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Assessing landscape fragmentation in a desert-oasis region of Northwest China: patterns, driving forces, and policy implications for future land consolidation

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Abstract Landscape fragmentation is considered a serious threat to eco-environmental integrity and socioeconomic development. Although many studies have focused on landscape fragmentation resulting from agricultural production and urbanization, landscape fragmentation from the aspects of patterns, driving forces, and the policy perspective of ecosystems has rarely been investigated. Oases, as a unique landscape, face severe fragmentation in arid and semiarid regions. This study applied a combination of approaches, including remote sensing image interpretations, landscape fragmentation metrics, and community surveys, to analyze patterns and their driving forces, as well as the policy implications for future land consolidation, in the Hotan oasis of Northwest China from the space and time perspectives. Results show that the frequent occurrence of summer flood events changes the patch number, density, size, and splitting degree of oasis–desert ecotone vegetation. The socioeconomic factors including total population and irrigation area are more important driving forces on oasis landscape fragmentation, compared with natural factors such as temperature and precipitation. Rural expansion, road and canal system developments caused by population growth, and the rising number of households increase oasis landscape fragmentation. Rapid economic development, such as agricultural expansion and urbanization, has imposed the intensification of landscape fragmentation. Fragmentation reaches peak when agricultural development makes up 40–50% of study area. Rural residential reconstruction and farmland transfer policies facilitate the intensive utilization of land toward oasis fragmentation solutions, but many factors, such as landholders' household characteristics and living conditions, are partly responsible for the challenges in

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land consolidation. This study also demonstrates that intense human activities pose a great threat for land consolidation and sustainable development of oasis landscape.

Keywords Landscape fragmentation · Oasis · Driving forces · Patterns · Land consolidation

Introduction

Landscape fragmentation is a worldwide phenomenon resulting from eco-environmental changes and socioeconomic processes, such as agricultural expansion, urbanization, and development of transport infrastructure (Weng, 2007; Girvetz et al., 2008; Manjunatha et al., 2013). The phenomenon has been considered a serious threat to eco-environmental integrity and socioeconomic development (Girvetz et al., 2008). Fragmentation occurs when continuous landscape patches segregate into smaller blocks. In the fragmentation processes, the connectivity of the landscape with ecological function linkages among habitat patches is disrupted (Guo et al., 2008). Thus, a decrease in patch scale and an increase in barriers caused by landscape fragmentation directly influence the efficiency of agricultural production, development of urbanization, and stability of natural ecosystems (Weng, 2007; Qi et al., 2014; Ciaian et al., 2018). Such fragmentation also changes the size, scale, pattern, and fragmentation degree of landscape ecosystems (Qi et al., 2014). Therefore, the study on landscape fragmentation is crucial for understanding landscape integrity and stability, and providing essential insights for landscape designers and land planners who aim to find spatial regularity in sustainable land use and urban planning.

Oases are a unique landscape composed of natural and artificial oases in desert environments in arid regions (Abulizi et al., 2017; Liu et al., 2018). In terms of their formation mechanism, a natural oasis landscape includes water bodies, shrubby grasslands, riparian forests, and desert areas while an artificial oasis landscape comprises farmlands, shelter forests, engineering facilities, and residential regions (Xue et al., 2016). The oasis landscape is essential for human settlement and economic development. In the arid regions of Northwest China, oases support over 95% of the human population given only 5–6% of available land (Liu et al., 2018; Xue et al., 2019). In recent years, human interventions under the context of global warming have aggravated the oasification processes, which mainly present as natural oasis evolution, agricultural expansion, and urbanization (Xue et al., 2019). The oasification process makes the fragile oasis landscape increasingly complicated by changing the shape, size, density, and pattern of oasis landscape patches (Guo et al., 2008).

Landscape fragmentation research has caught the attention of numerous scientists, including geographers, ecologists, economists, and anthropologists (Abdollahzadeh et al., 2012). A large number of studies have explored the definition, causes, impacts, and driving forces of landscape fragmentation worldwide, especially in central and eastern European countries, India, and China (Abdollahzadeh et al., 2012; Qi et al., 2014; Manjunatha et al., 2013; Ryan et al., 2015; Jürgenson & Land, 2016). The focus of existing research on landscape fragmentation mainly lies on the positive or negative effects of agricultural production, including agricultural production efficiency (Manjunatha et al., 2013; Latruffe & Piet, 2014; Hartvigsen, 2014), agriculture production cost (Sklemicka et al., 2009; Abdollahzadeh et al., 2012), and agriculture production income (Di Falco et al., 2010). The impacts of landscape fragmentation on biological diversity, urban design, and agricultural planning have also been reported (Deininger et al., 2012; Llausas & Nogue, 2012). Despite there are many studies of regional landscape fragmentation with various functions currently available, the topic of fragmentation of oases with a complex functional landscape, including agriculture, town, and natural vegetation, has rarely been explored from the aspects of patterns, driving forces, and policy perspectives under the oasification context.

The conclusions of a regional study can be extrapolated into similar regions in the landscape ecology (Guerschman & Paruelo, 2005; Guo et al., 2008). The current study selected the Hotan oasis, a representative oasis landscape at the southern margin of the Taklimakan Desert in Northwest China, as the study area to systematically investigate the patterns of landscape fragmentation and its driving forces, as well as the policy implications for future fragmentation solutions. The objectives of this study are (i) to examine the spatial and temporal variations of landscape fragmentation in the Hotan oasis between 1970 and 2013 using image interpretation and landscape fragmentation index methods, (ii) to identify the conclusive factors that drive oasis landscape fragmentation, and (iii) to discuss the feasible policy implications for sustainable landscape management. This study can enrich the understanding of spatial regularity and land planning and effectively inform landscape management decisions via the dynamic analysis of landscape fragmentation and its policy governance solutions.

Study area

The Hotan oasis is situated in the southern part of the Taklimakan Desert and the northern foot plain of the Kunlun Mountains in Northwest China. It covers an area of approximately 8.05×10^4 km^2 and extends within a latitude of 34°22′ N to 39°38′ N and a longitude of 78°01′ E to 81°33′ E (Fig. 1). The Hotan oasis is a representative alluvial fan landscape. Natural and agricultural oases are two major landscape units (Amuti & Luo, 2014). The Hotan oasis is characterized by extreme drought within the Taklimakan Desert. It has an annual mean temperature of 12.2 °C, accumulated precipitation of 35.6 mm, and pan evaporation of 2602 mm (Amuti & Luo, 2014). The water supply in the Hotan oasis depends on Hotan River, which originates from the alpine valley of the Kunlun Mountains, runs through the Hotan oasis, and finally flows into the Tarim River (Liu et al., 2018). Its annual average runoff during 1970–2010 is 45.23×10^8 m^3. The glacier and/or snow-melt water as well as precipitation in the high-altitude valley contribute Hotan River runoff. The precipitation occurring in Hotan oasis and desert zones cannot form effective streamflow. The mountain and plain oasis in the study area have greater climate variability. The soil is mainly classified as fluvisols, gleysols, solonchaks, arenosols, and anthrosols (Amuti & Luo, 2014; FAO, 2006). Sand/dust storm is common in this area between spring and summer, and it impacts plant photosynthesis and growth.

Agricultural landscape is the largest type of land use along the Hotan River. Agricultural management depends on the household responsibility system (Amuti & Luo, 2014). Agricultural parcels are fragmented and are generally less than 1 ha in size (Amuti & Luo, 2014; Yang et al., 2013). The arable land per capita is less than 0.09 ha. The mosaic patches vary in shape and size. The natural vegetation, including riparian forests (e.g., *Populus*) and dense shrubs (e.g., *Tamarix* and *Phragmites*), is chiefly distributed in the riparian zone, as well as in the desert–oasis ecotone, which consists of semi-shrubs and perennial herbaceous grasses (e.g., *Calligonum*, *Tamarix chinensis*, and *Alhagi sparsifolia*) (Liu et al., 2018).

