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Impacts of major vehicular roads on urban landscape and urban growth in an arid region: A case study of Jiuquan city in Gansu Province, China

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A B S T R A C T

Urbanization has brought about dramatic changes in the urban environment in China and its associated human population and transportation systems in recent years. However, urbanization in the oases of arid regions of China has been little studied and remains poorly understood. This paper aims to analyze spatiotemporal changes in an urban landscape along major vehicular road transects and compare the relationship between urban growth and transportation in Jiuquan, an oasis city in an arid region of China. We integrated remote sensing images, landscape metrics, and urban-rural gradient analysis to address these questions. The results showed that major vehicular roads stimulated Jiuquan's urban expansion, especially with regard to built-up land containing urban green land areas. Oasis urbanization not only increased landscape fragmentation and structural complexity, but also followed a linear branching, leapfrogging growth pattern characterized by "axial clumps" extending from downtown into rural areas along the road network. The primary source of urban land was not agricultural land, but unused land. These results also indicated that the transect approach implemented along representative roads was effective for studying the urbanization of oasis cities. Such an approach could be applied to master planning in similar oasis cities throughout arid China.

1. Introduction

Rapid urban growth is a key concern for local authorities and urban planners, as it results in extremely complex landscape change processes, and profoundly influences the structure and function of both natural ecosystems and human livelihoods (Luck and Wu, 2002; Buyantuyev and Wu, 2009; Li et al., 2013a,b). In 2014, more than half the world's population lived in cities and towns, a figure that is estimated to increase to 70% by 2050 (United Nations, 2014). This increase implies that the spatial pattern of urban landscapes and land-cover conversion will continue to be complex (Wu, 2014; Wu et al., 2014). Therefore, it is important to understand the spatial patterns of urbanization and their impacts on ecological processes from global to local scales.

The urbanization process is dynamic, and the direction and magnitude of urban landscape change may vary over time and space (Li et al., 2013b; Xu and Min, 2013). To understand and capture the process of urbanization and its ecological consequences for landscapes, a more synthetic approach needs to be implemented in order to quantify landscape changes (Solon, 2009). The classical approach is an urban-rural gradient analysis, which is based on a moving window (Luck and Wu, 2002). The urban-rural gradient is a systematic and effective approach to detect the spatiotemporal complexity of urban dynamics. The approach has been more recently integrated with landscape metrics to understand urban ecological processes (McDonnell and Hahs, 2008). In addition to being used for demonstrating landscape change across space along urban-rural transects, this method has also been extended by incorporation of temporal trend analysis (Weng, 2007; Li et al., 2013b) and multiplication of transects (Kong and Nakagoshi, 2006; Yu and Ng, 2007; Solon, 2009). Most of the past studies of the transect directions in these gradient paradigms were west-east and/or north-south (Luck and Wu, 2002; Weng, 2007; Li et al., 2013b), along eight directional transects (Kong and Nakagoshi, 2006; Yeh and Huang, 2009; Zhou and Wang, 2011; Shrestha et al., 2012), around a concentric circle (Zhou and Wang, 2011;

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Solon, 2009), or along a specific transect that crosses the area disturbed by urbanization (Luck and Wu, 2002; Yu and Ng, 2007; Li et al., 2013b). These approaches may limit the ability to detect urban change because although most urban expansion appears to have taken the form of dispersed or sprawling pattern alternating between diffusion and coalescence phases, the trajectories and rhythms of urban landscape change may vary in certain ways according to specific geographical and historical characteristics as cities evolve. For example, the developmental form of oasis cities in arid areas may be different from that of coastal cities in humid regions (Tian and Wu, 2015; Yeh and Huang, 2009; Yu and Ng, 2007; Li et al., 2013b).

In arid areas, oases form a unique geographical landscape with higher productivity than their surrounding landscape (deserts). Oasis cities have been the primary sites for flourishing vegetation and human settlement in these areas (Jia et al., 2004; Xie et al., 2014). Oasis cities, mostly based on oasis-irrigated agriculture, are also the production and living centers of humankind in oasis systems (Zhang et al., 2009). From an urban ecology perspective, an oasis urban region is a complex and comprehensive ecosystem (Liu et al., 2010; Yang and Liu, 2014) due to the fragility of the environmental system and intensive human activities in arid areas (Xie et al., 2007; Liu et al., 2010). However, few papers have been published on oasis urbanization and its associated landscape change, especially in arid regions of China.

Oasis urbanization is a complex process which is affected by water resources and by social and economic factors such as transportation, migration, exploitation of mineral resources, and public policies (Hawbaker et al., 2004; Zhang et al., 2009). In addition, the areas experiencing the most intense oasis urbanization have not shown homogeneous urban development in all directions, but often along a preferential direction (or in shifting preferred locations) depending on specific factors (such as vehicular roads and other related infrastructure). Vehicular roads have played an important role in urban development through the accessibility they provide for land and material exchange (Saunders et al., 2002; Aljoufie et al., 2013). An example is the tendency for industrial areas to develop close to motorways (Müller et al., 2010; Xie et al., 2013). Major vehicular roads could also possibly be considered as "pioneers" and could be used to indicate the direction of urban development and exert a profound influence on urban landscape changes (Fan et al., 2009; Müller et al., 2010; Tian and Wu, 2015).

Recently, several studies have explored the relationship between vehicular roads and urbanization across diverse urban systems. The results showed a significant relationship between transportation and urban sprawl (e.g., Handy, 2005; Müller et al., 2010). Results also indicated that vehicular roads are a significant factor in urban growth and influence landscape change (Aljoufie et al., 2013; Tian and Wu, 2015). However, the relationship between major vehicular roads construction and landscape changes in urban oases in arid areas is still unknown, especially in arid regions of China. This gap exists perhaps due to the poor economic status of such cities and their small size relative to other cities in China (Xie et al., 2007). At the same time, it has been widely hypothesized that "there must be some impacts or interactions between major vehicular roads construction and its surrounding landscape change" (Müller et al., 2010), but few studies have considered the spatial and temporal effects of different vehicular road transects on the urban landscape using quantitative methods. Does the urban landscape of an oasis city take the form (or model) of sprawling patterns along a road axis (such as the linear branching form of urban leapfrogging growth) and would it vary along an urban-rural roadside gradient? Empirical case studies are needed to answer this question.

