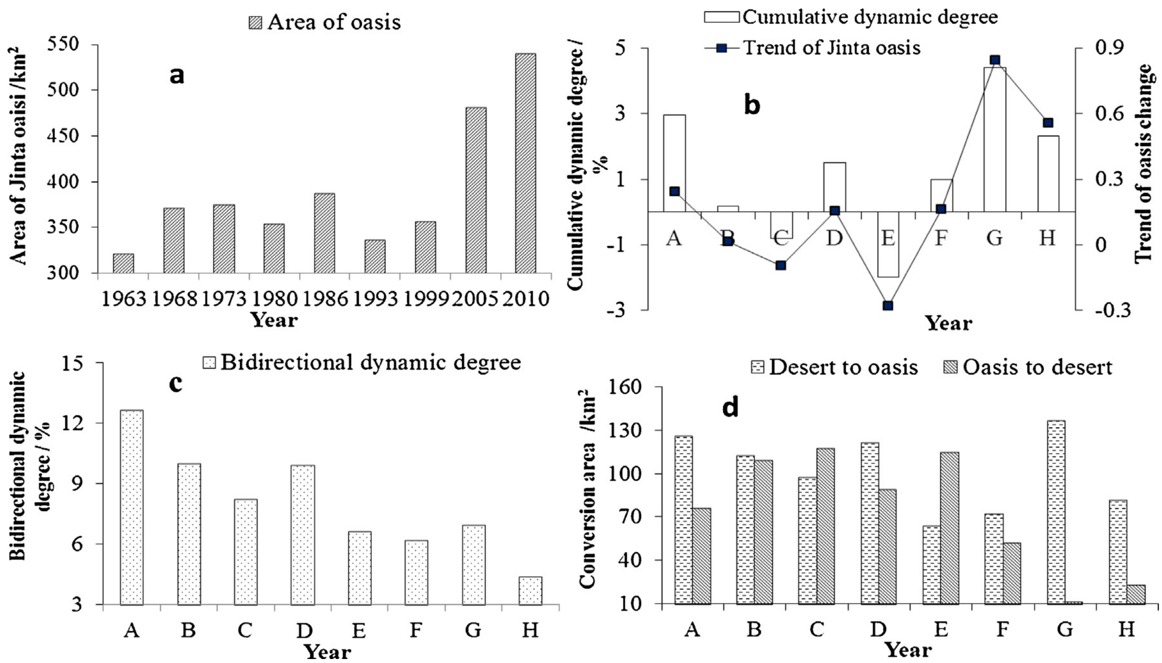

Fig. 3. The dynamic degree and trend of Jinta oasis from 1963a to 2010a A: 1963–1968; B: 1968–1973; C: 1973–1980; D: 1980–1986; E: 1986–1993; F: 1993–1999; G: 1999–2005; H: 2005–2010.

system. For example, the reclamation area of wasted land was 21.63 km^2 along Dongganqu canal, which had 29.98 km length and was constructed in 1968a. The areas of oasis sprawl were mainly located in Xiba town, Precinct of Jinta County, Dongba town, Gucheng town and Jinta town (Fig. 4A and B). Until 1977a, the whole trend of oasification was in the southern sub-region while the desertification came out slightly (Fig. 4C). During the period of 1981a–1999a, the oasis underwent fluctuation and showed an extremely unstable status (Fig. 4D–F), and the most change of the oasis took place in the abandoned land and the outer marginal area of oasis. In the early of 1990s, the oasis area of some townships increased significantly (e.g., Yangjingziwan township) (Fig. 4F). After 2000a, Jinta oasis expanded gradually and reached its peak in 2010a which great change happened in Yangjinziwan township, Dongba township, and Zhongdong township, Chaohu Forestry Station, Lanhewan Horticultural Farm, and Shengdiwan State Farm (Fig. 4H). Overall, Jinta oasis expanded apparently in the latest 47 years most due to the reclamation of both abandoned land and the outer marginal area of the oasis which covered by shrub, grassland or desert grasslands, especially in the sub-regions of the inner