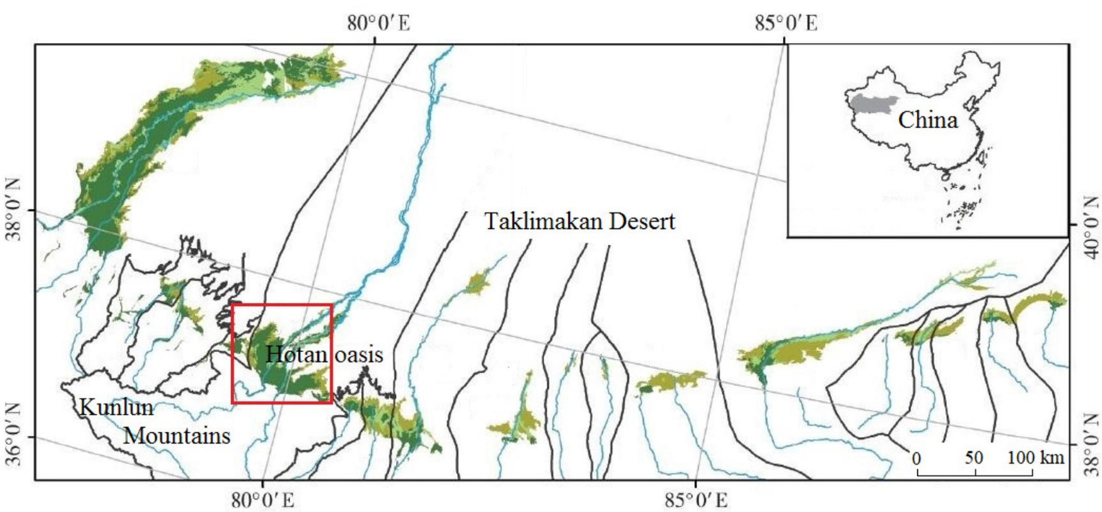


Fig. 1 Location of the study area (adapted from Xu et al. (2016))

Data and methods

Data sources

The data for analyzing oasis landscape fragmentation were obtained from remote sensing images in 1970, 1990, 2000, and 2013. The data used to acquire land use information in 1990, 2000, and 2013 was multispectral TM/ETM + images with 30 m × 30 m spatial resolutions, while the data in 1970 was MSS images with 58 m × 58 m spatial resolutions. Moreover, the land use maps of the Surveying and Mapping Bureau of Xinjiang extracted by visual interpretation of aerial photography in combination with fieldwork sampling were used to assist the validation and accuracy assessment of images. The images were digital and scales of 150,000. All the selected images were taken during summer/autumn seasons to determine vegetation phenology (Amuti & Luo, 2014). The images were clear and free of clouds, and they were interpreted via human–computer interaction (Song & Zhang, 2015). According to the land classification system, the oasis landscape was categorized into six land use types, namely water bodies, farmland, built-up land, forestry land, shrubby grassland, and desert area with a vegetation cover of < 5% (Table 1). The accuracy of the interpreted images was determined to have a kappa coefficient of > 95% (Liu et al., 2005, 2014). The data processing and classification processes were aligned with the recommended values proposed by Jensen et al. (1994).

To examine the influences of climate change and socioeconomic factors on the landscape fragmentation of the oasis, this study collected the hydrological and meteorological data (i.e., temperature and precipitation) for the period of 1970–2010 recorded by hydrological and meteorological stations in the Hotan oasis. The socioeconomic data, including human population, GDP, cultivated land, and crop yields, irrigation area, and primary industrial output, were obtained from the Xinjiang Statistical Yearbook (1990–2013). Such data were applied as ancillary data to analyze the main driving forces of landscape fragmentation in the Hotan oasis.

Detection approaches for oasis landscape variation

The spatiotemporal change of oasis landscape types is a major indicator of landscape changes and dynamics. It reveals the pattern of landscape fragmentation and facilitates the exploration of the interrelationships between landscape changes and human activities. In this study, the spatiotemporal changes of landscape types can be identified based on the remote sensing images of four periods. According to Xie et al. (2014), the annual change rate (R) can be used to quantify the oasis landscape variations of each land use type. The rate is written as:

$$R = \left(\sqrt[t_2 - t_1]{A_2 / A_1} - 1 \right) \times 100\% \tag{1}$$

where A_1 and A_2 denote the interpreted land cover areas of the Hotan oasis at the starting period (t_1) and the last period (t_2), respectively.

The reciprocal relationships between oasis land use types can be described by the transition matrix, which IS calculated as follows (Liu et al., 2018):

$$A_{ij} = \begin{bmatrix} A_{11} & \cdots & A_{1j} \\ \vdots & \ddots & \vdots \\ A_{i1} & \cdots & A_{ij} \end{bmatrix} \tag{2}$$

Table 1 Explanation for the landscape units in the Hotan oasis (Liu et al., 2018)

Landscape type	Explanation
Farmland	Agricultural area including annual crops, crop residues, vegetables, and bare soils
Water bodies	Entity water including rivers, lakes, reservoirs, and wetlands
Build-up land	Built-up area including buildings and facilities
Shrubby grassland	High-coverage shrubby grassland with vegetation cover > 60%, medium-coverage shrubby grassland with vegetation cover of 20–60%, and low-coverage shrubby grassland with vegetation cover of 5–20%
Forestry land	Shelter forest for protecting farmland from aeolian sand disaster
Desert area	Sandy land with vegetation cover < 5%, barren rock, and Gobi

where A_{ij} is the transition matrix and i and j are the landscape types from the starting period i to the last period j in the Hotan oasis.

Measurement of landscape pattern fragmentation

The oasification process characterized by the sprawling and shrinking phenomena of an oasis affects its shape, size, connection, splitting degree, and stability and integrality (Xie et al., 2014). To measure oasis landscape fragmentation with the general landscape index from the landscape and class levels, this study considered the landscape pattern indices from a geometric perspective (e.g., perforation, dissection, dissipation, incision, shrinkage, and attrition) (Table 2). The landscape fragmentation metrics included the fragmentation index (FI) and patch density (PD), patch coherence (PC), splitting index (SI) and splitting density (SD), and dissection index (DI).

Fragmentation index and patch density are indicators of landscape dispersion degree from the size and shape perspectives in landscape types and whole space scale. These two metrics are calculated as follows (Gui et al., 2017; Guo et al., 2008; Xie et al., 2014):

$$FI = \frac{\sum_i n_i}{A_i} \tag{3}$$

$$PD = \frac{\sum_i n_i}{A} \tag{4}$$

where n_i denotes the patch number of landscape type i, A_i stands for the total area of landscape type i, and A is the total landscape area.

