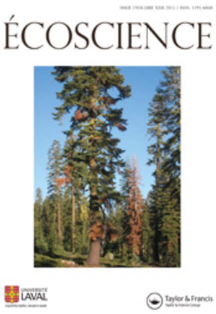

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ISSN: 1195-6860 (Print) 2376-7626 (Online) Journal homepage: http://www.tandfonline.com/loi/teco20

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ÉCOSCIENCE
2015, VOL. 22, NO. 1, 33–46
http://dx.doi.org/10.1080/11956860.2015.1047140

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Spatio-temporal changes in oases in the Heihe River Basin of China: 1963–2013

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ABSTRACT

Artificial oases have flourished as human activities have intensified. Changes in oases in the Heihe River Basin are typical for the arid areas of China. Based on images from 14 separate periods during 1963–2013 that were compiled from multi-sensors, data on the boundaries of oases were extracted using the methods of object-oriented image segmentation and Normalized Difference Vegetation Index thresholds as well as visual interpretation. Based on extracted data, the spatio-temporal changes in oases were analyzed using models i.e. grid transformed model for rate of change. The drivers were analyzed based on data from Statistics Yearbooks and field surveys. The results show that from 1963 to 2013 sprawl dominated oasis evolution and occurred not only in the surroundings but also in interior patches. Oasis evolution patterns of "unchanged," "expanding," "shrinking" and "oscillating" were observed. The development exhibited three stages, the unstable (1963–1980), the steady development (1980–2002) and the rapid expansion (2002–2013), which correspond to the Planned Economy Period, the Commodity Economy Period and the Market-oriented Economy Period, respectively, in China. Oasis expansion was mainly determined by the human instincts for survival and for human well-being and was governed by population growth, agricultural policies and economic development.

RÉSUMÉ

L'intensification de l'activité humaine a entraîné la prolifération des oasis artificielles. Les changements qui se sont produits dans les oasis du bassin de la rivière Heihe sont typiques des zones arides de la Chine. Sur la base d'images prises durant 14 périodes différentes s'étalant de 1963 à 2013, compilées à partir de multi-senseurs, des données sur les marges des oasis ont été extraites en utilisant des méthodes de segmentation orientée sur les objets et de seuil d'indice normalisé de différence de végétation, ainsi que par interprétation visuelle. Basé sur les données extraites des images, les changements spatiotemporels dans les oasis ont été analysés à l'aide de modèles, p.ex. le modèle de taux de changement avec transformation en trame. Les causes de ces changements ont été analysées en utilisant les données de bilans annuels statistiques et de relevés de terrain. Les résultats pour la période de 1963 à 2013 indiquent que l'expansion a dominé l'évolution des oasis. Les types de patrons d'évolution des oasis de « stable », « en expansion », « en régression » et « en oscillation » ont été identifiés. Le développement des oasis a suivi trois étapes: instabilité (1963–1980), développement continu (1980–2002) et expansion rapide (2002–2013), correspondant respectivement aux périodes de l'Économie planifiée, de l'Économie des commodités, et de l'Économie orientée vers les marchés en Chine. L'expansion des oasis a principalement été déterminée par l'instinct humain de survie et de bien-être, et a été régie par la croissance de la population, les politiques agricoles et le développement économique.

KEYWORDS
Oasis; spatio-temporal changes; Heihe River Basin; human development; landscape change; arid ecosystems

MOTS-CLÉS
Bassin de la rivière Heihe ; changements des paysages ; changements spatiaux et temporels ; développement humain ; écosystèmes arides ; oasis

1. Introduction

Artificial oases have flourished as human activities have intensified. An oasis is an isolated green fertile land in a desert that often surrounds a water source such as a spring; it provides habitat for animals, including sometimes for humans. Vegetation, water bodies and settlements are the three main landscape types of oases (Han 1999; Luo et al. 2002). Although oases constitute only 4–5% of arid regions in China, oases support over 90% of the regional population and 95% of the social wealth in these arid areas (Han 2001). Since the 1950s, due to the dramatic growth in area, the economic productivity of these oases has also increased, which has effectively promoted the development of local economies (Luo et al. 2009; Dong et al. 2013). However, the disorganized, low-tech exploitation of these oases in the past caused serious ecological problems such as the decrease in groundwater levels, land salinization and natural vegetation degeneration (Li et al. 2007a; Zhang et al. 2013; King & Thomas 2014). Research on oasis

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evolution is fundamental to the analysis of the mechanisms of oasis development and response to human activity and climate change; such research also provides the basis for the development of strategies to ensure sustainable oasis development in arid areas.

The Heihe River Basin is the second largest inland river basin in the arid region of northwest China and is one of the most ecologically vulnerable areas. The Basin experienced dramatic changes in socioeconomic development in terms of food and clothing in the Planned Economy Period (1963–1980), more commodity grains in the Commodity Economy Period (1980–2002) and more benefits in the Market-oriented Economy Period (2002–2013). However, with more lands being cultivated to support the local economy, the water shortage was more severe. In this region, water consumption increased in the middle reaches, the water table dropped and the river and terminal lakes gradually dried up (Feng et al. 2001; Ji et al. 2006); moreover, the local ecological functions degraded in the lower reaches (Wang et al. 2005; Fu et al. 2008). Studying the changes in the spatial distribution of the Heihe River oases over the last 50 years can provide basic data for regulating oasis exploitation and data for the government to use to develop measures for optimizing oasis development.

Many studies on the spatio-temporal changes in oases in western China have been conducted using remote sensing and geographic information systems. For example, land use and land cover change patterns of the oases in the Tarim River Basin for the years 1960, 1990 and 2000 have been reconstructed, and their spatial–temporal changes have been analyzed (Dou & Chen 2009). In addition, the stability at four different times of four similarly sized oases within the Manas River Basin has been analyzed (Ling et al. 2013). Moreover, the spatial–temporal processes of oasis development in the middle reaches of the Heihe River Basin from 2000 to 2009 have been studied using moderate-resolution imaging spectrometer Normalized Difference Vegetation Index data (Tian et al. 2011). Changes in vegetation in the Zhangye oasis have also been detected using Landsat Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+) data from 1989, 2000 and 2011 (Wang et al. 2013). Finally, temporal and spatial changes in cropland in the arid and semi-arid region of northwest China from 1980 to 2010 have been analyzed, and the major drivers have been discussed (Zuo et al. 2014). However, the previous studies focused on the evolution of oases over a short period of time or with a coarse time resolution (Luo et al. 2003; Feng et al. 2014; Mamat et al. 2014), or they used remote sensing data with a coarse resolution (Li et al. 2008; Jin et al. 2010; Yang et al. 2014), which causes significant uncertainty in the extraction of oasis data. Therefore, research on the evolution of oases with smaller time intervals and fine spatial resolution is necessary.