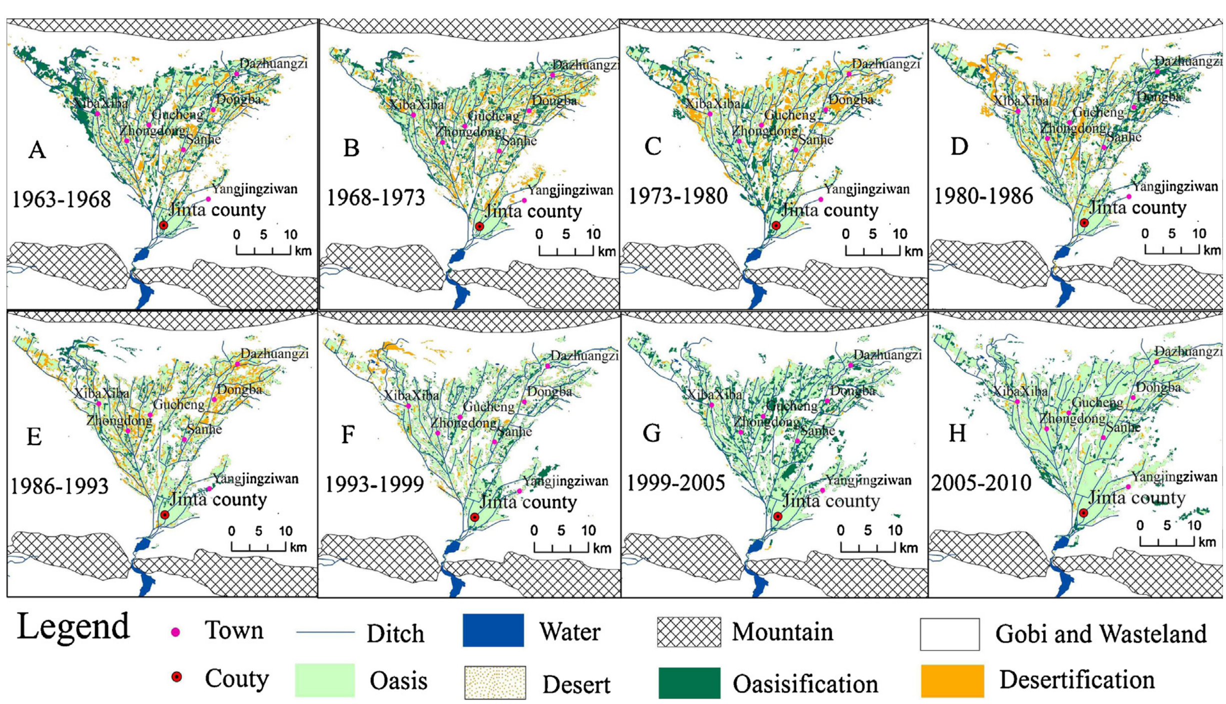

Fig. 4. Maps of expansion and shrinking of Jinta oasis from 1963a to 2010a.