Patch coherence (PC) is indicator of landscape coherence degree. The PC is expressed as (Jaeger, 2000):

$$PC = \sum_i^n \left(\frac{A_i}{A}\right)^2 \tag{5}$$

Splitting index (SI) and splitting density (SD) are indicators of the effective mesh number and isolation degree in the landscape size and shape, respectively. These metrics are written as (Jaeger, 2000):

$$SI = \frac{A^2}{\sum_i^n (A_i)^2} \tag{6}$$

$$SD = \frac{1}{A \cdot \sum_i^n \left(\frac{A_i}{A}\right)^2} \tag{7}$$

Dissection index (DI) is indicator of the landscape dissection degree. The DI is given as (Freudenberger et al., 2013; Jaeger, 2000):

$$DI = \frac{\sum_j L_j}{A} \tag{8}$$

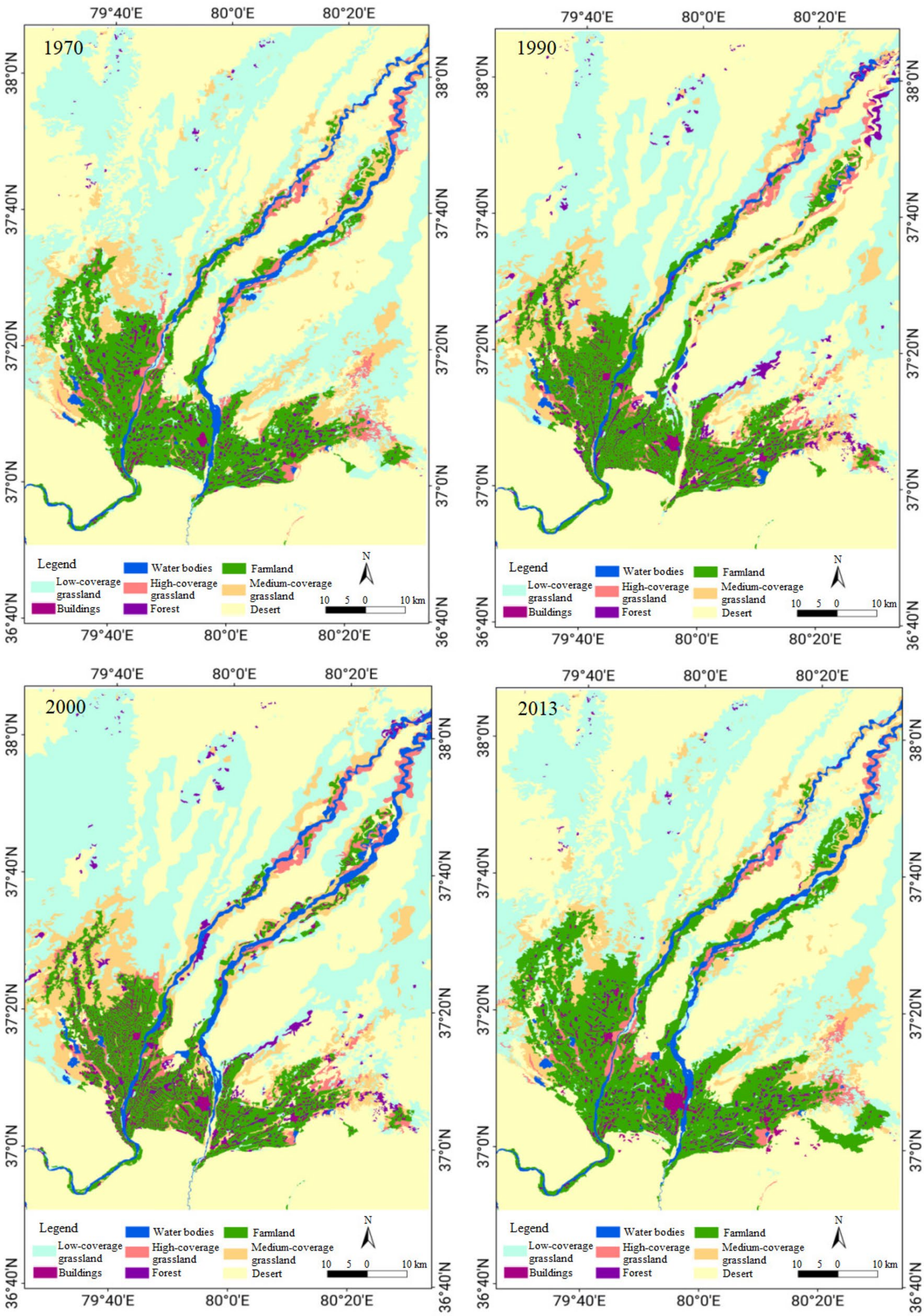
where L_j is the cumulative length of corridors j (including the shelter belt, channel, and road) per unit area.

Driving forces assessment of landscape pattern fragmentation

The forces resulting in oasis landscape pattern fragmentation are drove by a variety of factors related to natural elements and human activity. In this study, the factors including annual temperature, precipitation, runoff, total population, GDP, irrigation area, and primary industrial output were selected to examine the impacts of natural variables and socioeconomic development on oasis landscape fragmentation. Through the stepwise regression, the selective primary factors were performed to quantify the direct and indirect effects on fragmentation by path analysis

Table 2 Fragmentation metrics considering the geometric perspective

Fragmentation indices	Explanation	Geometric description
Fragmentation index	Landscape dispersion degree in the size	Perforation
Patch density	Landscape dispersion degree in the shape	Dissipation
Patch coherence	Landscape coherence degree	Attrition
Splitting index	Landscape isolation degree in the size	Incision
Splitting density	Landscape isolation degree in the shape	Shrinkage
Dissection index	Landscape dissection degree	Dissection


1970
1990
2000
2013
79°40'E
80°0'E
80°20'E
38°0'N
37°40'N
37°20'N
37°0'N
36°40'N
Legend
Water bodies
Farmland
Low-coverage grassland
High-coverage grassland
Medium-coverage grassland
Buildings
Forest
Desert
N
10 5 0 10 km

◂**Fig. 2** Changes of land cover types in the Hotan oasis during 1970–2013

(Xue & Gui, 2015). The path analysis is a multivariate statistical method, evaluating the causal relationships between various factors (Wright, 1921; Wright, 1934; Kozak & Kang, 2006).

Assuming that there is a dependent variable y and n variables$x_1, x_2, \cdots x_n$, the correlation coefficient between any two variables isr_{ij}. The direct path coefficient from x_i to y isP_{yi}, while the indirect path coefficient of variable x_i through x_j to y is$r_{ij}P_{yj}$. The expression can be written by (see Xue and Gui, (2015) for details):

$$r_{iy} = p_{yi} + \sum_{j=i+1}^{n} r_{ij}p_{yj} \quad (9)$$

Results

Spatiotemporal variations of oasis landscape over the last 50 years

The variations of oasis land cover types reflect the general changes in landscape patterns for fragmentation assessment. Figure 2 shows the spatial distributions of oasis and desert landscapes, and Fig. 3a displays the changes in the oasis and desert area at the landscape level from 1970 to 2013. The results indicate that the land cover types fluctuated over time during the whole study period. The Hotan oasis area annually decreased from 7273.72 km^2 with a rate of − 0.76% between 1970 and 1990 and increased rapidly to 7690.00 km^2 at a rate of 13.28% during 1990–2000. The oasis area then decreased to 7352.76 km^2 with a rate of − 0.45% during 2000–2013 (Fig. 3a). As for the period of 1970–2013, the Hotan oasis first shrunk from 1970 to 1990, gradually expanded in 1990–1920, and finally shrunk between 2000 and 2013. The phenomenon reflected the "shrink–sprawl–shrink" process (Fig. 2). By contrast, the desert area increased slightly from 8185.81 km^2 at a rate of 0.63% in 1970 to 8720.05 km^2 in 1990. The area then decreased dramatically to 7769.53 km^2 with a rate of − 1.15% in 1990 and then increased to 8106.77 km^2 with a rate of 0.43% in 2013. Generally, at the temporal scale, the change trends of the oasis and desert areas fluctuated with the alternate process at a time period.

The spatial distributions of the oasis land cover types at the landscape level during the study period of 1970–2013 are shown in Fig. 2, and their area changes are displayed in Fig. 3b. As the most important natural vegetation (including high-coverage, medium-coverage, and low-coverage shrubby grasslands) for wind prevention and sand resistance, the shrubby grasslands changed with the rates of − 0.91%, 1.88%, and − 1.76% during the periods of 1970–1990, 1990–2000, and 2000–2013, respectively. The area of shrubby grassland in the Hotan oasis decreased by 19.47% in 2013 relative to that in 2000. Moreover, the built-up area, forestry area, and water area in the Hotan oasis showed a synchronous change trend during 1970–2013.