In this paper, we reconstructed the evolution of the oases in the Heihe River Basin from 1963 to 2013 using 14 periods of multi-sourced remote sensing images. We analyzed the changes in oasis boundaries over this 50-year period of development and discussed the driving factors in the context of social economic development.

2. Study area and data

The Heihe River originates at the northern slopes of the Qilian Mountains, and the basin is representative of the utilization of water and land resources in northwest China (Cheng et al. 2009). The Basin is located between 96°42′–102°00′E and 37°41′–42°42′N and has an area of approximately 128,000 km^2 (Figure 1). The main stream of the Heihe River, which has a length of 821 km, flows through the central Hexi Corridor in Gansu Province and empties into Juyan Lake, which is a terminal desert lake in Inner Mongolia. There are three major geomorphological units in this area: the southern Qilian Mountains, the middle Hexi Corridor and the northern Alxa High Plain. The annual precipitation ranges from >255 mm in the central corridor plains to <50 mm in the lower reaches, where the average annual potential evaporation is 3750 mm. The water source is sufficient in the upper and middle zones, and the oases are chiefly distributed on the alluvial fan of the piedmont and fluvial plain in the middle reaches. This study area includes the prefecture-level cities of Zhangye (including the counties of Ganzhou, Shandan, Minle, Gaotai and Linze), part of Jiuquan (governing Suzhou District and Jinta County) and Jiayuguan, as well as part of the Alxa League (governing Ejina County) in Inner Mongolia.

To map and quantify the oasis changes in the Heihe River Basin, the remotely sensed images were used to extract the oases boundary data, which are presented in Table 1. The images acquired in July and August were the first images selected in this study, whereas those from June and September were used as substitutions if high-quality images from July and August were unavailable. Other data, such as population data for the sample years, Gross Domestic Product (GDP) data, annual average temperature and precipitation data, were obtained from the County Statistics Yearbooks. Mountain runoff data were obtained from the Yingluo Gorge hydrological station, which provides the main water supply for the Basin.

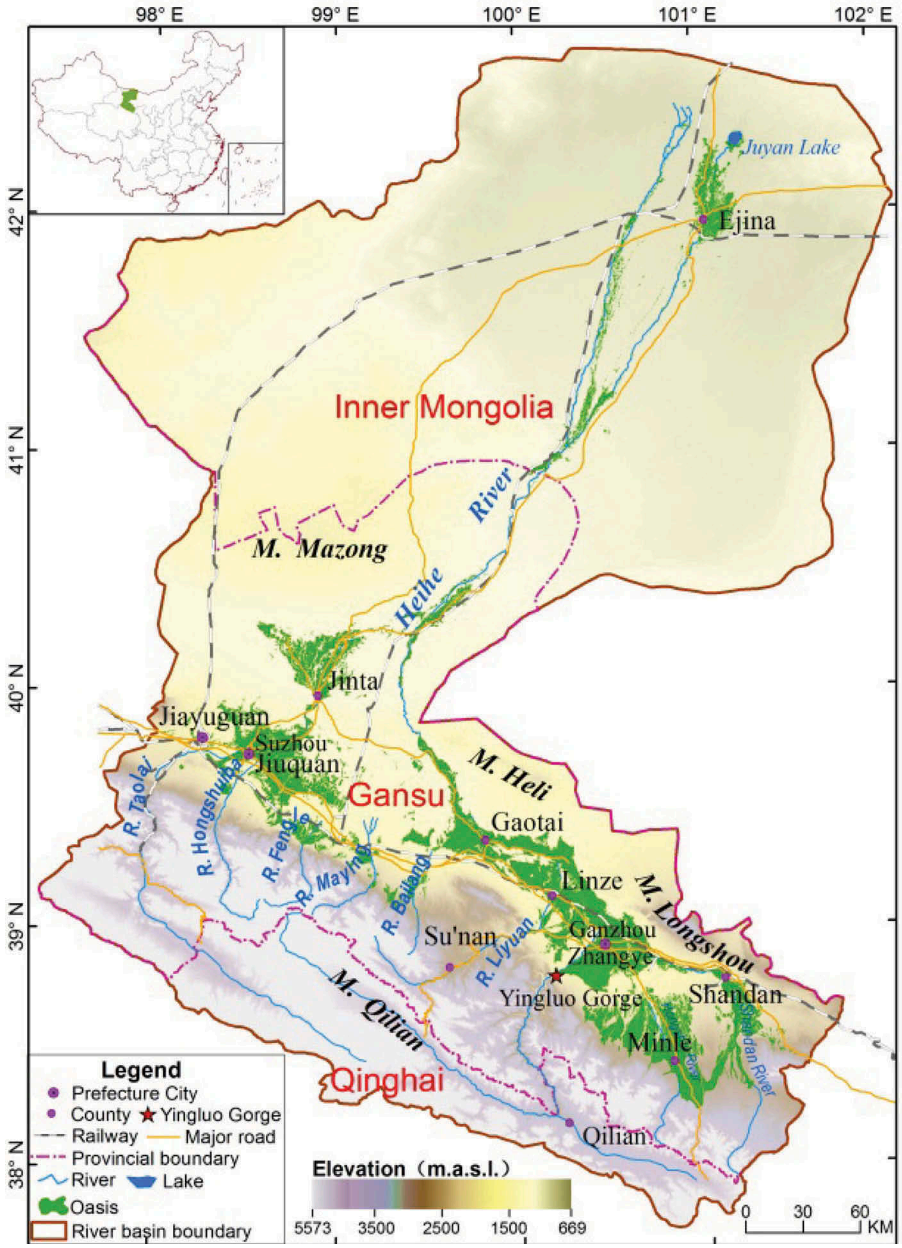

Figure 1. Location of the Heihe River Basin of China.

Note: The terrain of the Heihe River Basin is higher in the south and lower in the north. The terrain variation in this region is represented using a color gradient: white–purple represents high mountains in the upper stream, light yellow represents the plain in the middle stream and dark yellow represents the flat plain in the downstream. The bright green parts are the areas occupied by oases in 2013.

Table 1. Image resources used, with dates and resolutions.

Year	Data resource	Resolution/m
1963, 1968	KeyHole[a]	2.7–7.5
1973, 1977	Landsat *Multispectral Scanner System*	79
1980	KATE-200[b]	8.9
1986, 1990, 1993, 1996, 1999, 2002, 2006, 2009, 2013	Landsat TM/ETM+	30

Note: [a]A series of American optical reconnaissance satellites that were launched in 1960 to acquire defense-related data on the Soviet Union. [b]Reconnaissance camera carried by the Resurs-F1 satellite, which was launched in 1977 by the Soviet Union to survey the natural resources of interested countries.