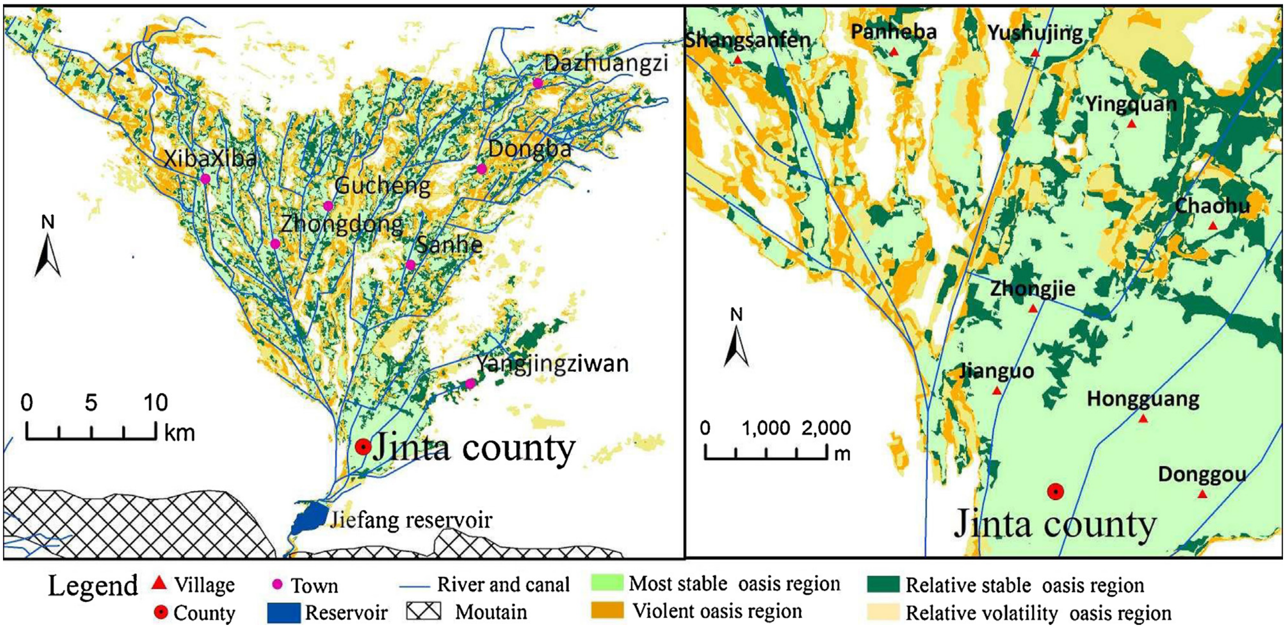

Fig. 5. The change of barycenter and oasification region and stable region in Jinta oasis from 1963a to 2010a.

and outer marginal of the oasis, such as Yangjingziwan township, Xiba township, Sanhe–Dongba–Dazhuangzi township zone, and Jinta–Zhongdong township zone.

4.1.3. Changes of stability zoning in Jinta oasis

The oasis stable area accounted for 28.5% of the oasis area. The oasis stable area mainly distributed along the main canal and lateral canal of Yuanyangchi irrigation area and both sides of the irrigation canals, such as the Dongganqu, Zhandouqu and Xiganqu, the main irrigation canals of Jinta. In contrast to the stable area, the relatively stable area of Jinta oasis was smaller and only accounted for 20.60% of the oasis area, mainly distributed in the marginal area of the stable region as cultivated land, woodland, shrub and grassland, e.g., the northern of Gucheng township, ecotone from Shengli village to Yangjinziwan township, and the riparian zone along the Beidahe River. The drastic change area of Jinta oasis was 19.55% and mainly located in the sub-region between Shengdiwan Farm, Beihaizi Salt Field and Xiba township, both the sides of the river from Dongba township to the northern of Dazhuangzi township and Desert Forest Park (Fig. 5).

4.2. Landscape pattern analysis in response to oasis change

It could be drawn from Fig. 3a and Table 1 that the percentage of the cultivated land area increased greatly from 39.19% to 42.38% of the total change while the percentage of the oasis area increased sharply from 18.02% to 30.35% from 1963a to 2010a. In contrast, the values of LSI in Jinta oasis decreased from 40.94 to 25.05, indicating that the geometry of the oasis landscape tended to be simple and the irregular degree of patch shape gradually declined. As to 1963a–2010a, the trend of AWMPFD also fluctuated and the values were lower than 1.30, which indicated that the oasis fractal index was simple. The degree of correlation between the percentage areas of cultivated landscape and the values of AWMPFD was more apparent than the degree of correlation between percentage areas of cultivated landscape and the values of LSI, indicating that the characteristic changes of the oasis landscape fractal were affected by the oasis patch number, size, composition and structure.

The DIVISION index increased in the whole period though it declined firstly. In contrast, the oasis sprawled rapidly and the component and structure of the oasis tended to be complex. The degree of the fragmentation and spatial distribution in Jinta oasis also increased continuously, while some oases patches experienced some sudden development. The maximum and minimum values of oasis fragmentation index C_i are 2.913 (in 1968a) and 0.171 (in 1973a). The change trend of C_i was similar to LSI, as the values decreased as the oasis area increased and the correlation between cultivated land and C_i was not significant.

4.3. Major driving forces of the oasis spatio-temporal change

In the study area, although both natural conditions and human activities were responsible for Jinta oasis changes, the effect of human activities was more profound in the latest 50 years (Liao, 2011; Gong et al., 2013), especially population, policy, water availability, economy and technology (Jia et al., 2004; Gong et al., 2013).