In China, most oasis cities are connected with each other by national highways, expressways, provincial roads, county and township roads (rural roads) (Li et al., 2010; Liu et al., 2011). Most oasis cities are of medium size (with a population between 300,000 and 1 million people) or small size (with a population between 50,000 and 300,000 people). This research considered one medium-sized ancient city along the Silk Road[1] in northwestern China named Jiuquan, for which urban area increased more than eight times from 1949 to 2013. The rapid urban expansion of Jiuquan not only turned it into the pacesetter of urbanization in the arid area of northwestern China, but also attracted attention from economists, environmentalists, and urban planners. Therefore, taking Jiuquan city as a case for understanding and exploring urban development in this area would serve as a good pilot project for learning lessons and providing theoretical and practical guidance for the sustainable development of northwestern China (Fang and Xie, 2010; Wu et al., 2014).

The aim of this study was to quantify the spatiotemporal patterns of an urban landscape and to evaluate the influence of representative vehicular road axes (such as national highways and provincial roads). For this purpose, a contrast analysis of gradient transects was conducted along national highways and provincial roads to answer the following questions: (a) what are the spatiotemporal patterns of this urban landscape, and (b) can vehicular roads affect urban expansion (or urban landscape change) in an oasis city in arid China, and if so how?

2. Materials and methods

2.1. Study area

Jiuquan city (98°12′–99°18′E, 39°10′–39°59′N) (Fig. 1a), a typical agricultural oasis city with a history of more than 2000 years, is located in the Hexi corridor of arid, northwest China. This region is dominated by an arid temperate continental climate, with a mean annual temperature of 7.4 °C and a mean annual precipitation of 85.3 mm. Jiuquan city originated with the prosperity of the silk trade and the establishment of a garrison in 121 BC. Today, it is not only a famous tourist city benefitting from its historical heritage, but it also has become an important inland agricultural-industrial city and transportation center after the implementation of China's economic reforms (an opening-up policy of economic liberalization launched in 1978). The urban population increased from 40,804 in 1980 to 210,043 in 2012 and the total value of industrial output has doubled over the past thirty years (Suzhou Statistics Bureau, 2012) (Fig. 2). This increase has resulted in great demand for transportation infrastructure and influenced the urban landscape in Jiuquan city.

The study area covered the landscape along two main roads in Jiuquan city, specifically national highway 312 and provincial road 214 (Fig. 1b). National highway 312 is a key east-west route beginning in Shanghai and ending at Khorgos in the Xinjiang Uygur Autonomous Region. Provincial road 214, constructed in 1946, is another trunk highway connecting Jiuquan city in Gansu Province with Ejina Banner in the Inner Mongolia Autonomous Region.

2.2. Data and land-use classification

Landsat TM/ETM + images (Path 135, Row 32, acquired on 22/9/

[1] The Silk Road: a historically important international trade route between China and the West, established during the Han dynasty (approximately 200 BC to 200 AD), along which Han silk fabrics, china, and other products were transported to Southwestern Asia and Europe, and which linked China with the West both in ancient and modern times.

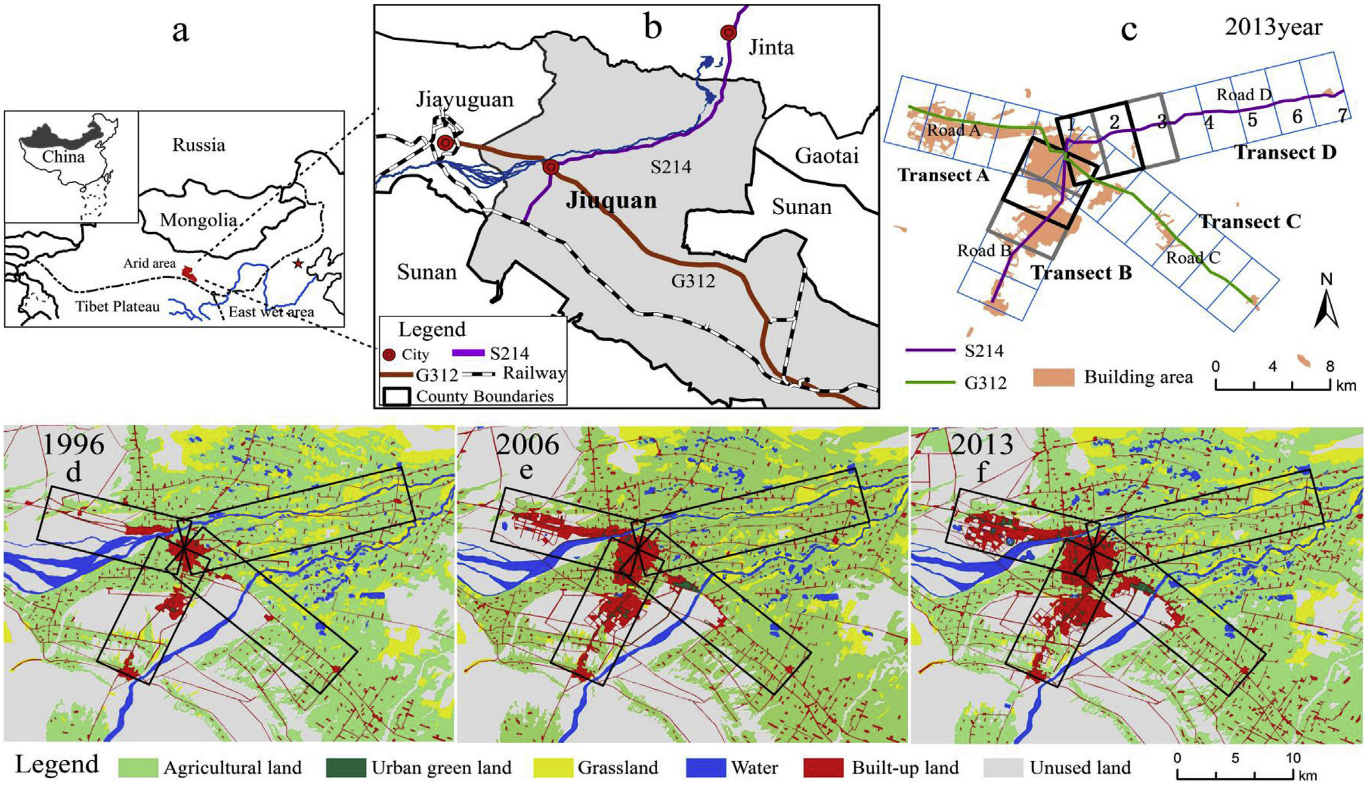

Fig. 1. Location of Jiuquan city in arid China and transect layout, land use change.