These data were combined with field survey material and used to analyze the driving factors of oasis change.

3. Method

3.1 Extraction of oasis data

ll images were geometrically registered to the same coordinate system as the 2013 images. To reduce the gap caused by the spatial resolution, the Keyhole and

KATE-200 images were resampled to be consistent in terms of spatial resolution with the Landsat Multispectral Scanner System/TM/ETM+ images. In the Heihe River Basin, oases are dominated by vegetation. Vegetation data can be easily extracted because the spectrum of the vegetation is distinctly different from the environmental background; therefore, vegetation data were extracted first. An object-oriented image segmentation method was used for the KeyHole and KATE-200 images (Yu et al. 2006). The Normalized Difference Vegetation Index threshold method, which extracts vegetation information from the background based on the maximum variance between the objective and the background, was used for the Multispectral Scanner System/TM/ETM+ images (Xie et al. 2012).

To refine the extraction, the missing and false areas were processed by visual interpretation after the initial classification. Owing to the spectral similarity between settlements and the Gobi Desert in the remote sensing images, settlements – especially those located in the junction zone – cannot be easily detected. In addition, the boundaries of water bodies often vary with season, and there is an obvious difference between water bodies and surrounding oases. These features were therefore manually added. Fallow and harvested land had been excluded due to their low Normalized Difference Vegetation Index values; hence, we manually added this feature using a series of images acquired in different phenological periods. Geographically proximate patches were merged, and scattered patches with an area of less than 1 ha were artificially deleted because they are too small to constitute an oasis unit (Han 2001).

Following data extraction, the accuracies were verified through field validation. For the early periods before 2009, data gathered from interviews with local residents were used for validation (Xie et al. 2012); for the recent periods (i.e. 2009 and 2013), the "hotspots" (regions where the changes in oases frequently occurred) were detected through an overlay analysis in the laboratory. The "hotspots" with margins and spatial continuities that were in agreement with the characteristics of the oasis were selected. Finally, 139 and 103 samples for 2009 and 2013, respectively, were used for validation, and the accuracy was 94.8%.

3.2 Methods for analysis of oasis evolution

Changes in oases over time can be identified based on the change in the oasis area between the beginning and final years. The evolution is characterized by the rates of change and the change patterns that oases exhibit (Luo et al. 2008; Zhou et al. 2010; Tian et al. 2013). Land use and land cover change models, such as the single dynamic degree model (SDD; Liu et al. 2002) and the bidirectional dynamic degree model (BDD; Liu & He 2002), are widely used to analyze changes in oases (Luo et al. 2008; Zhou et al. 2010; Xie et al. 2014). SDD describes the rate of net change and neglects the increasing and decreasing components during the evolution. BDD supplements the SDD model by incorporating both increasing and decreasing rates of change into a composite metric that captures rate of change regardless of direction of change. However, these models are temporal models, and the spatial variations cannot be displayed. Overlay analysis is a method for detecting spatial changes and is used to identify patterns of change. To quantify the change intensity in space, a gridding method is used. This method employs a matrix consisting of rows and columns to determine the positions; the values of the grid cells represent the rate of change. As a substitute for the SDD model, the grid transformed model for rate of change (K_g) expresses the rate of change of a specific position over one period (Ma et al. 2012), and the rate of change over the long term can be determined using the derived models of the absolute cumulative rates of change (ACK). Change in a specific stage is described by the relative cumulative rates of change (RCK). These time-oriented and space-oriented models portray oasis changes in different manners; they were all used in this study and can be applied to similar regions in arid areas.

3.2.1 Time-oriented rate of change models

The SDD is determined by the ratio of the difference in area between two adjacent periods to the area in the early stage (Liu et al. 2002); this value is used to depict the rate of change of the oasis for a certain period. The SSD can be calculated as:

$$SDD = \frac{LA_{(T2)} - LA_{(T1)}}{LA_{(T1)} * (T2 - T1)} * 100\% \quad (1)$$

where LA is the total area of the oasis and $T1$ and $T2$ are the beginning and final years in one period, respectively. T is the sample year (as below). SDD indicates the annual rate of net change.

The BDD is used to identify the absolute rate of change during two adjacent periods. This measure considers the unchanged land area, the increased rate of land (IRL) and the decreased rate of land (DRL) (Liu & He 2002). The formula is:

$$\begin{cases} ULA = LA_{(T1)} \bigcap LA_{(T2)} \\ DRL = \frac{LA_{(T1)} - ULA}{LA_{(T1)} * (T2 - T1)} * 100\% \\ IRL = \frac{LA_{(T2)} - ULA}{LA_{(T1)} * (T2 - T1)} * 100\% \\ BDD = DRL + IRL \end{cases} \quad (2)$$

where $\bigcap$ is an intersection symbol, the overlapped part can be obtained using this operation, and *ULA* is the area of the unchanged part of the oasis over time. *DRL* is the annual rate of decrease, *IRL* is the annual rate of increase, and *BDD* is the annual bidirectional rate of change.

3.2.2 Overlay analysis

Overlay analysis is a method for detecting change patterns by superimposing multiple phases of data for the same geographical region. According to the transformations between non-oasis and oasis, the change patterns of oases were divided into four categories: "unchanged," in which case no changes in the boundaries of the regions occur during the research time; "expanding," in which case the oasis experiences expansion without subsequent shrinkage; "shrinking," in which case the oasis experiences contraction without subsequent expansion; and "oscillating," in which case the oasis undergoes intermittent transformation between expansion and shrinkage. Owing to computer memory limitations, the overlay analyses were conducted between adjacent sample years. When the data for an extracted oasis in two adjacent years overlapped, the unchanged areas were detected, and the increased and decreased areas were ascertained by excluding the unchanged part from the data of the following year and previous year, respectively. Consequently, the overlapped areas of the total unchanged regions were classified as the "unchanged" pattern, and the overlapped areas of the total increased and decreased regions were classified as the "oscillating" pattern. After the areas with oscillating patterns were excluded from the total increased areas, the residual part of the total increased areas was classified as the "expanding" pattern. Similarly, the "shrinking" pattern was the residual part of the total decreased areas after the areas with "oscillating" patterns were excluded.

3.2.3 Space-oriented rate of change models

The formula for the grid transformed model for rate of change is (Ma et al. 2012):

$$K_g = \frac{LA_{g(T2)} - LA_{g(T1)}}{S_{grid}} \tag{3}$$

where LA_g is the total area covered by oases in a specific grid, $T1$ and $T2$ are the beginning and final years in one period, respectively, S_{grid} is the area of the grid and K_g is the spatial rate of change. If K_g approaches 1 or −1 the oases are characterized by expansion or shrinkage, respectively, whereas if K_g is close to zero the oases are stable.