According to the oasis land cover change, the most drastic variation in the Hotan oasis is attributed to the agricultural expansion. At the rates of − 0.81% and − 1.59%, the agricultural area decreased rapidly from 1655.83 km^2 during 1970–1990 and from 1301.59 km^2 during 1990–2000, respectively. It then increased rapidly to 2102.51 km^2 with an annual rate of 4.91% during 2000–2013 (Fig. 3b). With the oasis agricultural expansion, the farmland area increased by 26.98% in 2013 relative to that in 1970. In the recent decade, the agricultural land has increased by 61.53%. According to the variation of spatial distribution, the agricultural expansion mostly extended toward the northeast and northwest directions of the Hotan oasis along the Hotan River.

Figure 4 illustrates the transition proportion matrix for the variation from one land cover type to another during 1970–1990, 1990–2000, and 2000–2013, respectively. During 1970–1990, 12% of shrubby grassland was converted to farmland, and 47% of farmland was transformed into built-up land. Approximately 26% of the desert area was developed into shrubby grassland. The area without changes accounted for about 75.58% while the changed area accounted for 24.42%. During 1990–2000, 16% and 26% of the farmland areas were respectively transformed into forestry land and built-up land. The area without changes represented 90.43%. From 2000 to 2013, about 72% of farmland was converted into built-up land because of the development of cities and towns. The unchanged and changed areas accounted for 71.90% and 28.1%, respectively.

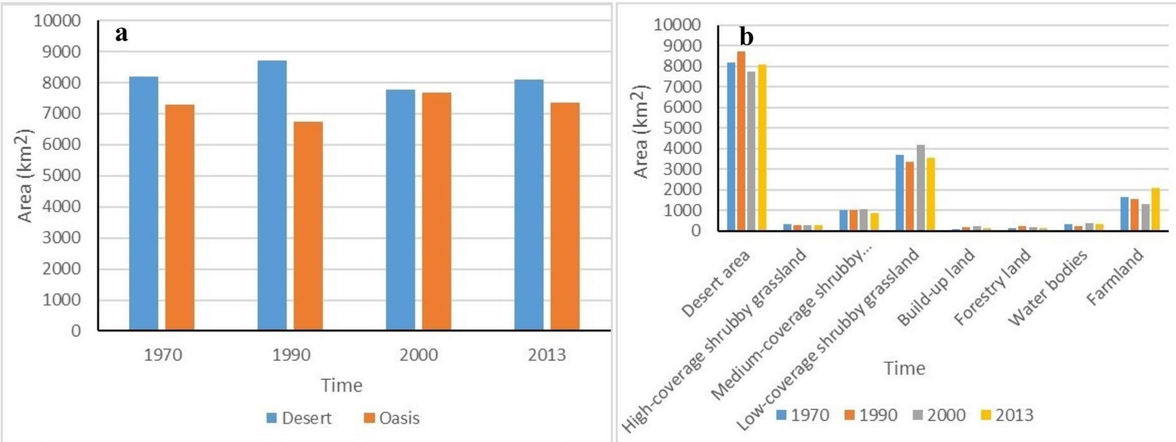


Fig. 3 Land-cover changes in the Hotan oasis from 1970 to 2013

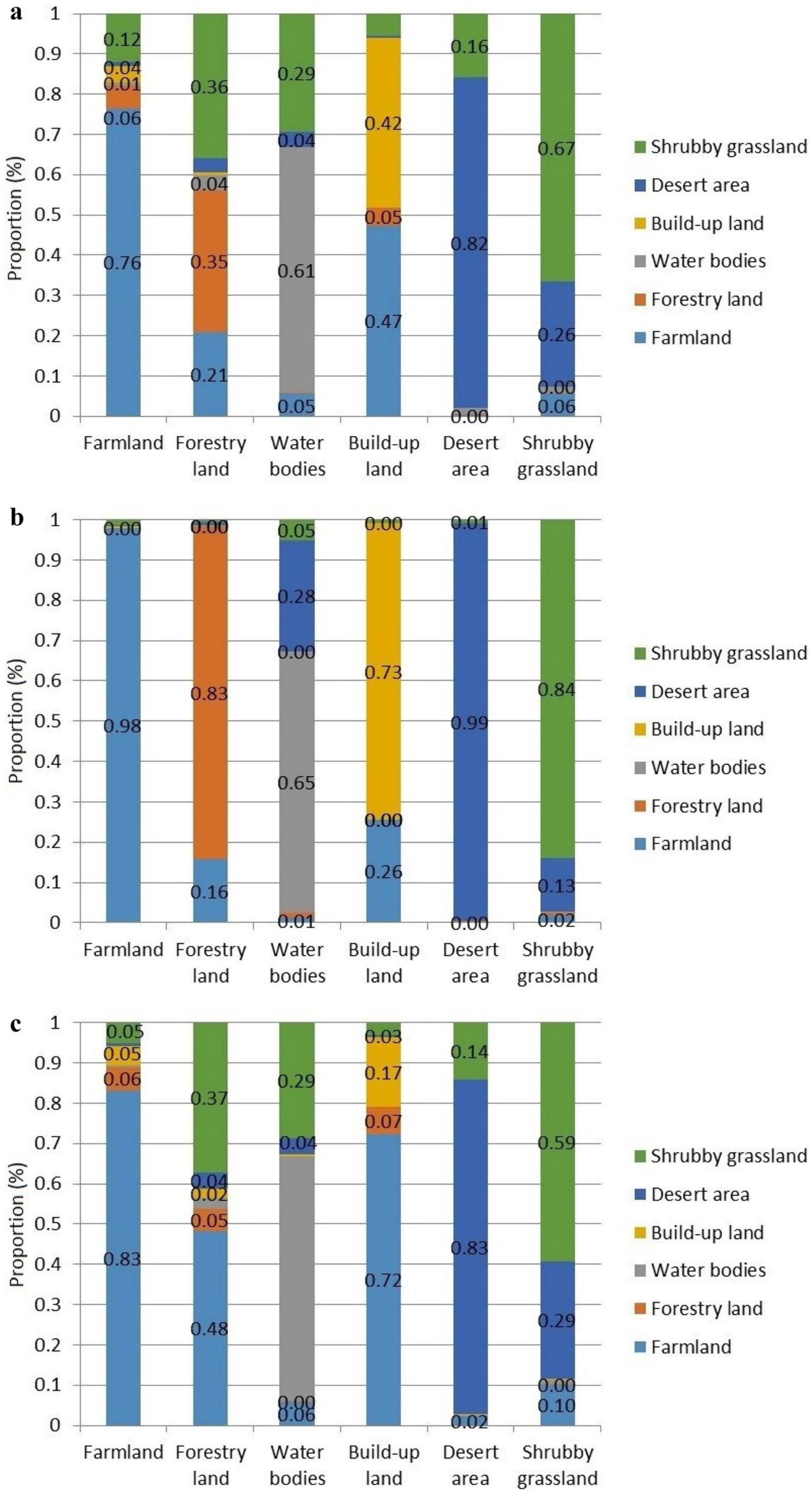
Oasis landscape fragmentation pattern analysis

The variations of the Hotan oasis landscape fragmentation metrics at the class level are illustrated in Fig. 5. As a result of the relatively stable patches, the PDs of the desert, water bodies, forestry land, and high-coverage shrubby grassland changed slightly. By contrast, the PDs of the medium-coverage and low-coverage shrubby grasslands changed significantly because the growth and spread of grasslands depend mainly on the support of summer floods provided by glacier melt/snowmelt water and summer rainstorm in the alpine region. Affected by climate change, the PDs of these grasslands fluctuated steadily during 1990–2000 and dramatically in the 1970s and 2013s. With the intensification of human activities, the PDs of built-up land, including buildings and facilities, showed the greatest variations, increasing significantly from 0.01 to 0.08 during 1970–2000 and decreasing rapidly to 0.02 in the 2013s. Moreover, the PDs of farmland showed increasing, steady, and decreasing fluctuations.