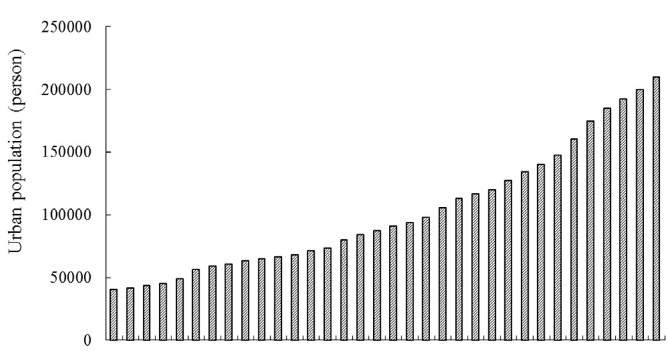

Fig. 2. Changes of urban population in Jiuquan city from 1980 to 2013.

1996, 17/8/2006, and 02/9/2013) and historical traffic maps were collected to facilitate spatial and temporal analysis of urban growth and transportation infrastructure. These image data were selected either in summer or autumn because these were the best times of year to study oasis distribution. Other data included a topographic map at 1:100,000 made in 1995; a land-use map of Jiuquan city at 1:100,000 and an administrative map made in 2007; urban master plans of Jiuquan for 1996 and 2010; the Jiuquan statistical yearbook from 1980 to 2013; and images on Google Earth with high spatial resolution gathered in 2012.

The Landsat TM/ETM + images were processed using the ENVI 4.8 software, which involves geometric correction, image enhancement and supervised classification (Yu and Ng, 2007; Xu and Min, 2013). A sufficient number of samples were collected, and sites were checked on the original images through field surveys, including ground control points collected using GPS and photographs to assist in image interpretation. Based on the methods described above, visual image interpretation based on experimental knowledge and field observation was used to modify the land-use dataset. Here, land-use types were classified as agricultural land (AL) (farmland, vegetable plots, orchards, and nurseries), urban green land (UG) (forests, parks, and green space), grassland (GL) (shrubs and grassland with vegetation cover >15%), built-up land (BL) (residential, commercial, and industrial land together with public transportation corridors, and construction sites), water areas (WA) (rivers, aqueducts, lakes, ponds, and reservoirs), and unused land (UL) (salinized land, derelict land, bare land, desert, and Gobi desert and low-coverage grassland with vegetation cover ≤15%). This classification is based on the classification criteria for the Chinese Current Land Use Classification (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China & Standardization Administration of the People's Republic of China, 2007) (Fig. 1d–f). In addition, a total of 250 points were randomly selected to verify the precision of classification through field surveys. The overall accuracies for 1996, 2006, and 2013 were 87.9%, 91.2%, and 90.5% respectively. In addition local residents were also interviewed about the history of land use in the area, and land transformation information provided by the local government was analyzed to understand and explain the factors responsible for triggering landscape changes.

2.3. Urban-rural transect along vehicular roads

As a starting point, the center of the Jiuquan urban area was taken as a breakpoint dividing National highway 312 into two sections: the Jiuquan–Jiayuguan road (abbreviated as Road A) and the Jiuquan–Qingshui road (abbreviated as Road C). The Jiuquan–Jiayuguan road was broadened to a motorway with six traffic lanes in 2008 due to urban integration between Jiuquan and Jiayuguan city. Provincial road 214 in Jiuquan city was also divided into two sections. The southern part of provincial road 214 was called the Jiuquan–Xidong road (abbreviated as Road B). This road runs from the city center to the railway station of Jiuquan city (Xidong town) and was broadened to an expressway (motorway) in 2005. The northern part of provincial road 214 is the main expressway to Jinta county and was called the Jiuquan–Jinta road (abbreviated as Road D) (Fig. 1b and c).

Subsequently, four representative transects were selected that run through the whole of Jiuquan city along roads A, B, C, and D respectively (Fig. 1c), and urban-rural gradient analysis based on landscape pattern metrics was performed. Specifically, these transects extended from downtown (the Drum Tower of Jiuquan) into the rural area and stopped in the first town along national highway 312 or provincial road 214. Each block was designed to be 5 km × 5 km in size with a 2.5 km overlap with the neighboring block (Fig. 1c) because the range of the road effect zone along the oasis urban-rural gradient was about 3 km (Xie et al., 2013) and because of the winding nature of the roads. Therefore, transects A and B (forming part of national highway 312 and provincial road 214 respectively) were composed of four blocks 12.5 km long, whereas transect C (forming part of national highway 312) was composed of six blocks 17.5 km long, and transect D (forming part of provincial road 214) consisted of seven blocks 20 km long.

2.4. Landscape pattern analysis

Numerous pattern metrics were developed to provide quantitative measurements of various aspects of the urban landscape, specifically focusing on size, density, shape, clustering, diversity, and connectivity. In order to quantify the spatial patterns of urbanization in oasis cities and to ensure comparability with previous studies (Luck and Wu, 2002; Zhu et al., 2006; Yu and Ng, 2007; Li et al., 2013a,b), a set of landscape metrics were used, including patch density (PD), percentage of landscape (PLAND), largest patch index (LPI), landscape shape index (LSI), edge density (ED), and Shannon's diversity index (SHDI) (Table 1). The selected metrics have proven in the past to be effective at reflecting their intended landscape properties and have also been shown to reduce correlation and redundancy (Yu and Ng, 2007). They were calculated for each block at the class and landscape levels using FRAGSTATS (version 4), as described in McGarigal et al. (2012). The appropriate spatial resolution to study landscape patterns and changes depends on the characteristics of the study area and the details and trajectories of interest to the researcher (Luck and Wu, 2002; Wu et al., 2014; Li et al., 2013b). In this study, the land-cover map was resampled with a cell size of 10 m × 10 m due to the low urbanization level of oasis cities and the small size of rural residential areas. A 10-m pixel size was chosen because it retains more details of the landscape pattern and avoids or smooths noise caused by smaller pixel sizes (Zhu et al., 2006; Weng, 2007).

2.5. Urban change intensity

Landscape changes along different urban transects have been profoundly affected by many factors such as urban development history, geophysical template, land and water sources, and characteristics of a particular urban core (Solon, 2009). It is important to compare these factors among major vehicular road types as well as to calculate the amount and expansion rate of urban land and road density, factors generally considered as important parameters for representing change intensity (Zhou and Wang, 2011). Change intensity was calculated here using equation (1) and analyzed for two time periods (1996–2006 and 2006–2013).

$$R = \frac{(U_{i+t} - U_i)}{U_i + t} \times 100\% \tag{1}$$

where R is an index of annual urban expansion rate, t is the time interval of the calculations (in years), and U_{i+t} and U_i are the built-up land area in the target blocks at times i + t and i respectively. In this study, main roads greater than or equal to 4 m in width (rural roads) were investigated, and road data were based on the transportation map of Jiuquan city. The spatial effects of vehicular roads on urban growth were then investigated for each block.