The distribution of rate of change over a long period can be represented through the superposition of K_g in each period. The absolute values of $\underline{K_g}$ are summed, and the formula for the ACK is:

$$ACK_{grid} = \sum_{i=1}^{N-1} \left| K_{grid_{T_{i+1}-T_i}} \right| \tag{4}$$

where N is the number of periods, $K_{grid_{T_{i+1}-T_i}}$ is the spatial rate of change in one period calculated using Equation (3), T_i and T_{i+1} are the beginning and final years in one period, and *ACK* is the absolute rate of change over the entire study period; a high value of *ACK* indicates rapid changes. ACK can therefore be used to detect sensitive areas with frequent changes.

The average rate of change in a focused stage can be expressed through the RCK:

$$RCK_{grid} = \frac{1}{N-1} \sum_{i=1}^{N-1} K_{grid_{T_{i+1}-T_i}} \tag{5}$$

where *RCK* is the average of K_g over several adjacent periods and has the same implications as does K_g.

The size of the grid has a critical effect on the value of the three indices. When determining the grid scale, the spatial resolution of the image and computational efficiency need to be considered. In this study, the spatial resolution is 30 m, and grid sizes of 60, 90, 120 and 150 m were tested. As a trade-off between resolution and computational efficiency, a grid scale of 120 m × 120 m was finally selected.

3.2.4 Interviews to determine driving factors

The causes of spatio-temporal changes in oases in the Heihe River Basin are very complex, and it is very difficult to simulate such changes using a simple quantitative model; therefore, a logical reasoning method is necessary and is used for a top-down analysis. To determine the main human factors driving oasis changes, we conducted semi-structured interviews in the field. More than 550 local people from 74 villages accepted to be interviewed and 74 investigation reports were obtained. Instead of using a formalized list of questions, the interview framework, such as the interviewee and the interview content, are ascertained according to field experience and land use and land cover change driving factors discussed in the literature (Ma et al. 2007; Li et al. 2007b; J. Y. Liu et al. 2010). The content of these interviews included the time and location of large-scale land exploitation and abandonment, population growth and immigration, agricultural policy, water sources for irrigation (rivers, spring water or underground water), construction events for water conservancy facilities, changes in plantation structure and economic income. Ecological problems such as the level of the underground water table, the status of natural vegetation and wind storms were also surveyed. The interviews were mainly conducted in the villages where the oasis experienced remarkable changes in each county. The interviews were conducted with local experts such as older villagers and leaders who knew the local history well. The results of the interviews were collected by note-taking and digital recording.

4. Results

4.1 Changes in number of oases

The measured total oasis areas, shown in Figure 2, demonstrate an overall growth over the past 50 years, reaching a peak of 7191.923 km^2 in 2013, which is 1.6 times the area in 1963 (4479.309 km^2). Oasis area increased significantly in the periods 1963–1973, 1977–1980, 1990–1993 and 2002–2013, with SDDs of +0.9, +2.1, +2.4 and +2.5%, respectively, and shrinkage occurred from 1973 to 1977 with an SDD of –2.6%. During the periods 1980–1990 and 1993–2002 there was not much change in oasis area.

Figure 3 shows the oasis rate of change over the last 50 years. Changes in BDD, IRL and DRL exhibit a decreasing trend. These results indicate that over the entire period oases experienced great change in which growth in size predominated, but the growth rate gradually decreased due to a decrease in the annual rate of expansion and shrinkage, indicating a trend toward stabilization.

However, the rate of transformation between non-oasis and oasis was different in each period. The BDD was steady from 1963 to 1977, and after peaking during the period 1977–1980 it sharply declined with fluctuations during the period 1980–2009 and substantially decreased during the period 2009–2013 (Figure 3). The IRL and DRL peaked during the period 1977–1980 (Figure 3), implying that obvious bidirectional transformations occurred during this period. In the periods 1980–1990 and 1993–2002, oases also experienced bidirectional transformation despite minimal differences between IRL and DRL, which indicates that the overall oasis area was roughly unchanged, as is also shown in Figure 2.

4.2 Spatio-temporal changes in oases

4.2.1 Patterns of oasis change

Figure 4 shows the distribution of the four patterns of oasis change: "unchanged," "oscillating," "expanding" and "shrinking". Established oasis areas remained unchanged and accounted for 29.0% of the total area of oases in the basin. These oases with unchanged patterns were distributed in the alluvial–proluvial piedmont fans, the river plains of the Basin's middle reaches and the triangular alluvial fans in the lower reaches (Figure 4).

Oases with oscillating patterns constituted 52.3% of the total area of the oases in the basin, which means that more than one-half of the Basin's oases experienced bidirectional changes (i.e. from oasis to non-oasis and from non-oasis to oasis). This pattern principally occurred in the margins of the oasis areas; that is, along gullies in the north of Minle, the southeast of Shandan, areas in the east of the

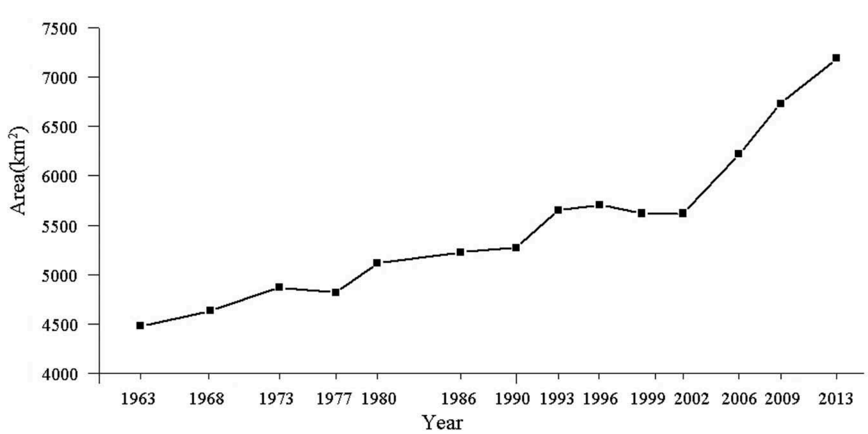

Figure 2. Changes in total oasis area in the Heihe River Basin over the last 50 years.
Note: The oasis areas of sampled years were drawn in the figure, with 1963 as the initial year and 2013 as the final year.