Oasis expansion is often correlated with an increase in human population (Qi et al., 2007). Population growth had been considered a major factor leading to oasis land cover change (Jia et al., 2004; Zhou et al., 2010). In the period of 1963a–2010a, the population increased from 75,007 to 123,602 people (64.79% increase), as oasis area increased from 320.32 to 539.47 km^2 (68.42% increase). There was a strong positive relationship between the growth of the population and the increase of oasis area (coefficient = 0.737,

Table 1
The spatial pattern eigenvalue in Jinta oasis and its regression equation.

	1963	1968	1973	1980	1986	1993	1999	2005	2010	Regression analysis with area proportion
LSI	40.941	65.268	24.129	28.103	32.579	35.892	30.112	29.984	25.050	$y = 0.6929x^2 - 57.352x + 1214.4$ $R^2 = 0.326$
AWMPFD	1.2148	1.2949	1.2474	1.2044	1.2500	1.2179	1.2092	1.2136	1.2375	$y = 0.0021x^2 - 0.1768x + 4.8913$ $R^2 = 0.7382$
N_i	0.0046	0.0081	0.0020	0.0032	0.0039	0.0037	0.0033	0.0048	0.0053	$y = 7E{-}05x^2 - 0.0057x + 0.1198$ $R^2 = 0.1171$
C_i	1.4579	2.9134	0.1711	0.5149	0.6035	0.7176	0.5593	0.4031	0.3963	$y = 0.034x^2 - 2.8556x + 60.441$ $R^2 = 0.2962$