3. Results

3.1. Synoptic analysis of land-use patterns along major vehicular road transects

The urban land-use pattern changed substantially during the study period (Figs. 1 d–f, 3 and 4). From 1996 to 2006, the BL along all road axes experienced the greatest amount of urban sprawl, except for transect D. UL and AL clearly decreased along transects A and B, whereas UL and GL along transect C decreased by 401.53 ha and 229.95 ha, respectively. UL along transect D also decreased from 243.71 ha to 88.52 ha. During 2006–2013, the BL area clearly increased, while AL and GL decreased, except for that of transect D. UL along all road transects displayed a similar decreasing trend.

During the entire period from 1996 to 2013, urban growth was maintained at a rapid speed. Along transects A and B, the BL increased from 770.69 ha to 1208.64 ha in 1996, –2239.10 ha and 2739.03 ha in 2013, respectively (Fig. 3a–b). This increase was mainly due to the conversion of UL (about 1007.92 ha and 786.76 ha was converted into BL respectively) and AL (about 530.22 ha and 775.35 ha was converted into BL respectively) (Fig. 4). In contrast, urban growth along transects C and D occurred slowly, and the landscape matrix changed continuously, with a distinct slowdown

Table 1
Landscape metrics selected in this study.

Metric (units)	Abbreviation	Description	Range	Justification	L^a/ C^a
Patch density (number per 100 ha)	PD	Number of patches per 100 ha.	PD > 0	Fragmentation index	L^a, C^a
Largest patch index (%)	LPI	Largest patch of a certain class divided by total landscape area, multiplied by 100.	0 < LPI ≤ 100	Dominance index	L^a, C^a
Landscape shape index (none)	LSI	Patch perimeter divided by the minimum perimeter possible for a maximally compact patch of the corresponding patch area.	LSI ≥ 1	Shape index	L^a
Edge density (m/ha)	ED	The sum of the lengths of all edge segments divided by the total landscape area.	ED ≥ 0	Shape index	C^a
Shannon's diversity index (none)	SHDI	A measure of patch diversity, which is determined by the distribution of the proportion of different land-use types in a landscape.	0 ≤ SHDI ≤ 1	Diversity index	L^a

Note: 1. L^a = Landscape-level metrics; C^a = Class-level metrics; 2. Details of the parameters can be found in McGarigal et al. (2012).

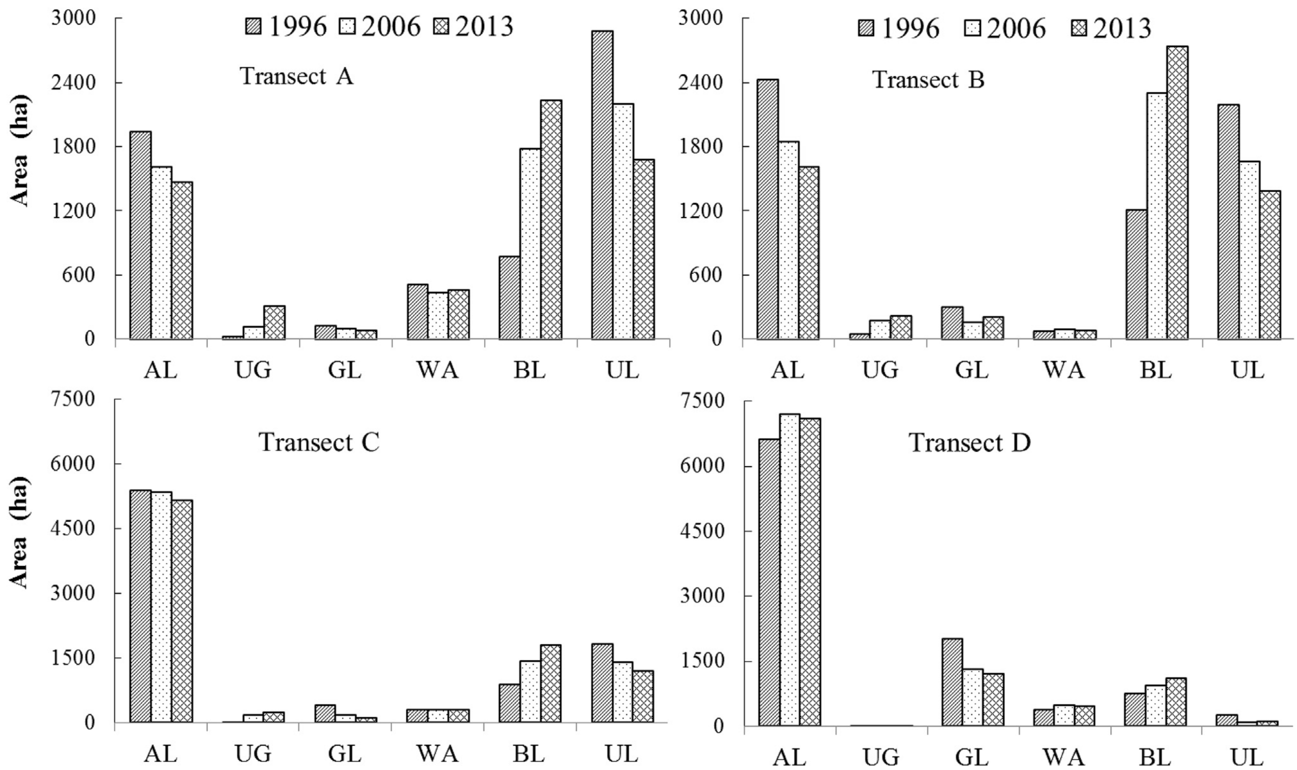

Fig. 3. Areal change of land use types along the major vehicular road transects from 1996 to 2013.