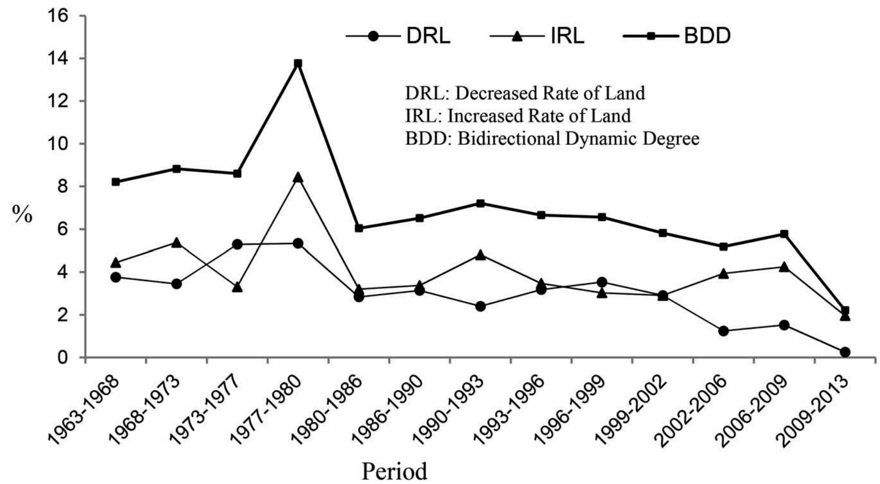

Figure 3. Intensity of changes in oases in the Heihe River Basin during the past 50 years (%).
Note: DRL is the annual rate of decrease of the oasis area in a period, IRL is the annual rate of increase of the oasis area and BDD, the sum of the value of IRL and DRL, is the annual bidirectional rate of change of the oasis area. Larger values of BDD indicate more frequent conversions between non-oasis and oasis.

Basin along the Heihe River in Ganzhou, the northern areas of Linze located on the alluvial plain margins, and the northern areas of Suzhou adjacent to the desert (Figure 4). The oases along Fengle River and Maying River and in the corridor between Suzhou and Jinta fluctuated, and the oases in Jinta and Ejina changed in this manner as well (Figure 4). These areas are located in the margins of the alluvial–proluvial fan, in low-lying areas next to rivers and ditches, and in the transitional zones between oasis and desert.

Oases with patterns of expansion accounted for 16.8% of the total area of oases in the Basin. They were distributed beyond and within the main oasis region, particularly in the middle reaches of the Heihe River, and certain oases were diffused in the lower reaches; for example, the Shandan River's termination in central Shandan County, the northern areas of Ganzhou along the Heihe River, the southern desert frontier of Ganzhou, and along the Hongshui River termination in Minle (Figure 4). Beyond the Heihe River in Linze and within the alluvial plain, a similar situation was also observed in the western desert belt of Gaotai at the Bailang River termination, the uninhabited lands to the southeast of Suzhou along the Fengle River and the eastern regions near the county of Jinta (Figure 4). These expanded oases were located alongside river terminations or in desert margins where irrigation is convenient.

Oases exhibiting a shrinkage pattern predominated along the lower river courses and in the northwest areas of Gaotai, and some were scattered throughout the Basin (Figure 4). The area from these oases was the smallest and constituted 1.9% of the total oasis area.

4.2.2 The space-oriented rate of change

The ACK distribution of oases from 1963 to 2013 indicates regional differences in terms of the oasis changes, as shown in Figure 5. In the Basin's lower reaches, areas far from the waterway are susceptible to water shortages, and soil salinization is easily developed as fierce evaporation brings the salt to the surface. Oases in this area with higher ACK therefore frequently changed. Furthermore, in the middle reaches, because the surface soil in the piedmont belt and alluvial plain margins is composed of medium or fine sand and silt, groundwater is prone to overflow onto the surface. The oases that exhibit intense changes in ACK, which are affected by groundwater seepage, are located in the overflow spring zones of the alluvial–proluvial plain such as the oases in northern Minle and Linze. In addition, low-lying regions within the established oasis zone are prone to become highly saline–alkaline as a result of high evaporation; hence, oases in this area exhibit higher ACK (e.g. oases in Ganzhou).

In addition, most areas with high ACK, such as oases in Suzhou, are located on the periphery of oases with unchanged patterns in the Basin's middle reaches, especially the sides of waterways and lakes (see Figure 5). In these areas, oases changed frequently but less severely than those in the Basin's lower reaches.

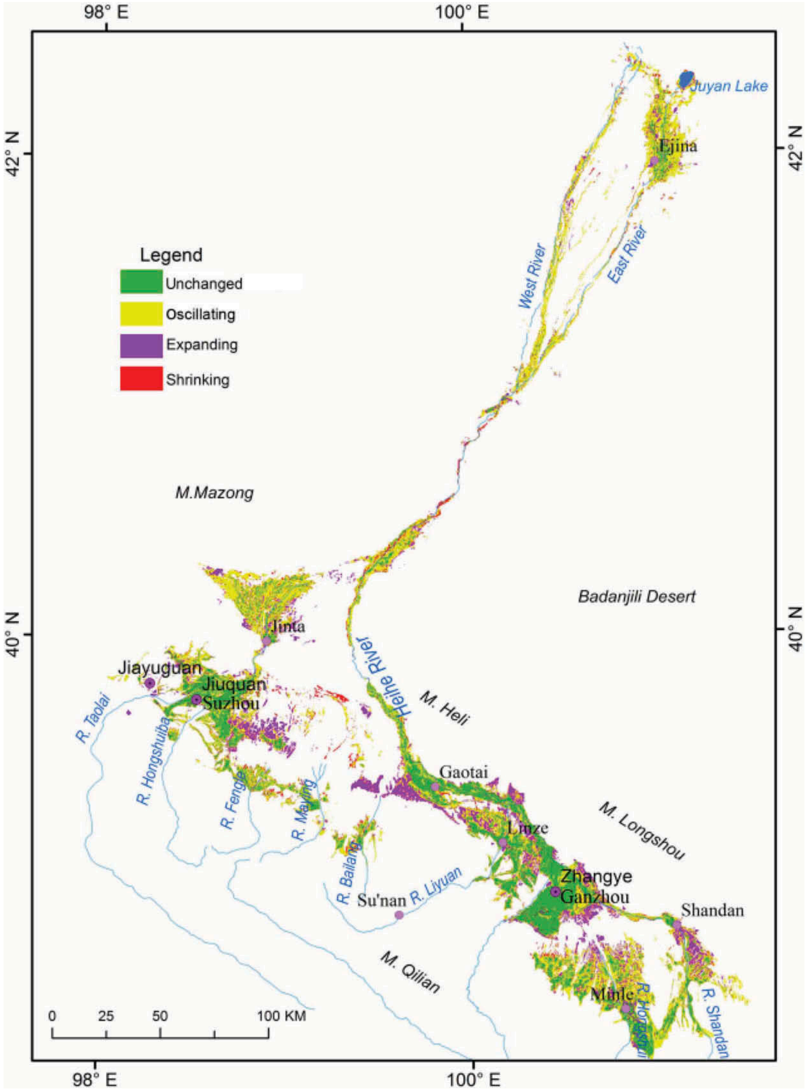

Figure 4. Evolution of the oases in the Heihe River Basin, 1963–2013.