The PCs of the desert area, low-coverage shrubby grassland, and farmland presented remarkable changes during 1970–2013. The PC values fluctuated frequently, indicating that the geometry and size of the patch shape are susceptible to natural conditions and human activities. The changes in PC properties were similar with those of the other landscape types. Furthermore, the differences in the split index reflected the splitting and irregular degrees of landscape types. The greatest value change of FI was observed in the built-up land (6.98 in 1990). Influenced by buildings, roads, and irrigation facilities, the FIs of the built-up lands increased dramatically from 3.35 in 1970 to 6.98 in 1990, but it decreased sharply from 5.60 in 2000 to 2.48 in 2013. Owing to the shelterbelt and irrigation canal construction, the FIs of the forestry land and water bodies showed noteworthy fluctuations during 1970–2013. The FIs of the other landscape types indicated relatively stable variations in the study period. The SD values showed similar properties to the FIs. The SDs of forestry land and built-up land showed remarkable fluctuations during the study period of 1970–2013.

In general, the landscape fragmentation in the study area comprises natural barriers against desert vegetation through the Yurungkash River and Karakash River, and artificial barriers against farmland via roads and built-up lands. The Hotan oasis landscape is transected by roads, rivers, agricultural expansion, and extension of settlement areas. From the geometrical fragmentation perspective, the Hotan oasis landscape shows different morphologies, including perforation, dissection, incision, dissipation, shrinkage, and attrition. The desert land, shrubby grassland, and built-up lands are well-connected and less fragmented, whereas the farmland, water bodies, and forestry areas show an uneven distribution and high fragmentation status.

Fig. 4 Transition proportion of oasis landscape types during 1970–1990 (**a**), 1990–2000 (**b**), and 2000–2013 (**c**)



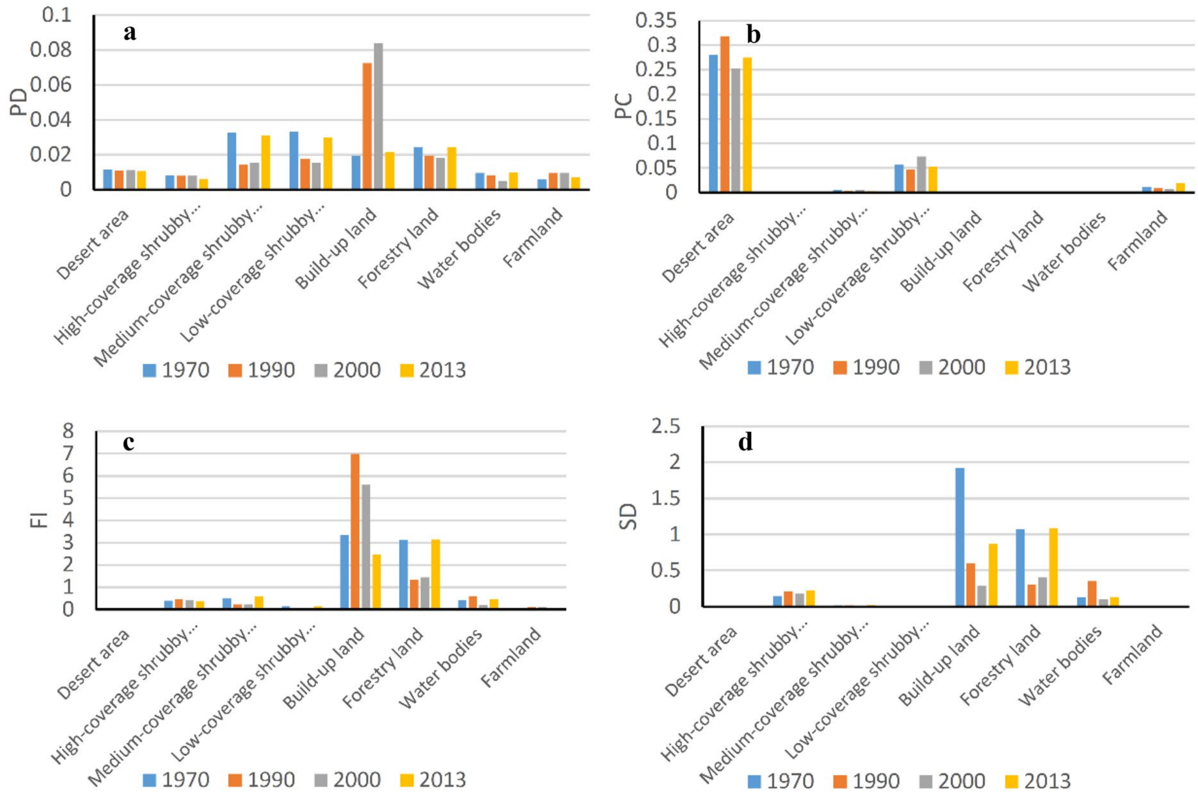


Fig. 5 Variation of Hotan oasis landscape fragmentation metrics during 1970–2013

Driving forces of oasis landscape fragmentation

The interaction of natural factors and human activities impacts the degree of oasis landscape fragmentation at the landscape and class levels. Climate change, as an important natural factor that influences oasis landscape fragmentation, is mainly reflected in the shelter forests and shrubby grasslands in the desert–oasis ecotone. Although landforms and groundwater dynamics impact the degree of spatial fragmentation of desert vegetation, the summer floods resulting from climate variability support the existence, growth, and spread of desert vegetation provided by glacier melt/snowmelt water and summer rainstorm in the alpine region. According to the meteorological and hydrological observations in the study area, the annual mean temperature, annual precipitation, and runoff of the Hotan oasis exhibited increasing trends (Figs. 6a and b). Especially during the last decades, the frequent occurrence of summer flood events has continually changed the patch number, density, size, and splitting degree of desert vegetation.

In the last decades, the effects of human activities on oasis landscape fragmentation have become prominent in socioeconomic development, especially in terms of human population growth, rural development and urbanization, transportation infrastructure construction, improvement of agricultural irrigation systems, and land use policy. Oasis landscape fragmentation is correlated with an increase in population, which is regarded as a key factor of rural development and urbanization, transportation infrastructure construction, and improvement of agricultural irrigation systems. The population in the Hotan oasis increased from 848,657 in 1990 to 1,277,505 in 2009 (Fig. 6c). The population in 2009, relative to that in 1990, increased by 33.56%. The continuous population growth will further change the cultivated area of the oasis, the GDP (Fig. 6d), and, consequently, the land use pattern and fragmentation degree.