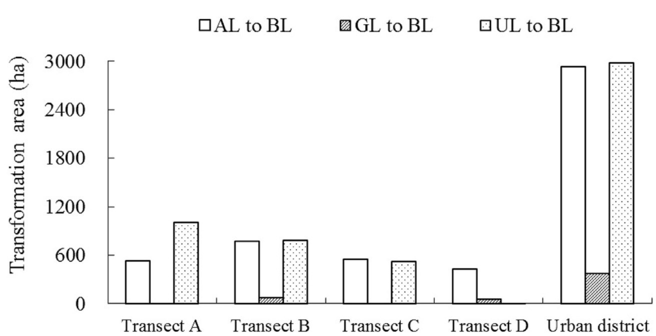

Fig. 4. Transition matrix of land use along the major vehicular road transects from 1996 to 2013.

in development (Fig. 3c–d). In transect C, the new BL originated from the conversion of AL and UL, which accounted for 49.78% and 46.72% of the total conversion area respectively. In transect D, the new BL areas only accounted for 514.32 ha, with more than 82% originating from AL, and GL and UL only accounting for 11.6% and 3.33%, respectively. In the whole urban district of Jiuquan city, the most considerable change was the transformation of UL to BL (industrial, commercial, and residential land), accounting for 46.51% of the total transformed area of BL. AL was the next most transformed land type, accounting for about 45.79%. Spatially, along transects A and B, the region with the highest urban expansion rates was not the zone closest to the city center, but rather the industrial and built-up areas in the suburbs, while the increase in the urban built-up area occurred at the edge of the urban district.

3.2. Gradient analysis along vehicular road transects with landscape metrics

The results of the landscape metric analysis show that landscape patterns changed both spatially along these transects of different vehicular road axes and temporally through the past 18 years (Fig. 5). Fig 5 (a–d) shows the change in patch density (PD) along the major vehicular road transects in Jiuquan city from 1996 to 2013. Generally, transect A showed a similar trend to transect B, with increasing values of PD. The density of patches along roads A and B from urban to rural was first low, but then increased to reach peaks at distances of 7.5 and 10.0 km respectively. PD has increased over time, indicating an increase in landscape fragmentation. The PD of transects C and D from the city center to the fringe and into the countryside decreased. During the period from 1996 to 2013, the rate of PD change along transect A was the highest (157.86%), followed by transect B (69.6%), and the lowest rate was for transect D (13.43%). These phenomena showed that the levels of urbanization and landscape fragmentation along transects A and B were both higher than those along transects C and D. The PLAND values of BL supported this trend. The PLAND values of BL along transects A and B were higher than those of transects C and D (Fig. 6a–d).

As for the largest patch index (LPI), the highest LPI value appeared as a peak near the city center in 2013, although it had appeared along 10 km of transect A in 1996, indicating a shift in the landscape matrix from UL to BL (Fig. 5e). BL (such as industrial land) grew rapidly, resulting in a dramatic increase not only in landscape fragmentation but also in the LPI value of BL (Fig. 6e). Along transect B, the LPIs showed that agricultural and unused land were still the dominant land-use types at a distance of 7.5 km in 1996, but their dominance had decreased by 2013, indicating that agricultural and unused land were being converted to BL (Fig. 5f). In 2013, BL was the dominant landscape type at distances of 1–5 km and its LPI value was high.

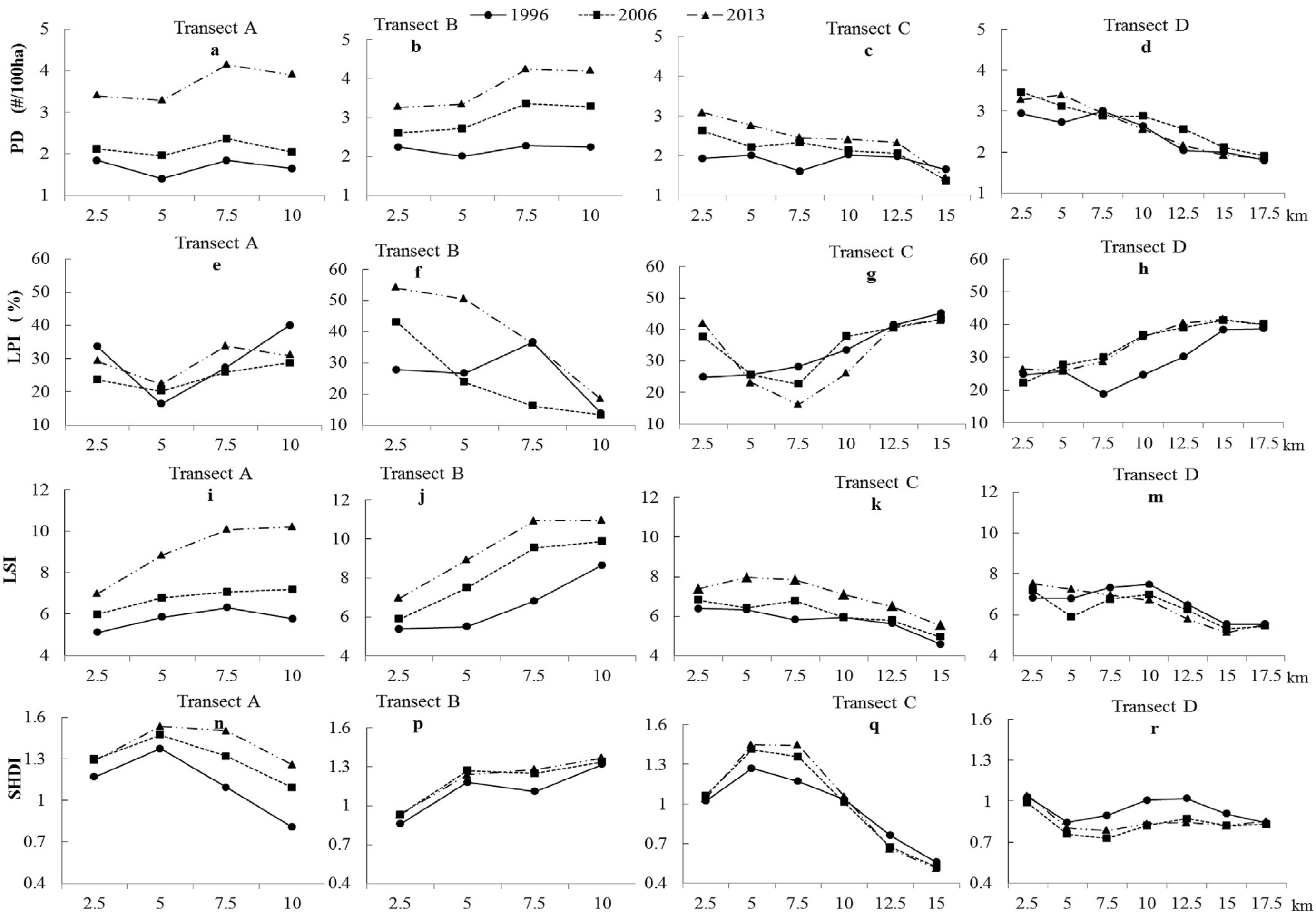

Fig. 5. Landscape pattern metrics at the landscape level along the major vehicular road transects from 1996 to 2013.