Note: The "unchanged" oases are those that always exist. The "expanding" oases are those that were reclaimed since 1963. The "shrinking" oases are those that have been abandoned and not restored by 2013. The "oscillating" oases are those with intermittent expansion and shrinkage. The distributions of all four patterns are shown in the figure using distinct colors.

4.3 Stages of oasis change

As shown in Figure 2, the oasis area exhibited fluctuations during 1963–1980, moderate increases from 1980 to 2002 and rapid growth from 2002 to 2013. Oasis change has been visually divided into three stages: an unstable stage (1963–1980), a steady development stage (1980–2002) and a rapid expansion stage (2002–2013). In Figure 6 the areas with RCK values close to 1 were expanding, and areas with RCK values close to −1 were shrinking. Bidirectional changes in the oases occurred during these three stages, but the degrees of change were different.

In the unstable stage, oases experienced expansion, shrinkage and recovery. As a whole, expansion at a rate of 37.29 km^2 per year occurred, and the total area increased by 14.2% over that 18-year period. Figure 6a shows that during this period oases largely expanded outward from the settlements and towards the desert, as exhibited by the oases in northern Ganzhou and Linze. Areas along piedmont gullies and alluvial fans were cultivated. In this period, areas of shrinkage were distributed downstream such as along the Heihe River in Jinta.

In the steady development stage, oases expanded slowly, with a growth rate of 22.94 km^2 per year, and the total area increased by 7.5% over 22 years. Most of the oases that expanded during the previous period remained stable, and some oases continued to expand; for example, the uninhabited lands in the southeast of Shandan, western Gaotai, and the edge of the alluvial

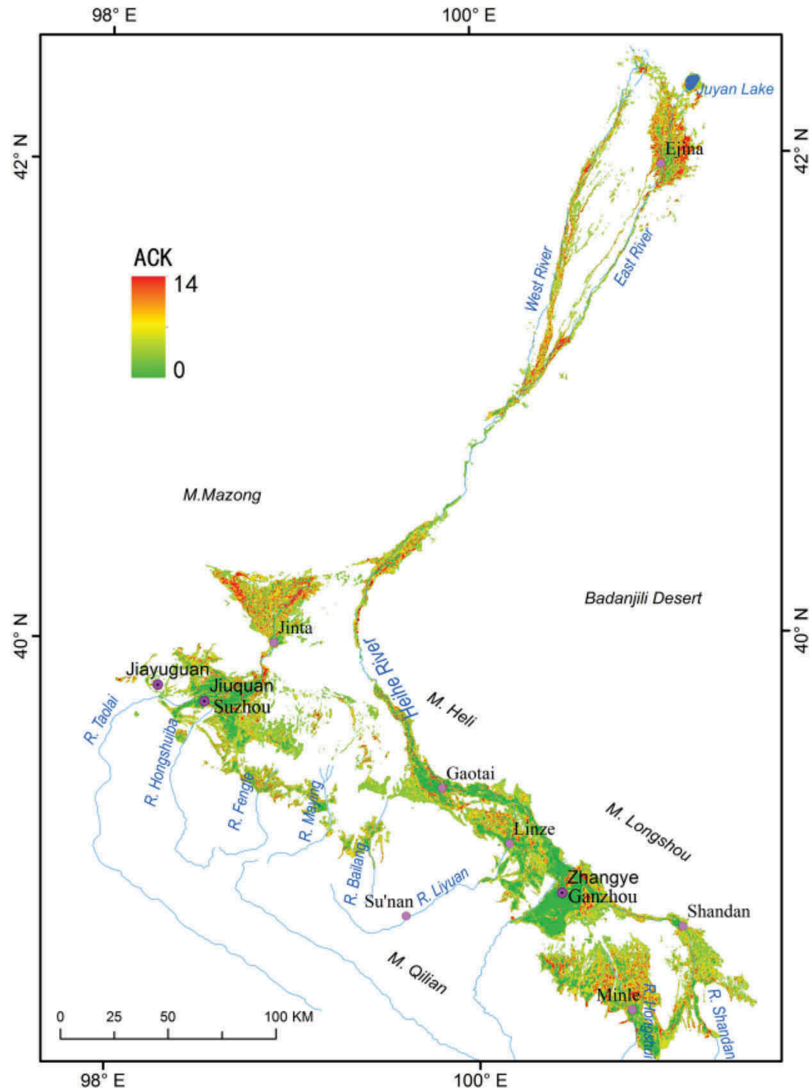

Figure 5. ACK values for oases in the Heihe River Basin, 1963–2013.

Note: ACK is the absolute spatial rate of change of the oasis; higher ACK values indicate that more frequent changes have occurred.

plain in Linze and Ejina (Figure 6b). During this period, shrinkage mainly appeared in areas where expansion occurred during the previous stage.

In the rapid expansion stage, oases rapidly expanded at 143.09 km^2 per year, and the total area increased by 28.0% during 12 years. Areas of expansion were widely distributed in the Basin (Figure 6c). Most of the oases that had previously shrunk had recovered, and expansion occurred not only in the margins of alluvial plains located in the middle reaches of the Basin but also in the lower reaches, such as the majority of patches cultivated in the alluvial fans of Jinta and eastern Ejina.

Overall, over the last 50 years, the distribution of the oases in the Heihe River Basin became more continuous, clumped and uniform in space. Additionally, the edges of the oases in the Heihe River Basin became more straight and smooth.

