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Temporal-Spatial Changes of the Oasis in the Heihe River Basin over the Past 25 Years

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1. Introduction

In China, the arid area occupies a quarter of the total area of the land. It mainly distributes in five provinces: Gansu, Ningxia, Qinghai, Xinjiang and Inner Mongolia. In the arid area, oasis is the special landscape on the background of deserts. It is not only the most centralized area of human activities but also the largest area where human disturbances happen at the regional scale. Oasis covers only 4%–5% of the area of the arid region, whereas they load over 90% of the population and 95% of the social wealth in this area (Li et al., 2007). Therefore, oasis plays very important roles in the economic and social development. In recent 60 years, the artificial oasis of this region kept expanding, as a result, living space of human beings became larger, and the overall productivity and capability were improved as well, which made great contribution to the development of regional economy. However, the ecological environment of the arid area is fragile due to the dry climate, scarce rainfall and short water resource. Consequently, over exploitation on oasis led to imbalanced and unreasonable reallocation of water resource, which further make the local water cycle process changed and finally results in salinization, desertification and wind erosion in other parts (Wang, 2009). If no effective measures are taken, stability of the oasis and sustainable development of the economy in arid area of China will face serious threats.

Britannica Concise Encyclopedia defines oasis as fertile tract of land on the background of a desert where a perennial supply of fresh water is available. Oases vary in size, ranging from about 2.5 acres (1 hectare) around small springs to vast areas of naturally watered or irrigated land (Britannica Concise Encyclopedia, 2006); Wikipedia considers oasis as an isolated area of vegetation in a desert. In this study the oasis particularly refers to the dominated vegetation coverage growing in oasis area in view of the value of ecosystem services and research conveniences.

Remote sensing images have been used as a source of information for detecting land-use and land-cover changes at local, regional, and global scales in recent decades. Many scientists have investigated oasis ecosystem of western China using satellite data and some valuable results have been obtained. Luo (2003) constructed the process of land use/land cover change in the oasis of the arid region using remote sensing imagery data of 1979, 1987 and 1998; Tian (2011) studied the spatial-temporal processes of oasis development in the middle reaches of the Heihe River based on a time series of the normalized difference vegetation index (NDVI) derived from the 16-day composite MOD13A2 data with a spatial

resolution of 1km. These studies used either a few phases' imageries or low spatial resolution data to detect changes of the oasis, but few of them reflected the detailed process of dynamic changes in complete time series.

This chapter selected 8 phases of Landsat TM/ETM images that cover a period of 23 years from 1986 to 2009 to reconstruct the process of temporal and spatial changes of the Heihe oasis in northwest China. In order to separate and extract study object directly and accurately, an improved threshold method was proposed for vegetation extraction, and the characteristics and development laws of oasis were further analyzed and discussed.

2. Study area

The Heihe River is the second largest continental river in China .The Heihe River Basin is the representative in the arid area of northwestern China. It is located between 96°42'-102°00' E and 37°41'-42°42' N, with an area of 128,000 km² approximately. It is one of the areas with the earliest development of irrigating agriculture in the arid area of China, and supports a population more than 1.9×10^6 nowadays. The main stream, with a length of 821 km, originates from the Qilian Mountains of Qinghai Province, flowing through the middle basin called the Hexi Corridor of Gansu Province, and ends in the Juyan Lake, a terminal lake in the desert in the Inner Mongolia Autonomous Region. The runoff from thousands of glaciers, snow and permafrost in the mountainous catchment basically constructs the water resources of the Heihe river basin. Because of its relatively abundant water resource (mean annual runoff is 37.3×10^8 m³), the Heihe River Basin was developed as the important commodity grain base in north-west China. Additionally, it has experienced rapid socioeconomic development and an increase in population density. 95 percent people of the basin are living in agricultural area of the oasis, and approximately 80 percent of them are engaged in husbandry production. However, the extensive exploitation of the water and land resources in the upper and middle parts of the basin has led to a sharp decrease in the water resource in the lower reaches.