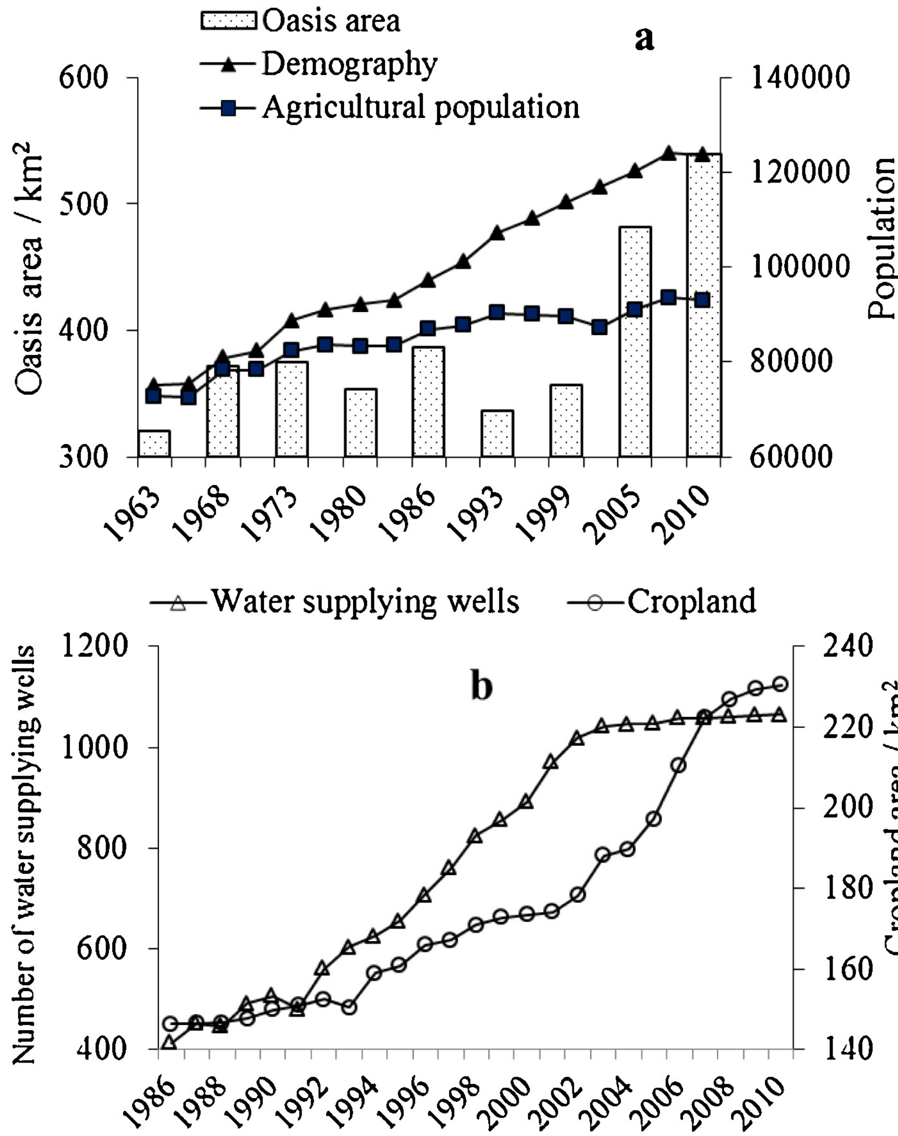

Fig. 6. Changes of human population, number of water supplying wells and cultivated land areas in Jinta oasis from 1963a to 2010a.

Fig. 6a), in addition to a correlation between human population growth and increase specifically in cultivated land area (coefficient = 0.855). This indicates that agricultural production played a vital role in oasis change (Fig. 6a). The increase of population would inevitably lead to an increase in demand of land production, such as food, housing and others (Qi et al., 2007). On other hand, migration was another main driving force of the oasis expansion. For example, Yangjingziwan township was a migrant town established in 1986a and formed by an inflow of new migrants to reclaim wasteland. As a result, the oasis area in this township increased from 0.21 km^2 in 1986a to 14.23 km^2 in 2010a and cultivated land area increased to 7.52 km^2 in 2010a.

Water resource availability, such as the amount of the consumed water and the construction of an irrigation system, directly affected the size, scale and the distribution of the oasis (Jia et al., 2004; Kong et al., 2009). With the increase of the population and the increase of the irrigated cultivated land, the amount of consumed water increased by 2.48×10^8 m^3 in the latest 30 years (The local history and annals editorial committee of Jinta county, 2009). Also, water conservancy facilities and constructions, such as the reservoir, irrigation canal and water supply wells, were built. As a result, there were eight main canals and 72 branches, the length of the entire canal was 2985.20 km and the channel irrigation occupied about 62% of irrigation area in Jinta oasis in 2007a (Ma et al., 2003). Moreover, the number of water supplying wells with power-operation increased from 414 in 1986a to 1064 in 2010a, as cultivated land area increased (Fig. 6b). However, this also caused the gradual decline of groundwater level which threatening the local sustainability.

Policies, such as China's economic reforms policy and economic development strategies, played an important role in the area change and sustainability of Jinta oasis (Fig. 7). Local residents were poor before 1980a, under the Socialist Planned Economic policy, wasted land reclamation was a way to get more food and money. With the construction of Water Conservancy Project (such as Yuanyangchi and Jiefangcun Reservoir), the area of Jinta oasis was expanded and had become one of the key grain and cotton production bases. In the 1980s, the Household Production Responsibility System (HPRS), Poverty Alleviation Policy and Migration Project were launched by Chinese government. As a result, a large proportion of the wasted lands were reclaimed, the protection forests corridor and vegetation restoration zones of shrubs and grass along the oasis margin were also constructed. After 2000a, the Great Western Development Strategy, Grain for Green Project,