LPI values at distances of 0–2.5 km and 12.5–15 km along transect C were both high (Fig. 5g), indicating that BL and AL were the dominant land-use types. However, LPI values at distances of 2.5–17.5 km decreased over time while LPI values of BL increased, especially at distances of 5–7.5 km, suggesting that different land-use types were at equilibrium. Along transect D, the variation in the LPI increased with distance from the city center (Fig. 5h), indicating that AL was still the dominant land-use type. The variation in the LPI for BL decreased with distance from the city center, which confirmed this indication (Fig. 6g–h).

The landscape shape index (LSI) along transects A and B took on its lowest value at the city center, with the values markedly increasing along the urban-rural gradient. Over time, the average patch shape complexity increased (Fig. 5i–m) and the ED of BL along transects A and B became more complex. In addition, the LSI of transects A and B increased with distance from the city center, although the extent of variation along transect B was more pronounced than that along transect A. LSI values along the transect C and D expansion axes were similar, with high LSI values close to the city center, whereas the peak of ED values of BL for transects C and D were also close to the city center (Fig. 6k–m), indicating that the level of urbanization at the edge of the urban area was higher than at other places along transects C and D.

Shannon's diversity index (SHDI) represents the proportion of different land-cover types in a landscape. Spatially, changes in SHDI along transects A and C were similar; both followed an inverted V-shape with high values at 7.5 km and low values in rural areas (Fig. 5n–q), indicating that the proportions of different land-use types were more even at a 7.5 km distance than in rural landscapes. Over time, the SHDI of transect A increased, and diversity of land-cover types became richer. The lowest value of SHDI along transect B was close to the city center, and the temporal rankings of these values were 2006 > 2013 > 1996 in suburban areas, with all values increasing gradually as time went on (Fig. 5p). SHDI values along transect D were high within the urban fringe, but tended to decline with increasing distance from the city center. Over time, SHDI tended to decrease, which may have reflected the decrease in GL from 1996 to 2013 (Fig. 5r) due to increasing landscape complexity and urbanization.

3.3. Urban growth along different vehicular road types

It can be inferred from Fig. 7 that urban land change (taking the total area of BL and UG as an indicator) had the strongest positive relationship with road density along the major vehicular road types. As the motorway between Jiuquan and Jiayuguan city, road A had brought about changes in the urban landscape pattern, meaning that BL occupied large areas and that individual patches of development were relatively large; meanwhile, the density of the road network increased quickly. Furthermore, there was a positive relationship between BL area and road network density (Fig. 7). Temporally, urban growth also generally increased as the road network developed. Spatially, urban growth was more likely to occur in places where it could be easily handled, such as the Jiuquan

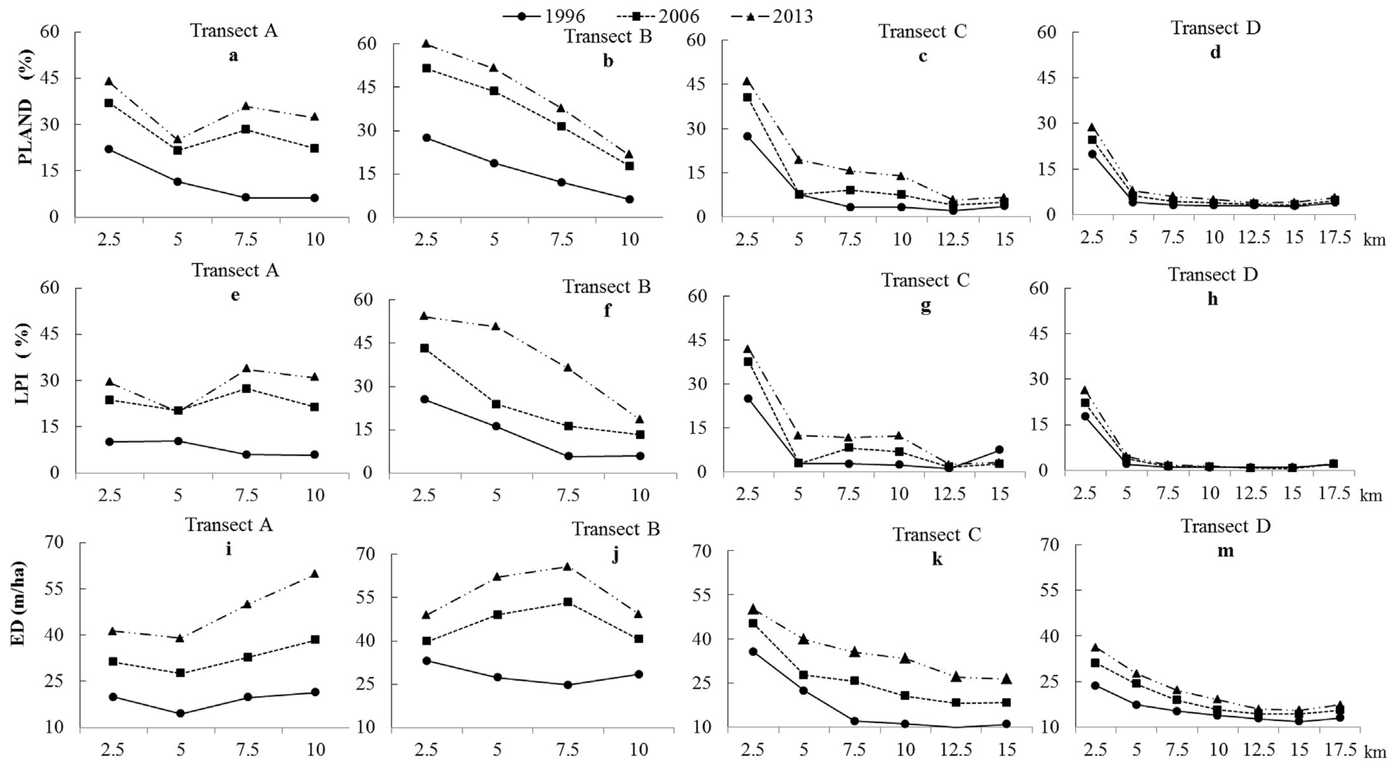

Fig. 6. Landscape pattern metrics of built-up land along the major vehicular road transects from 1996 to 2013.