Due to the influence of the water resource distribution and human activities, the oasis of Hehei River Basin distributes mainly on the piedmont lower alluvial fan and fluvial plain in the middle reaches of the river. Administratively, this study area includes Zhangye Prefecture-level City (governs six counties named Ganzhou, Shandan, Minle, Gaotai, Linze, and Sunan Yugur Autonomous County), part of Jiuquan Prefecture-level City (governs Suzhou and Jinta County), Jia Yuguan Prefecture-level City and part of Alxa League (governs Ejin Banner) of the Inner Mongolia Autonomous Region. The location of the Heihe River Basin and the approximate range of its oasis are illustrated in Figure 1.

3. Data and methodology

3.1 Data acquisition and processing

Data selection is very important in a spatial-temporal change analysis: the imagery must completely cover the whole study area; the time period should be suitable to capture the change; the images should be obtained during vigorous growing seasons of the vegetation given oases' phenological differences. Therefore, Landsat TM/ETM dataset was selected to detect the oases change, considering its advantages of multi-bands, high spatial resolution, high temporal resolution especially the continuity over years and free availability. 40 cloud-

free images covering the whole basin acquired every 3 or 4 years from 1986 to 2009 were selected and analyzed (Table 1).
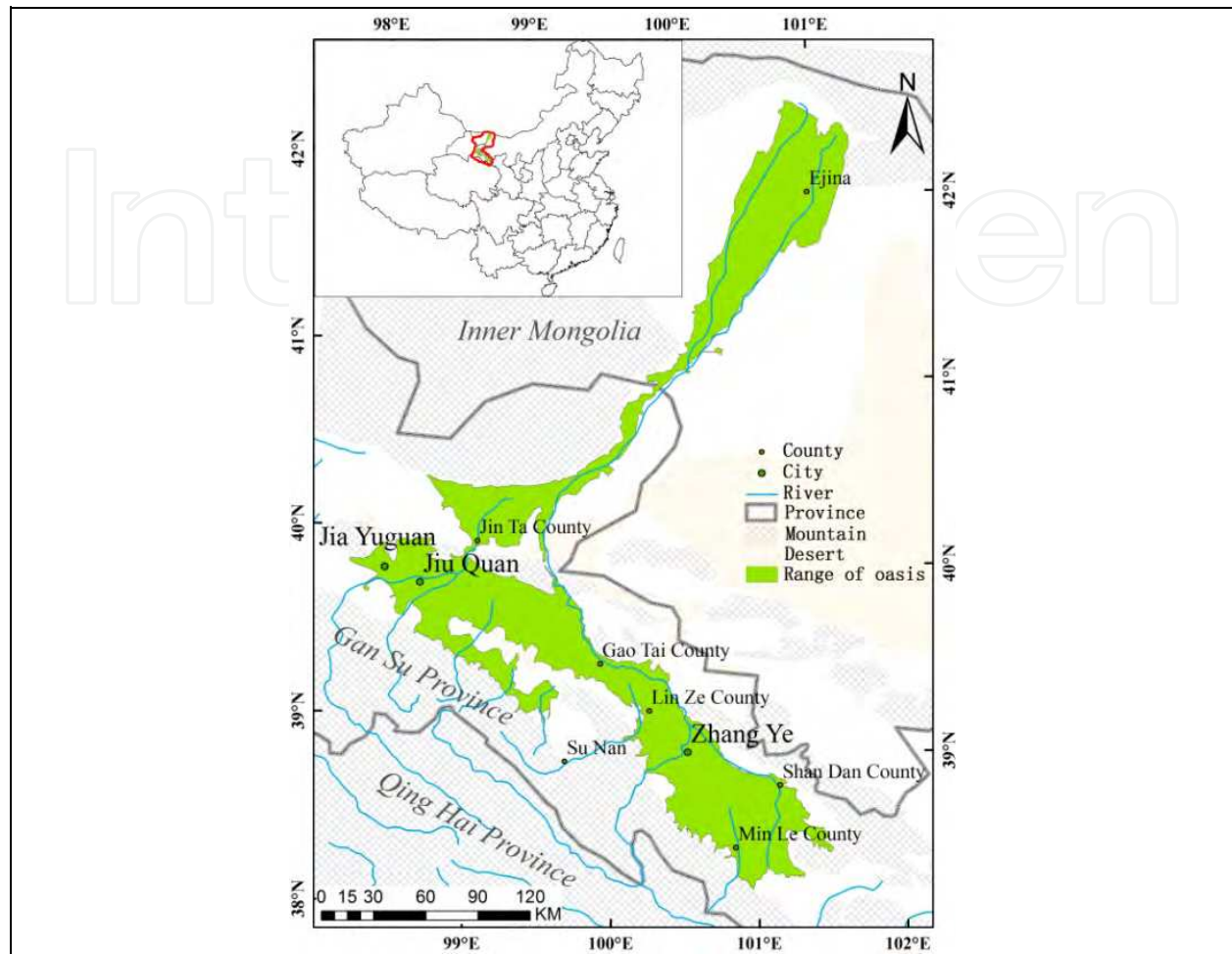