5 Discussion

5.1 Discussion of the evolution of oases

This study shows that expansion was the main change trend exhibited by oases in the Heihe River Basin over the last 50 years. This finding is consistent with the results reported by Liao (2011) and Liu et al. (2014), and the situation was similar in other arid areas such as the Aksu Oasis (Zhou et al. 2010), the Hotan Oasis (Amuti & Luo 2014) and the Keriya Oasis (Eziz et al. 2014) of Xinjiang in northwest China. The expansion pattern with “outward extension and inward filling”

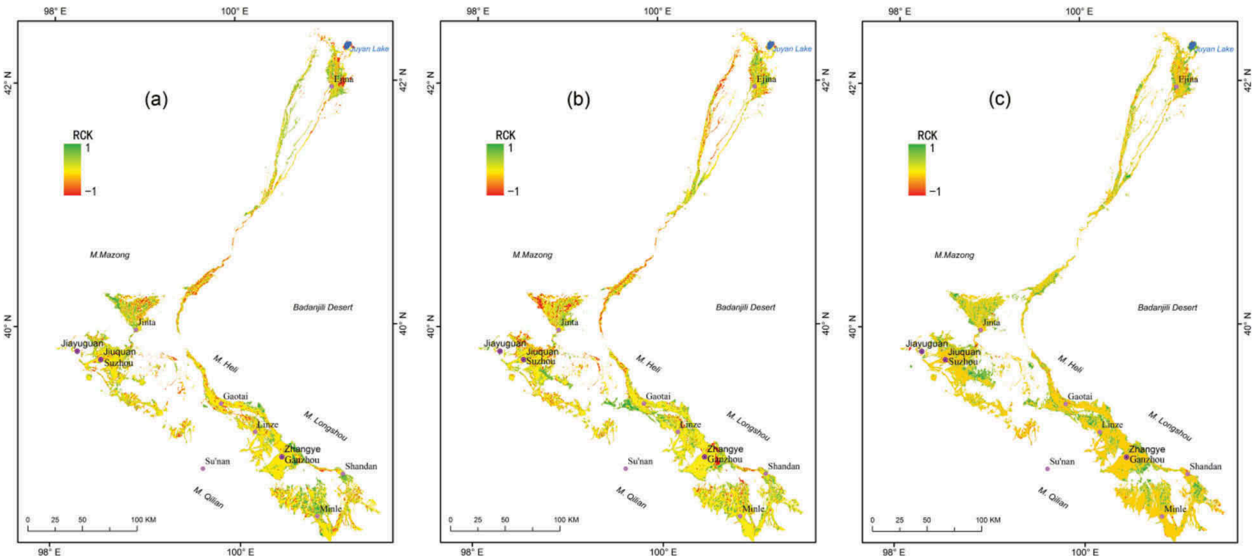

Figure 6. RCK values of oases in the Heihe River Basin at various stages. Distribution of RCK values of the three stages: (a) the unstable stage (1963–1980), (b) the steady development stage (1980–2002) and (c) the rapid expansion stage (2002–2013).
Note: RCK is the average rate of change of the oases during a specific stage. If RCK approaches 1 or −1, then the oases are experiencing expansions (green hue) or shrinkage (red hue); an RCK close to zero (yellow hue) indicates stability.

also occurred in the oases of the Manas River Valley (Cheng et al. 2006) and Sangong River watershed (Luo et al. 2008). The three stages of oasis change were also reported in studies on the Jinta oasis (Xie et al. 2014), the Minle oasis (Chang et al. 2013) and the oasis of the Yanqi Basin in northwest China (Mamat et al. 2014). These stages were consistent with occurrence of economic growth and economic reform in China, and changes in oases in China were related to policy changes and social development.

5.2 Driving forces of the oasis changes

Both natural and human factors were responsible for changes in these oases. The natural factors include climatic factors related to precipitation and air temperature and hydrological factors such as runoff. Over the past 60 years, precipitation slightly increased at a speed of 0.2128 mm/year and exhibited fluctuations (Ding et al. 2009); therefore, the effect of precipitation on oasis expansion was negligible. There was an increasing trend exhibited by the annual average temperature of 0.0268°C/year, which may have led to an increase in runoff from mountain regions (Wang & Meng 2008). Sufficient runoff supports oasis expansion; however, its division, distribution and utilization efficiency, which are mainly influenced by human activities, affect oasis changes (Tang et al. 1992; Jia et al. 2004; Huo et al. 2008; Zang et al. 2013; Sang et al. 2014). As a result, climatic factors are probably not the chief driving factors of oasis change in the short term, which has also been reported by Hong et al. (2003), Cheng et al. (2006), Li et al. (2007b) and Xie et al. (2014).

The results of the interviews show that population growth, agricultural policies (e.g. Free Agriculture Tax), population policies (e.g. Immigration Policy), mechanization of farming, adjustment of planting structure and increased income are the main factors that drove oasis change over the last 60 years. With the development of social economy, dominant factors are different. For example, 90% of interviewers thought that people's pursuit of increased economic benefits is the main driving factors in recent years, while in the 1960s population growth was more important because people needed increased agricultural income.

The stages of oasis development corresponded to economic development periods described as the Planned Economy Period, the Commodity Economy Period and the Market-oriented Economy Period. During the Planned Economy Period from 1963 to 1980, based on the Statistics Yearbooks and field surveys, the population of the Heihe River Basin rapidly increased by 58.2% (Figure 7b); hence, more land was needed to support the livelihood of the population. The oasis area was therefore expanded to satisfy the demands of a growing population (Qi et al. 2007; Mamattursun et al. 2010). However, the area occupied by oases showed a net decrease because the expansions were offset by the decrease in mountainous runoff (Figure 7a), by unplanned, excessive exploitation of land and water resources, and by the instability of