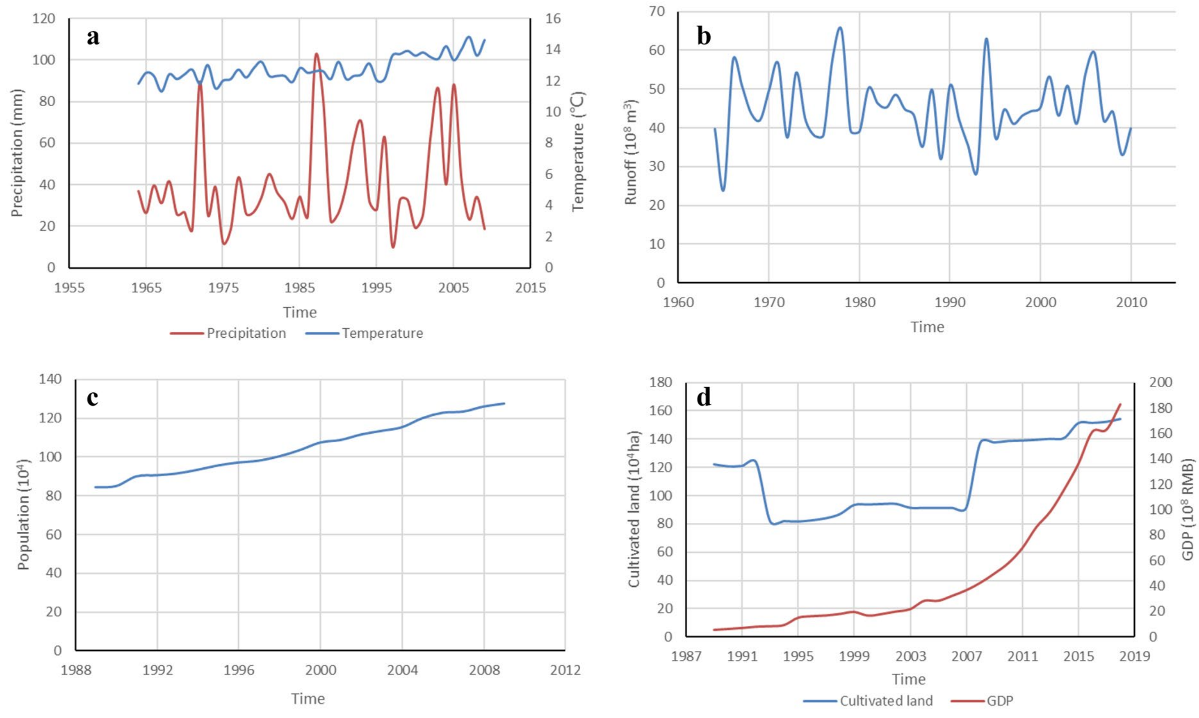


Fig. 6 Variations of the environmental variables selected in this study

Prior to the path analysis, the stepwise regression regarding PD was performed to select the primary factors using the F-test. The total population, GDP, irrigation area, and runoff pass the hypothetical test at the 0.05 significance level. Table 3 shows the correlation coefficients and direct and indirect coefficients between population, GDP, irrigation area, runoff, and PD. The population and irrigation area had a significant correlation with PD, while GDP and runoff did not (Fig. 7). The population and irrigation area impacted the PD with direct effects of 0.17 and 0.24, respectively. The indirect coefficient from population through irrigation area to the PD was 0.23, while the indirect coefficient from irrigation area through population to the PD was 0.14. This replies the total population is greater factor to oasis landscape fragment than the irrigation area.

The direct coefficient from GDP or runoff to PD (0.09 or 0.14) was quite small and not significant. The indirect coefficients from GDP through population,

Table 3 Path analysis of direct and indirect effects between population, GDP, irrigation area, runoff, and patch density (PD) in Hotan oasis

Parameters	Correlation coefficient with PD	Path coefficient				
		Direct effect	Indirect effect			
			Population	GDP	Irrigation area	Runoff
Population	0.35*	0.17**	—	0.04	0.23	0.12
GDP	0.19	0.09	0.07	—	0.22	−0.01
Irrigation area	0.37*	0.24**	0.14	0.18	—	0.13
Runoff	0.15	0.14	0.20	−0.02	0.31	—

*Means that the correlation coefficient is significant at 0.05 level, based on the F-test. **Means that the path coefficient is significant at the 0.05 level, based on the F-test

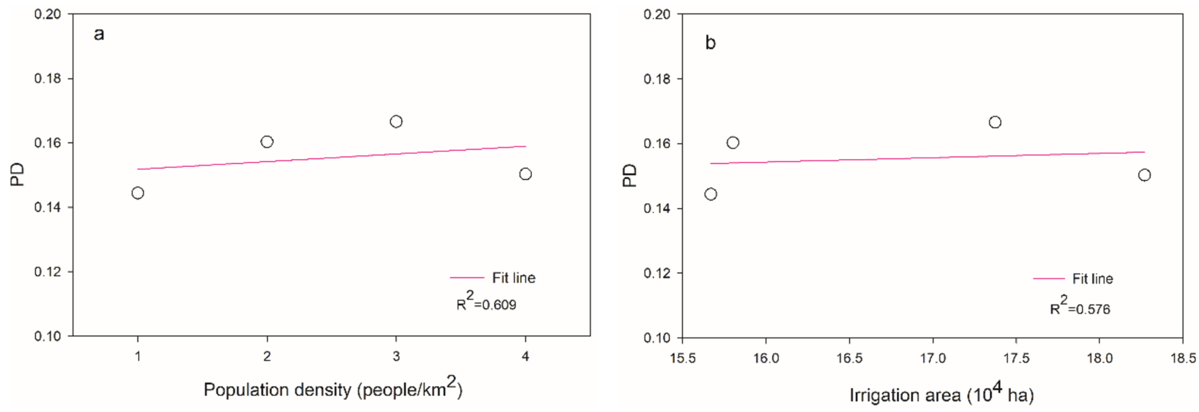


Fig. 7 Relationships between total population, irrigation area, and PD

irrigation area, and runoff to PD were 0.07, 0.22, and − 0.01, whereas those from runoff through population, GDP, and runoff irrigation area to PD were 0.20, − 0.02, and 0.31, respectively. This means that GDP and runoff are indirectly able to impact the PD by means of the irrigation area. Hence, it is obvious that the population and irrigation area contribute more to oasis landscape fragmentation than other factors. This further verifies that socioeconomic factors are the most key driving forces in the Hotan oasis, compared with natural factors such as temperature and precipitation.

With an increase in human population and irrigated agriculture, the construction of water facilities, including reservoirs and irrigation canals, as well as the improvement of agricultural irrigation technology (e.g., drip irrigation technology) leads to an increase in agricultural fragmentation. Agricultural oasis landscape patches are divided by human disturbance corridors, including canals and roads; planting corridors; and residential corridors. Toward the end of the year 2014, the total mileage of roads in the whole region had reached 18,358.67 km, which comprised 644 km of national highway, 532 km of provincial highway, and 17,147.12 km of rural roads (Zhang, 2017). The dissection index (DI) of the oasis landscape reached 456 km^2. The larger the corridor densities are, the larger the fragmentation degrees will be. In addition, an increase in population areas aggravated agriculture patches (Table 4). The splitting index (effective mesh number) of land fragmentation reached 4522.67 in 2014. However, according to the window moving method (McGarigal et al., 2012), agricultural development does not always aggravate the degree of landscape fragmentation. When agricultural expansion reaches a certain degree (40–50%), the degree of landscape fragmentation follows a downward trend (Fig. 8).

Discussion

Impact of oasis landscape fragmentation on regional sustainability under the oasification context in the arid regions of Northwest China

The selection of oasis landscape fragmentation indices is essential for the analysis of the long-term changes of oasis fragmentation degree (Guo et al., 2008; Xiao et al., 2013). In previous studies, landscape fragmentation indices were calculated by landscape metrics from remote sensing images in the software package FRAGSTATS (McGarigal et al., 2012; Qi et al., 2014). However, these indices often lack a geometric basis, including the six fragmentation phases of perforation, dissection, dissipation, incision, shrinkage, and attrition. This study selected

Table 4 Population areas and agriculture patches

Time (year)	Towns	Village	People/km^2	Patches
2000	42	877	450–600	89
2005	42	876	600–750	—
2010	44	879	600–750	—
2014	45	890	750–900	147