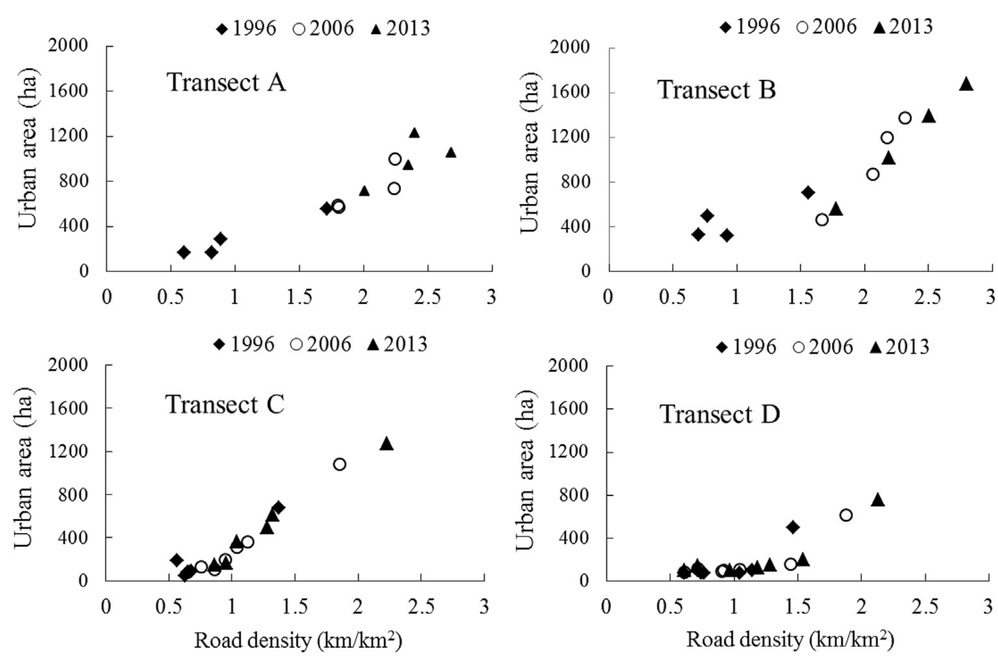

Fig. 7. Relationship between area of urbanized lands and road density.

Industrial Parks Western Zone. A similar pattern was found along road B, which is the main highway between the city center and the railway station, showing that "axial clumping" along road expansion axes was one characteristic of urbanization in Jiuquan city. However, the intensity of change in the urban area along road A was higher than that along road B. This phenomenon indicated that the effect on urbanization of national highway 312 was greater than that of provincial road 214.

Compared to transects A and B, urban growth along transects C and D was not noticeable (Fig. 7). Specifically, BL situated closer to the main roads occupied a limited land surface and was unevenly interspersed among patches of other land-cover types. Simultaneously, farther away from the city center, roads C and D, BL and UG were situated close to each other, even though they were strongly isolated. The relationship between urban land and road density showed two distinct patterns along the urban-rural gradient. At the urban fringe, BL (such as residential land) increased gradually as contiguous urban service infrastructures developed, especially roads and road networks. However, in rural areas, the proportion of BL was low, and the average density of the road network was less than 1.5 km/km^2, which indicated that urban development was constrained by the agricultural land pattern. Comparing transects C and D, the degree of urban expansion along the road C axis was higher than that along road D, especially at distances of 5–10 km. Overall, the urban expansion rates along the four typical road transects were different and could be ranked as follows: road A > road B > road C> road D.

4. Discussion

4.1. Spatiotemporal pattern of urban landscape change

This study demonstrated the effectiveness of gradient analysis along typical vehicular roads for identifying changes in landscape patterns in response to urbanization. In this paper, the process of land use change and urban growth exhibited in an unprecedented scale and rate. In the urban district, 19.63% of the total land has undergone changes, among which 33.11% was transformed from non-urban to built-up area. Combining with the field survey, we found that UL and AL were the main sources of such transformation to BL. Most of the transformation occurred at the urban fringes or outskirts, and in small towns. These areas were developed for commercial and residential areas, Economic and Technological Development Zones (ETDZ), or industrial parks. This was consistent with the results reported for Jiayuguan city (Xie et al., 2013) and Urumqi city (Zhang et al., 2009; Liu et al., 2010; Schneider et al., 2015) in the arid areas of northwestern China. An empirical analysis using a transition matrix of transect land and an urban–rural gradient across corridors, indicated that urban growth did proceed at the cost of UL and AL, which was a different from the patterns of land transformation in the coastal cities of China, where AL was the main source transformed for urban land use. In Jiuquan city, urban landscape types were found to be more diverse and more complex in their spatial configuration than rural landscapes. Urban growth increased the degree of landscape fragmentation and even changed the landscape matrix in some blocks. For example, BL expanded to the extent that the percentage of other land uses became small in the western and southern parts of Jiuquan city.

4.2. Impacts of major vehicular roads on urban growth

In Jiuquan, urban spatial expansion and land use changes seem to be driven by vehicular roads over time. Different vehicular road types had respective spatiotemporal influences on urban expansion. Initially, BL declined with increasing distance from roads. In the last 20 years, the main driving factors of urban expansion have not been urban water resources or the size of the oasis (Liu et al., 2010), but the joined effects of economic development, population growth, national policy, transportation, and resources. Vehicular roads were usually deemed to be "pioneers" in reflecting the changes brought about by these joined effects and investments by the Chinese central and/or local governments. Thus, areas close to roads were urbanized faster than those further from. This result was similar to those observed in metropolitan regions of Phoenix and Las Vegas in the western USA (Wu et al., 2011; Tian and Wu, 2015), and Jeddah, Saudi Arabia (Aljoufie et al., 2013), our results also indirectly indicated that oasis urbanization occurred mainly along road expansion axes. In other words, the linear branching model of leapfrogging development was observed, with a characteristic pattern of "axial clumping" along major roads in Jiuquan city. This pattern was distinct from those presented in coastal cities in China, where most of them experienced a diffusion-coalescence switching process or a spiraling process involving multiple growth modes (Li et al., 2013a; Tian and Wu, 2015). In this study, gradient analysis of land use/cover change and urban growth along major vehicular roads not only reflected the direction of urban sprawling, but also revealed the dominance of linear branching leapfrogging development although infilling and edge expansion were likely to be happened during the urbanization processes.