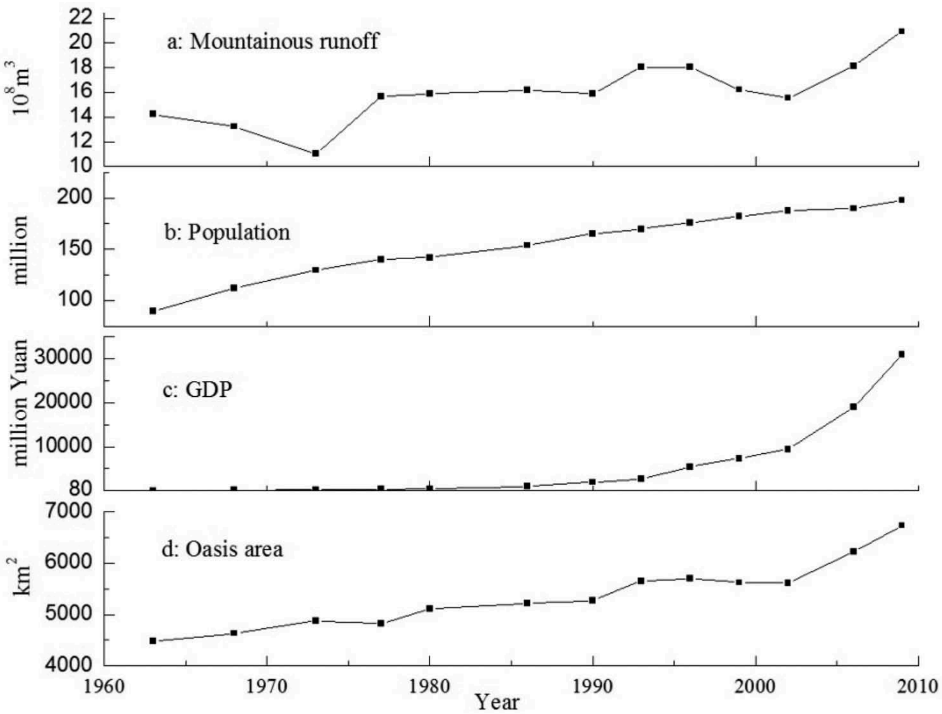

Figure 7. Changes in mountainous runoff, population, gross domestic product (GDP) and oasis area of the Heihe River Basin since 1963. (a) Runoff (over an annual time period) changes observed at the Yingluo Gorge Hydrological Station, which is located at the exit mouth of the Qilian Mountain. (b), (c) Changes in the population and GDP in the Heihe River Basin, summarized according to the County Statistics Yearbook. (d) Changes in oasis area obtained from this study.

society (Hao et al. 2008). To satisfy the needs for food and clothing of the local population, national development plans were implemented and stimulated the restoration of lost oases (Y. Liu et al. 2010); moreover, the arable lands surrounding former oases were cultivated.

During the Commodity Economy Period from 1980 to 2002, family-based agricultural agreements were developed by the national government to improve crop production (Lin 1992; Wu & Zhang 2008). During this period, the inflow of the Basin was high and relatively stable (Figure 7a). With this economic development (Figure 7c), the irrigation infrastructure – including channels, dams, wells and reservoirs – was either repaired or constructed. In addition, the immigration policy facilitated migration from Dingxi (a poor and harsh region in the center of the Gansu Province) to the Hexi Corridor region in 1983 to improve standards of living (Shao 1990). Uninhabited lands in the margin of western Gaotai and northeastern Jinta were cultivated to support the immigrants (Tian et al. 2014; Xie 2012), and oases were steadily expanded.

Later, with the market-oriented economy booming during 2002–2013, the benefits of pursing economic development became increasingly apparent (Chang et al. 2013). Local residents reclaimed enormous areas of land to enable greater crop production (Jie et al. 2003; Wu et al. 2009) so that additional benefits could be obtained, as evidenced by marked economic improvement since 2002 (see Figure 7c). Water conservation facilities and water utilization efficiencies were improved, and advances in agricultural technology were obtained (Luo et al. 2005). For example, the number of pumping wells increased by 13.2% in the Basin's middle reaches (Zhou et al. 2011) and by approximately 50% in Jinta, which is located in the Basin's lower reaches (Xie 2012). In addition, the annual inflow rapidly increased during this period (see Figure 7a). Under these conditions, oases grew rapidly and mirrored the gross domestic product increase (see Figure 7c and 7d).

In summary, human activity was shown to be the dominant factor driving oasis change over the last 50 years. This finding has parallels in other countries, where oasis expansion has occurred due to intense human activities, as in Egypt (Badreldin & Goossens 2014), the Sahara (King & Thomas 2014) and Syria (Udelhoven & Hill 2009). In the Heihe River Basin, the principal driving factors for each of the three stages were the increased population, the implementation of family-based agricultural agreements and the development of the economy. In summary, the essential driver of oasis change is the desire by people to obtain material benefits under the mediation of various governmental policies, facilitated by a growing economy.

5.3 Implications for the management of the sustainable development of oases

Since 2002 oases have rapidly expanded, and the influence of human activities on nature has accelerated, which will inevitably cause serious environmental problems such as groundwater recession, vegetation degradation and soil salinization. Beginning in 2002, the policy of "Prohibition of Reclaiming, Welling and Immigrating" was implemented to alleviate a shortage of water resources and to protect the environment, but the improvement of the environment was not significant. The government should pay more attention to the fragility of the environment and enhance environmental compensation in response to oasis changes. This study shows that most arable lands in the oasis–desert ecotone were cultivated, and lands that will be available for exploitation will be limited in the future. Efforts to improve land use efficiency, to encourage water conservation, to improve irrigation practices, to optimize planting structure and to increase crop yield should therefore be urgently implemented. Furthermore, increased levels of research and monitoring of environmental conditions in oases are warranted.

6. Conclusions

Remotely sensed images from multi-sensors and geographic information system techniques were used to reconstruct oasis distribution patterns corresponding to the period 1963–2013 in the Heihe River Basin, and the spatio-temporal changes were analyzed. This long-term analysis shows not only the evolution of oases but the extent and degree of the impacts of human activities on the environment in a semi-arid region undergoing socio-economic expansion. This study reveals that expansion was the predominant change exhibited by oases over the last 50 years. The total area of oases exhibited an oscillating increase from 1963 to 1980, moderate increases from 1980 to 2002 and an abrupt increase after 2002, reaching the maximum value of the study period (1963–2013) in 2013 with an area 1.6 times larger than in 1963. Expansion occurred in the arable lands surrounding the established oases and interior patches, thereby constituting "outward extension and inward filling." Oasis development gradually stabilized, with the landscapes becoming more integrated, homogeneous and connected. Four spatial change patterns of "unchanged," "expanding," "shrinking" and "oscillating" were displayed in oasis development, and the oases with oscillating patterns were dominant, whose area accounted for over 50% of total area occupied by oases. In the lower reaches of the Basin, the margins of alluvial–proluvial fans and lower-lying regions that are susceptible to salinization, frequent transformation between non-oasis and oasis occurred. The evolution of oases over the last 50 years was divided into three phases – the unstable stage (1963–1980), the steady development stage (1980–2002) and the rapid expansion stage (2002–2013), which corresponded to the Planned Economy Period, the Commodity Economy Period and the Market-oriented Economy Period – which were defined using socioeconomic indicators. Population, policy and economic interests were found to be the main drivers of oasis change during these periods. In essence, the effort to obtain material benefits under the mediation of policies during an expanding economy plays a crucial role in oasis expansion. These results can provide basic data for regulating oasis exploitation and for the government to use to make strategies for optimizing oasis development and minimizing environmental impact.

Acknowledgements

The Landsat images used in this study were downloaded from the website of the Earth Resources Observation and Science Center. The authors appreciate the help of Lei Lu, an excellent researcher from Lanzhou University, and other native speakers with the improvement of English. Lastly, the authors would like to thank the editor Dr Hugo Asselin, the associate editor Dr Alan Yeakley and anonymous reviewers for their valuable comments on the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research is supported by the National Natural Science Foundation of China [41471163, 91025010] and the 973 Program of China [2009CB421306].

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