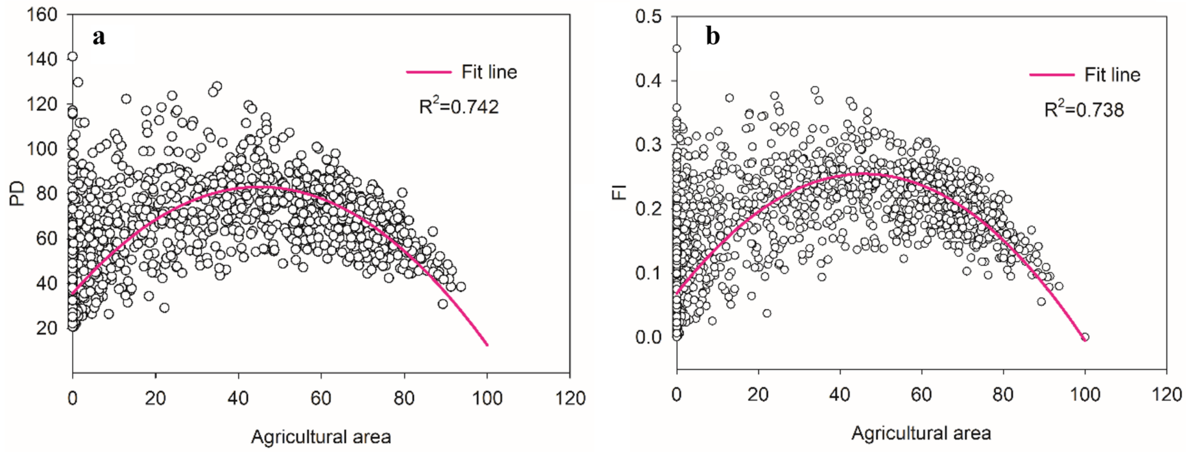


Fig. 8 Relationship between landscape fragmentation and agricultural development

fragmentation index and patch density, patch coherence and division, splitting index and density, and dissection index as the indices to analyze the oasis landscape patterns from a geometric viewpoint. These indices are suitable for accuracy assessment at landscape levels (Jaeger, 2000).

Owing to the interactive impacts of natural elements and human activities, the patterns and driving forces of oasis landscape fragmentation at the regional landscape level cannot be easily recognized (Xie et al., 2014). Many previous studies have pointed out that high-density human activity is the major reason for oasis landscape fragmentation (Jiang et al., 2014; Xie et al., 2014). This paper supports that finding. Rural expansion, the development of road and river drainage systems caused by population growth, and the number of households increase landscape fragmentation (Fig. 9). Meanwhile, rapid economic development, such as agricultural expansion, exerts an additional contribution to the intensification of landscape fragmentation. The results are basically similar with those for the other oasis areas in Northwest China, such as the Jinta oasis and Hotan oasis (Gui et al., 2017; Jiang et al., 2014; Xie et al., 2014).

Northwest China is a typical continental climate zone far from the oceans. It is characterized by extremely poor species diversity and vulnerable ecosystems because of the low precipitation (about 160 mm) and strong evaporation (greater than 2000 mm) (Xue et al., 2019). Because Hotan oasis is a remote and poor area inhabited by many nationalities. The droughts, sandstorms, and salt alkalization are very severe, so that the utilization of soil and water is limited and very low (Amuti & Luo, 2014). The limited cultivated land is managed by the family-based "Household Contract Responsibility System," and the fruit cultivation is the main agricultural development mode. The oasis agriculture changes little in shape and size. Furthermore, low-/medium-/high-grassland is synchronous with different hydrological years (including dry, normal, and wet year). Obviously, after 2010, the urban development shows significant growth under the poverty alleviation policy in 2013. In general, the land cover types at temporal and spatial scales show a relatively similar shape and size in recent 40 years. This result is consistent with the conclusion of other studies, such as Amuti and Luo (2014) and Dong et al. (2019). However, under the current oasification context, anthropogenic oasis landscape fragmentation caused by agricultural expansion (such as wasteland reclamation) and rapid urbanization (e.g., road line increase and extension of settlement areas) further affects scenery and land use (Guo et al., 2008).

Given the strong ideology, "Development is wasteland reclamation," the extensive desert, pasturelands, and wetlands have been increasingly converted into cultivated land and settlement areas in the regions, resulting in many potential ecological and environmental problems, including biodiversity losses, desertification, and oasis agricultural landscape fragmentation due to road line increase (Yamamoto et al., 2010;

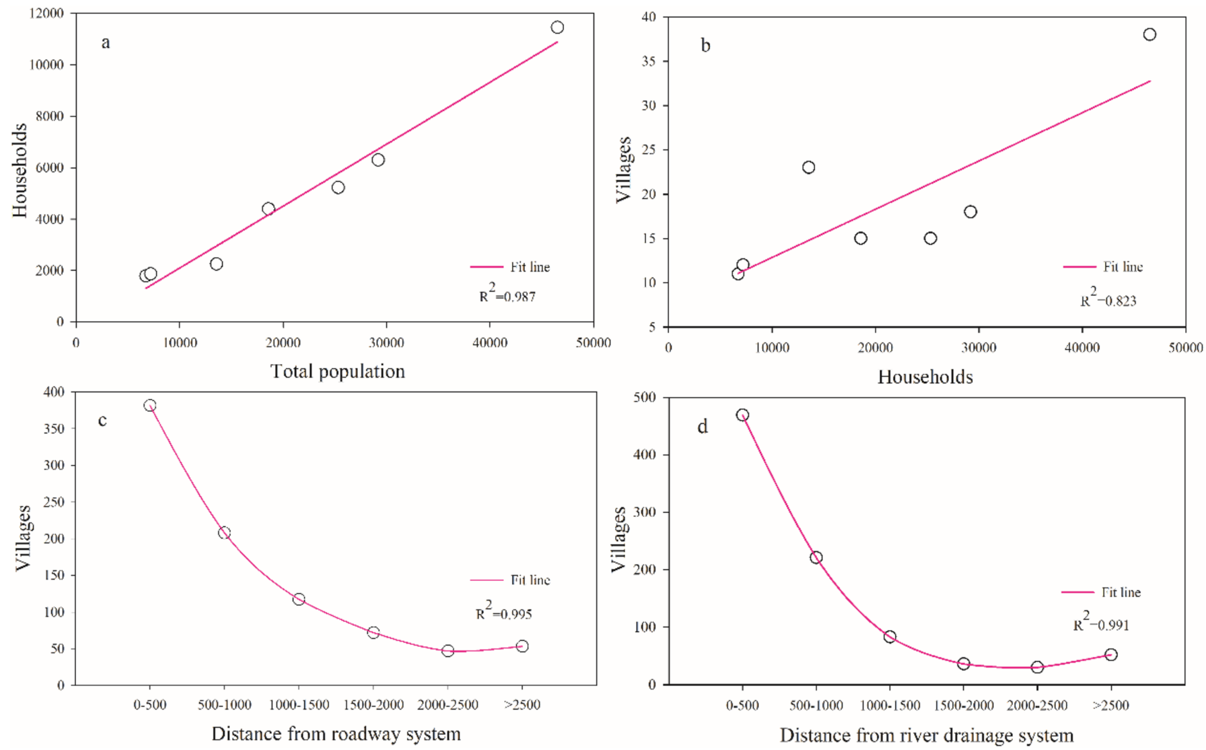


Fig. 9 Relationships between total population, households, and villages (**a** and **b**), and between distance from roadway, river drainage systems and villages (**c** and **d**)

Su et al., 2007; Su et al., 2010). As an important "ecological security barrier" for supporting ecological services, including wind prevention, sand fixation, and microclimate regulation, the fragmentation degree of desert vegetation (e.g., *Populus euphratica* and *Tamarix* spp.) in the desert–oasis ecotones has been partly aggravated because of insufficient water supply, agricultural expansion, and facility construction (Xu et al., 2008).