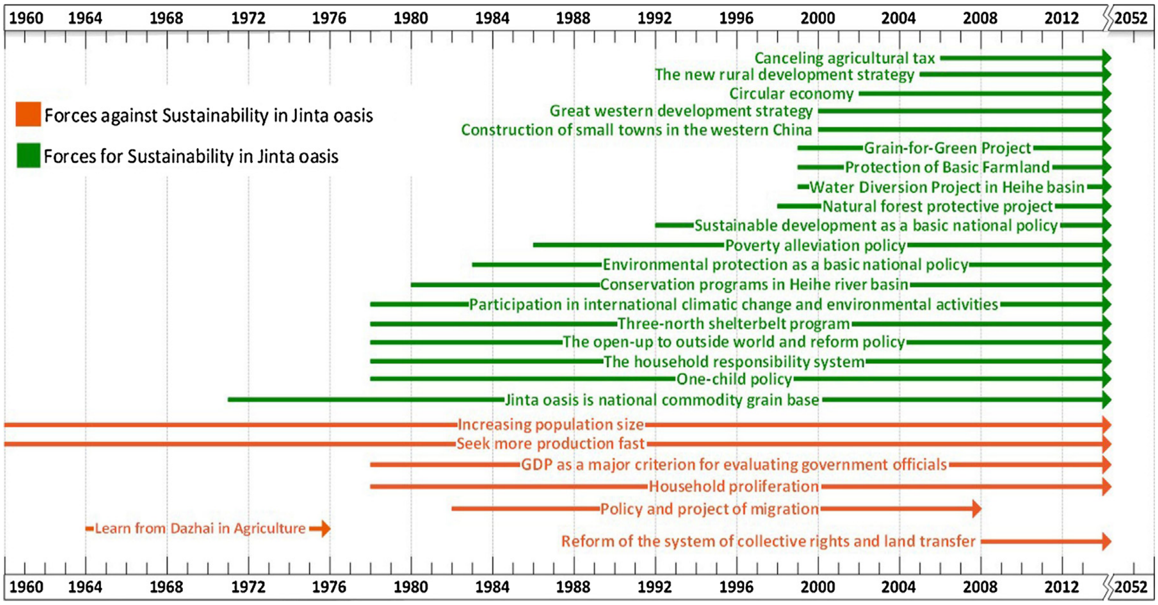

Fig. 7. China's major policy forces for and against environmental and economic sustainability in Jinta oasis.

Canceling Agricultural Tax and the new Rural Development Strategy had a profound impact on the regional economy and sustainability of Jinta oasis. Consequently, policy was a complex factor that not only influenced oasis area change, but also forced various changes that both threatened and promoted oasis sustainable development.

Economic development and technological innovations and advances in irrigation and farming, fertilizing application and the management system also played important roles in oasis change. For example, the investment in fixed assets rose from 4.81 million Yuan in 1950a to 76,405 million Yuan (Chinese Money Unit, 1 Yuan = 0.165 USD in 2013) in 2010a, and per person GDP (abbreviation of gross domestic product) increased from 285 Yuan in 1978a to 6426 Yuan in 2010a. With the development of economy, the demand of quality and variety for agricultural production and consumer goods was enhanced. At the same time, consumption of chemical fertilizers increased from 859 tons in 1963a to 31 896 tons in 2010a. Agricultural mechanization level also increased greatly and total power of agricultural machinery increased 2.8 times from 1985a to 2010a (Fig. 8). Furthermore, water-saving technologies, such as spray pumping and drip pumping technology, cryoprotective technology and low pressure pipe technology (Ma et al., 2003), were applied and spread gradually. All in all, economic development and technological innovation caused the expansion of Jinta oasis.

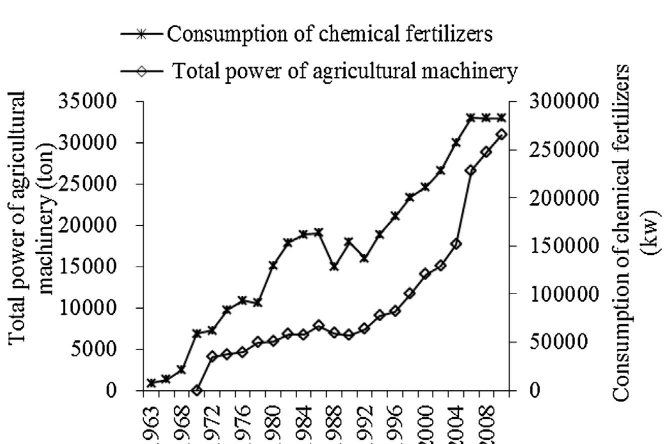

Fig. 8. Changes of chemical fertilizer consumptions and agricultural mechanization in Jinta oasis from 1963a to 2010a.

5. Discussion

5.1. Application and uncertainty analysis of multi-source images on oasis change

Satellite imagery is regarded as a good source of historical data (Petit and Lambin, 2001, 2002; Ruelland et al., 2010, 2011), and multi-source images provide a practical way for mapping and quantifying the oasis changes in arid area. Due to a complete time series of images produced by the same sensor was rarely available for a given site (Ruelland et al., 2010, 2011), the use of archive documents was thus imperative and the general trends were undeniable.