On the other hand, the variation in urban landscapes was different over time and along different vehicular road types in this study. First, the area of BL along different vehicular road transects was different. The rate of change in PD was also different, with the value along transect A the highest, followed by transect B, with the lowest value in transect D. There were also differences in the change of the landscape matrix during the period of 1996–2013. BL became the main component of the landscape matrix along transects A and B, replacing UL, while AL still was the dominant land-use type along transects C and D. Moreover, landscape diversity increased in the industrial parks along transects A and B, whereas they peaked in the urban fringe along transect D and in the suburban area along transect C. Furthermore, the influence of different vehicular road types on urban land differed markedly, and could be ranked as follows: road A > road B > road C > road D. This finding was consistent with that for Guangzhou, as reported by Fan et al. (2009), where the spatial clustering of urban land expansion along motorways and national highways was greater than that along provincial roads with the same environmental background.

4.3. Driving forces of urban landscape change along different vehicular road transects

The investigation of driving forces required the integration of urban development policies at the national, provincial, and municipal levels with the responses of the local economy and society. In the case of Jiuquan, urban growth and its landscape changes in the period of 1996–2013 were shaped by the impact of several mutually interrelated factors. The most important of them include: (a) population growth, which may result in a demand for the productive use of land, such as for housing, food production, public infrastructure, and other uses (Xie et al., 2014), due to the urban population of Jiuquan city increasing fivefold between 1980 and 2013; (b) urban-related industrialization and economic development, such as vehicular networks or new roads, ETDZ or industrial parks and government investment, which initiates urban development in new directions within a given area; (c) legislative and administrative decisions concerning environmental and agricultural protection, such as national basic farmland protection policy; (d) topography and water resources, which are basic factors determining the urban spatial pattern in arid areas; and (e) land price mechanisms. For example, UL occupied a large proportion of the study area and land prices there were lower, which attracted much interest from the government, residents, and investors (such as real-estate developers) for the development of industrial areas, warehouses, estates, and other new construction. In contrast, land prices restrained urbanization along transects C and D because the compensation cost was higher when cropland was converted to BL (e.g., residential land). Although a variety of social and economic factors triggered urban growth, changes to vehicular roads was the initial factor. In essence, vehicular roads or urban transportation systems are not only complex networks shaped by various geographical, social, economic, and environmental factors (Wang et al., 2008; Aljoufie et al., 2013), but are also deemed to be "representative" in reflecting the combined effects of these factors.

Thus, the distances from major vehicular roads and the urban center exerted a strong influence on the structure of the urban landscape in Jiuquan city.

4.4. Implications for urban planning and management in arid regions

Changes in the pattern of the urban landscape along these transects may have important ecological implications for land management and land use planning (Yu and Ng, 2007). In Jiuquan city, urban growth underwent a tremendous and fairly homogeneous gradual growth alongside the expansion of vehicular roads. Urban expansion often occurs in newly urbanized areas; for example, at 7.5 km and 5 km along road B and its transect. This area of abrupt change and the old city center may eventually coalesce to form a multi-nucleated urban pattern. This not only indicates that disconnected urban areas converge toward a pattern of contiguous urban fabric, but also suggests that ecological considerations can be integrated in such spatially explicit urban patterns during urban planning (Yu and Ng, 2007). For example, the increase in urban green space or vegetation within the urban area did not keep up with urban growth. The spatial distributions of green spaces were uneven, with most of the irregularities caused by artificial green spaces and non-native species, such as man-made parks, lawns, and street trees. In contrast, natural and semi-natural green space was very limited and tended to decrease. These highly managed green spaces cannot fulfill ecological functions (Li et al., 2013b) and will require large amounts of water to maintain. Hence, the effective design and management of oasis urban green space has been a huge challenge for city planners and governments. More case studies are needed to reflect the different geographical and historical realities and reveal the many facets of urban growth in general.

This study found that in the land substitution process due to urbanization, the primary provider of space for urban growth was UL rather than cropland. In other words, the most prevalent change was the transformation of UL to BL, revealing that urban growth in Jiuquan did not destroy or occupy AL on a large scale. This observation agreed with the results reported by Shahraki et al. (2011), and Nassar et al. (2014) in arid areas, but it clearly differed from the growth observed in other non-arid cities in China, such as Guangzhou (Yu and Ng, 2007; Tian and Wu, 2015) and Shanghai (Zhu et al., 2006; Li et al., 2013b), which has occurred mainly at the expense of AL. Generally, in arid areas of China, less fertile land will be used for urban construction if possible. In Jiuquan city, the direction of current and future development has tended toward the south and west, which is infertile land. This urbanization process has profound implications for land resource development and management in arid areas. However, it has also caused other problems, such as changes in the spatial patterns of water resource utilization and ecological processes. During the development of newly built regions, water withdrawals for industry and daily life will gradually increase. This phenomenon may lead to water scarcity, which will affect the stability and sustainable development of the oasis (Gober, 2010). For example, natural GL along the oasis margin as tended to gradually reduce (Xie et al., 2014). Therefore, further research should explicitly address the interactions among water resources and human activities (Zhang et al., 2009; Gober, 2010; Yang and Liu, 2014). Not only should more attention be paid to the balance of industrial and eco-environmental water requirements, but the development of water-saving systems and more efficient ways of using water that can serve as a win–win way for human activities (such as urbanization, industry, and agriculture) and natural systems (Bao and Fang, 2007; Yang and Liu, 2014; Nassar et al., 2014).

5. Conclusions

Based on the characteristics of oasis cities and urbanization processes in arid China, urban-rural transects were designed along major vehicular roads to investigate the processes of urbanization and landscape change. At the landscape scale, land-use types became increasingly more heterogeneous and fragmented, and the spatial configuration of the landscape varied over time along vehicular road transects. This study revealed that a vehicular road was a consistently strong factor influencing urban growth, especially for the polycentric urban area. In addition, national highways had a greater effect on urban growth than provincial roads with the same environmental characteristics. Specifically, the built-up land along transects A and B became a landscape matrix, with increases of 1469.41 ha and 1530.39 ha, although the average degree of change of urban green land area was at a maximum. Temporally, the rate of urban expansion between 1996 and 2006 was higher than that between 2006 and 2013, except for transect D. Moreover, oasis urbanization in Jiuquan city occurred mainly at the expense of unused land rather than agricultural land, and followed a linear branching leapfrogging growth pattern. This type of change in the urban spatial pattern was simpler than that experienced in the coastal cities of China. In this study, a gradient analysis of the changeability of landscape metrics along different vehicular road transects from urban to rural zones clearly illustrated the changes in landscape pattern in response to urbanization, and helped to test the existing theories and models of urban growth.

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