Policy implications and strategies for further oasis landscape planning and consolidation management

China's reform policies play a crucial role in land sustainability in the Hotan oasis (Fig. 10). Since the late 1970s, the central government of China has initiated several land reform policies. To overcome poverty and boost local economic development, the Chinese government launched the household responsibility system, opening up and reform policy, poverty alleviation policy, and great western development strategy in the 1980s. After the 2000s, the Grain-for-Green Project, great western development strategy, and Canceling Agricultural Tax exerted obvious influence on the regional sustainability of Northwest China, including the Hotan oasis. With the future increase in population and economy, the oasis landscape fragmentation in Northwest China will face further threats in the oasification process (Gui et al., 2017; Jiang et al., 2014; Luo & Timothy, 2017; Xie et al., 2014; Xue et al., 2019). "China's Grain Subsidy" (GS) policy has been offering farmers cash subsidies according to the actual cultivated area since 2004 (Xie et al., 2014; Yi et al., 2015). The policy has significantly raised the income of farmers. Owing to the low yield and income from agricultural production, the GS policy has encouraged numerous farmers to enhance land exploitation for considerable income at the expense of natural ecosystems and natural landforms. Wasteland reclamation has become profitable because of the absence of land rent and agricultural taxes (Shen, 2009; Shen & Lein, 2005; Shen et al., 2016; Song & Zhang, 2015). In addition, the popularization of drip irrigation technology and heavy machinery operation

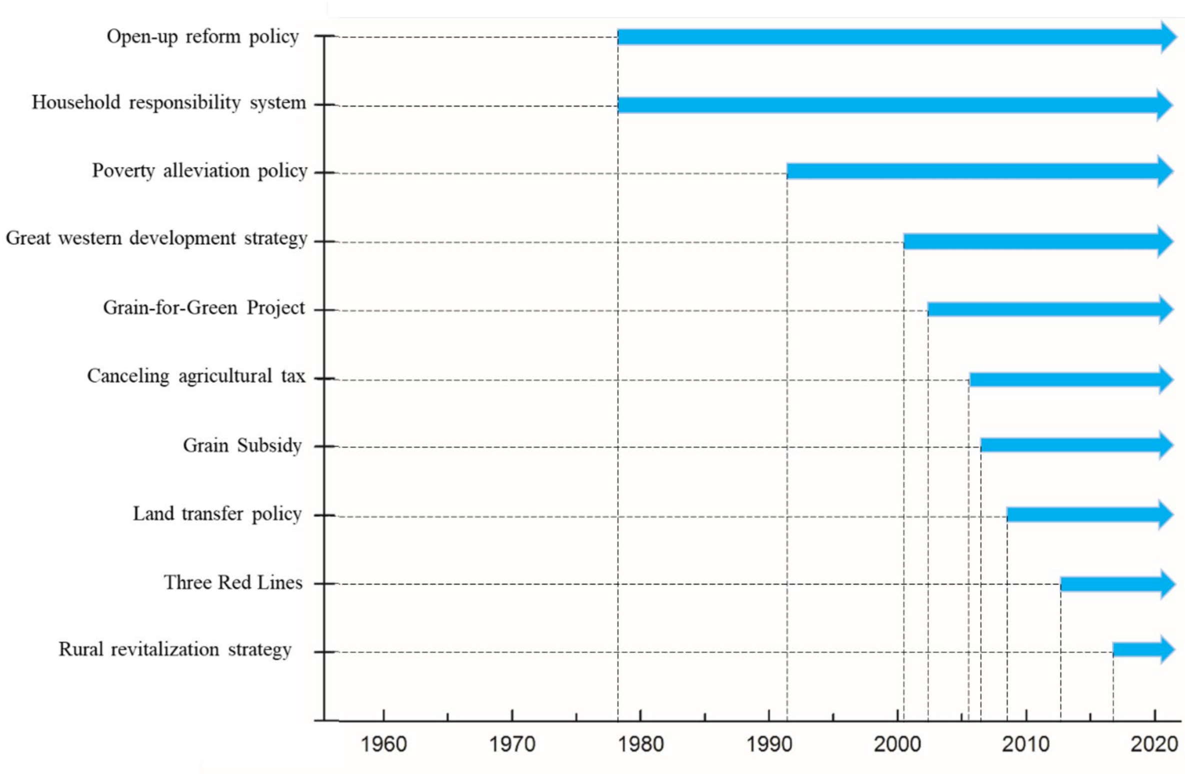


Fig. 10 China's major policies for land sustainability in Hotan oasis (adapted from Xie et al., 2014; Shen et al., 2016)

has been prompting farmers and land developers to exploit as much wasteland as they can afford. Parts of the desert–oasis ecotone, hillside land, wetland, grassland, and even the Gobi desert have already been reclaimed as cultivated land (Su et al., 2007; Zhang et al., 2017).

Although "The Three Red Lines" policy, which sets the limits on water supply, water quality, and water use efficiency, effectively provides a water governance system to mitigate water pressure and support water management, the water-saving irrigation in agriculture can never keep up with the water demand of land exploitation (Song & Zhang, 2015). Meanwhile, as urbanization increases in the fragile northwestern desert region, it is expected to incur potentially large patches (e.g., water area patches, planting mosaics, and residential patches) via the intervention of artificial facilities and corridor density, such as road lines and irrigation channels.

Rural revitalization and land transfer policies play an important role in realizing the intensive utilization of land toward oasis fragmentation solutions. Rural residential reconstruction enables the modernization of rural development with land consolidation (Niroula and Thapa, 2005). Farmland transfer advances the intensive development of farmland areas. An investigation involving 1162 households in the Hotan region was conducted via survey questionnaires to explore landholders' attitudes toward the two policies related to oasis landscape consolidation. The findings showed that 64% of the respondents were willing to accept rural residential reconstruction. Moreover, landholders in poor regions were more unwilling to move than those in the relatively rich areas. Landholders' acceptance of reconstruction is the joint result of multiple factors, such as residential and professional characteristics. In general, families with high incomes, few laborers, and moderate cultivated lands showed greatly favored reconstruction (Zhang et al., 2016). In addition, most substantial factors, including the knowledge of farmland transfer, household population, and land policy, have affected farmland transfer. Policy makers should thus comprehensively consider the situation of farmland transfer from the aspects of labor migration, implementation degree of land policy, educational level of rural population, and social security system in rural areas (Hu et al., 2017).

The aim of current oasis development policies in Northwest China focuses mainly on agricultural economy. The rational planning for fragmentation solution is yet lacking. The modification of existing policies is urgently needed for integrity and stability of the oasis landscape. For example, the rural revitalization policy should resettle and ban the scattered residential buildings occupied in farmland areas, increasing the continuity of farmland landscape. The land transfer policy should advocate intensive agricultural development mode through strengthening land transfer and land consolidation. In addition, forbidding the agricultural expansion of desert-oasis ecotone must be performed in the modification of open-up reform policy, because the agricultural expansion further aggravates oasis landscape fragmentation. Although this study evaluated the patterns and driving forces of oasis landscape fragmentation, as well as the policy implications for future land consolidation in Northwest China, the study of the eco-economic effects and sustainable management of oasis landscape fragmentation will be urgently needed in the future.

Conclusion

This study used a combination of approaches, including remote sensing image interpretations, landscape fragmentation metrics, and community surveys, to analyze patterns and their driving forces, as well as the policy implications in the Hotan oasis in Northwest China from the space and time perspectives. The results indicate that the frequent occurrence of summer flood events changes the patch number, density, size, and splitting degree of oasis–desert ecotone vegetation. The population and irrigation area have a significant correlation with fragmentation patch density using path analysis. The total population is greater factor to oasis landscape fragment than the irrigation area. The GDP and runoff indirectly impact the fragmentation patch density by means of the irrigation area. The socioeconomic factors are more important driving forces on oasis landscape fragmentation than natural elements. Rural expansion, the development of road and canal systems caused by population growth, and the number of households increase oasis landscape fragmentation. Meanwhile, rapid economic development, such as agricultural expansion and urbanization, imposes the intensification of landscape fragmentation. The oasis landscape fragmentation reaches peak, when agricultural expansion makes up 40–50% of the oasis area.

This study provides a valuable reference for the analysis of the patterns and driving forces of oasis landscape fragmentation, as well as the policy implications for future land consolidation. This paper also proves that the intense human activities pose a great threat for land consolidation and sustainable development of oasis landscape. The eco-economic effects and sustainable management of oasis landscape fragmentation caused by human activities should be urgently explored in further work.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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