Another question should be raised regarding the uncertainty of multi-source remote sensing imagery in oasis change. Combining heterogeneous data for land cover change analysis required a prior equalization of their levels of thematic content and spatial details by map generalization to minimize the artifacts on change detection due to inconsistencies. Several authors have attempted to integrate land cover data from different sources to increase confidence in change detection. For instance, a method was developed by equalizing their level of thematic content and spatial details for change detection on an African landscape (Petit and Lambin, 2001). However, there were differences because of the difference in the bands information, texture, color, and shape. In addition, oasis lands were not always used for cultivation as some areas were abandoned. It was also difficult to detect how long it was used as agricultural land before abandonment and when conversions or changes in land management took place (Lambin and Geist, 2006). Furthermore, the rapid land cover changes that had been observed were not randomly or uniformly distributed but clustered in particular locations.

Regardless, change detection from multi-temporal remotely sensed images has been widely used in many fields, such as LUCC, urban growth, and forest and vegetation dynamics, since many types of changes could be extracted at local, regional, and global scales (Lambin and Geist, 2006). Incorporating information from different sources to strengthen the credibility of monitoring assessments on oasis change would be needed, such as, by combining remote sensing data and field observations. Our study was first report of oasis change over long time-spans without consideration of the internal structure change of Jinta oases. At the same time, selection of an appropriate method for varying acquisition scales of different source images is also urgently needed, although it still remains a complex and difficult matter (Coppin et al., 2004; Ruelland et al., 2011).

5.2. General spatiotemporal pattern of oasis change

This study showed that oasification was growing from 1963a to 2010a with wasteland area converted into cultivated land, constructive land and forestland. This was consistent with the results reported by Ma et al. (2003) and Qi et al. (2007), and others from the similar arid areas, such as, Sangong river watershed (Luo et al., 2008), Heihe river watershed (Liao, 2011) and Aksu watershed (Zhou et al., 2010) of northwestern China. It indirectly indicated that our way of taking oasis as a single geographical landscape unit also would quantitatively reflect environmental change of arid land in northwestern China.

The most change of the Jinta oasis happened as the reclamation of abandoned land and desert, especially in the inner and outer marginal area of the oasis, and the oasis stable region mainly distributed in the sides of river channel, main canal and its branches of the reservoir irrigation area. Considering temporal scale, the oasis expanded rapidly in the middle 1980s and from 1995a to 2006a. These periods were also critical stage of social transformation, economic reform and rapid development in China. Evidently, oasis change in our study was closely related to policy shifts and social development, therefore, not a stationary and random process that could be predicted by Markov models. That is, the methods of our study provided a useful tool and insight into oasis change dynamics which were a non-Markovian process in the similar area.

5.3. Responses of landscape pattern metrics to oasis change

It was obvious that the Jinta oasis landscape changed during 1963a–2010a, the oases patches tended to be simple and regular, and the dispersion degree and fragmentation of Jinta oasis decreased over time. It was similar to the research results obtained in the other oases, such as Suzhou oasis (Li et al., 2001), the oases of Sangong river watershed (Luo et al., 2008) in arid China. Moreover, the change of oasis showed a state of "imbalance–balance–extreme imbalance condition", similar to the results of the analysis of the oasis corridor landscape and fragmentation in by Ma et al. (2003). These results revealed that oasis change process profoundly influenced its landscape pattern. Specifically, the area, size and spatial distribution of the Jinta oasis was affected by human activities and resulted in a fundamental change of oasis landscape pattern.

As a typical agricultural oasis, the change of cultivated land was the most important and the main cause of oasis change. In this study, the correlation between AWMPFD and cultivated land was remarkable while the other landscape metrics was not. This could be explained by the following reasons: (1) the oasis internal components and structure will affect the oasis landscape structure inevitably. (2) The inconsistency of spatial resolution on multi-source images. The difference of spatial resolution of the multi-source images might lead to a difference of the object feature, such as, shape, color and texture (Jensen, 2006). The degree of change shown in landscape indices might be overestimated in the process of visual interpretation because of the inconsistency regarding the scale and projection. For example, the values of LSI, DIVISION, C_i were low in 1973a while their values were larger in 1968a. In this study, though all the images were re-sampled and subjected to on-screen interpretation under the same scale while some geographical materials (topographic map, land use map and database, Google Earth satellite images, etc.) and ground surveys were also used to improve the accuracy and precision of interpretation, the effect of data emendation of different image solutions on the selected landscape indices were not very obvious due to the classification errors could not be completely eliminated (Saura, 2004; Shao and Wu, 2008). Hence, one of oasis research topics in the future would be methods to reduce the interpretation error of multi-source images (Ruelland et al., 2011). On the other hand, it indirectly showed that the relation between oasis change and its landscape pattern was a complicated process.

5.4. Driving forces of the oasis change

Due to the interactive influence of various kinds of natural conditions and human activities involved, it was difficult to reach an agreement on the causes and process of oasis change at the level of regional landscapes (Li et al., 2007). And then, the dominant driving factors of oasis changes were distinct in the different periods and positions, and they interacted with each other. Our study showed that demographic factors and government policy were responsible for Jinta oasis changes, water resources utilization was the prerequisite of oasis expansion, and immigration, economic development, scientific and technological advancements were the driving factors. It was similar to the research results of land use/cover change in the other arid area, such as Chyulu Hills squatters, Kenya (Muriuki et al., 2011), Northern Afar rangelands, Ethiopia (Tsegaye et al., 2010) and Aksu watershed (Zhou et al., 2010) in northwestern China.

5.5. Implications for oasis landscape dynamics and management

Our study found that the Jinta oasis expansion occurred along the ecotone between oasis and desert, which was typical for most of the oases in the arid area of northwest China, such as oasis in Manas River Valley (Cheng et al., 2006; Zhang et al., 2012), and the oases of Sangong river watershed (Luo et al., 2008). This will be some profound implications for ecological and sustainable development in the arid China. In China, 120 million ha (c. 1.8 billion mu) of cropland area is the minimum amount of arable land needed because it ensures food security (XinhuaNews, 2010). Efficient exploitation of land and water resources and improvement of the fragile oasis environment is very important to Ecological Red Line (It is a national policy launched in 2014a for ecological protection, implementing a system of paid use of resources and ecological compensation, and reforming the system for the protection and administration of ecological environment.) and national ecological safety in arid China, especially in the multi-ethnic and frontier region. Our study showed that Jinta oasis area increased from 320.32 km^2 in 1963a to 539.47 km^2 in 2010a with a net increase of 68.4%. In addition, according to statistics, per capita GDP increased from 285 Yuan in 1977a to 17,490 Yuan in 2010a. In contrast, natural grassland and desert shrub continually decreased. Furthermore, the goal of current land use policy more interested in preserving and reclaiming farmland, not the ecological rational of oasis system and watershed management. In the meantime, Jinta oasis was trending to become agricultural oasis that cotton hold dominant position, indicating that oasis diversity function loss. Therefore, more researches on oasis expansion and its ecological effect were urgently needed in the future. Here our study demonstrated the process of oasis change and its influence on the oasis landscape pattern and the methods could be extended and applied for the similar area.

6. Conclusions

This study showed that multi-source remote sensing data could be used together to monitor oasis change over a long-term period, like the monitoring of LUCC in other areas. This way made the change research at a larger spatial scale and a longer duration possible. The methods used to reflect the oasis change could be extended and applied to the similar region in arid area.

The oasis changed markedly at the spatial and temporal scale with the frequent and drastic conversion between oasis and desert in 1963a–2010a, although the degree of conversion varied in the different periods. The oasis area had increased for the whole time span, and the spatial distribution pattern of Jinta oasis mainly took place at the inner and outer marginal sub-region of the oasis. In addition, oasis change had profound influence on the pattern of oasis landscape, and reflected in the landscape shape, dispersion degree and fragmentation.

The dominant factors which affected Jinta oasis changes were distinct in the different periods and positions, and they interacted with each other. From 1963a to 1980a, the dominant driving forces were the population growth and policy, whereas the dominant driving forces from 1981a to 2002a were the changes in agricultural production ways, policy and population growth. After 2002a, the dominant forces were economic benefit and water utilization.

All in all, oasis change was a complex and gradual process in arid China. Understanding the oasis change and its landscape effect for the catchment was the basis for sustainable management and development of oasis landscape in the arid area. Numerous challenges, however, were also raised from this study, for example, the uncertainty in classification and change detection based on multi-temporal and multi-resolution remotely sensed images, the interactions between oasis and desert changes and how to quantify and develop comprehensive, representative parameters to describe spatiotemporal patterns. In the future, more attentions should be paid for rational governance and compatible with the fragile nature of arid area.

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