Fig. 1. The location of the Heihe River Basin and the approximate range of its oasis

	133/033	134/031	134/032	134/033	135/032
Landsat TM	09/06/1986	03/08/1986	03/08/1986	18/07/1986	25/07/1986
	23/06/1991	15/09/1990	27/06/1990	27/06/1990	18/06/1990
	12/06/1993	08/06/1993	08/06/1993	08/06/1993	25/07/1992
	23/06/1997	15/09/1996	15/09/1996	15/09/1996	22/09/1996
	23/07/2006	11/09/2006	23/06/2006	23/06/2006	17/08/2006
	24/06/2009	19/09/2009	17/07/2009	17/07/2009	09/08/2009
Landsat ETM	07/07/1999	14/06/2000	30/07/1999	30/07/1999	21/07/1999
	13/06/2002	24/09/2002	23/08/2002	23/08/2002	14/08/2002

Table 1. A list of Selected TM/ETM images

Atmospheric correction of multiple-date remote sensor data is required when the individual data images used in the change analysis algorithm are based on linear transformations of the data. A set of normalized difference vegetation index images were produced for each date in this study, atmospheric correction of multiple-date imageries was performed before image-to-image rigorous registration being conducted. According to the differences on

biophysical and phenological characteristic of the vegetation among the upper, middle and lower reaches of the Heihe River Basin, the images were divided into three parts. 133/033 and 134/033 were combined into a single composite image, 134032 and 135032 were combined into another single composite image.

3.2 Vegetation Index calculation

Since 1960s, scientists have extracted and modeled various biophysical variables of vegetation to provide vegetation information using remotely sensed data. Much of this effort has involved the use of vegetation indices that indicate relative abundance and activity of green vegetation. NDVI (Normalized Difference Vegetation Index) is the most popular vegetation index used to evaluate the variation of surface vegetation at regional and global scales across a range of temporal scales. It is calculated as: NDVI = (infrared - red) / (infrared + red). The ratio reduces many forms of multiplicative noise presenting in multiple bands of multiple-data imagery, such as sun illumination differences, cloud shadows, some atmosphere attenuation and topographic distortions. Seasonal and inter-annual changes in vegetation growth and activity can be monitored using NDVI (John, 2005). The standard MODIS land products include the global 16-day composite NDVI products with a spatial resolution of 500m and 1km respectively (Huete et al., 2002a). Many applications and studies have proven the value of NDVI for vegetation information analysis. Therefore, in this study, NDVI database based on the selected images was constructed for further monitoring vegetation status and dynamic change.

3.3 Threshold method for vegetation extraction

Threshold method is a simple and important form of image segmentation to be widely used in the field of pattern recognition by computer and image processing for gray-level image. It is particularly suitable for specific information and parts of interest extraction. This method takes the difference of gray value between the target objects and the background into account, and determines one or several thresholds of the image on basis of certain principle functions, which each pixel is assigned to one class if its gray value is greater than the determined threshold and otherwise to the other class (Chen & Li, 2006). For remotely sensed images, determining the optimal threshold is a critical task for a large amount of information of the data. At the meantime, this method not only compresses a great amount of data, but also greatly simplifies the analysis and processing steps of the images (Du et al., 2002a).

A great variety of threshold algorithms have been developed in the last few decades (Kittler et al., 2009; Lee & Chung, 1990; Sahoo et al., 1988; Sezgin & Sankur, 2004; Weszka, 1978; Waston, 1987; Yin, 1999). These algorithms can be classified into two types: edge-based algorithms and area-based algorithms (John, 2005), but selecting an appropriate one is difficult. The problem is that independent criteria definition in different algorithms typically produces different results with distinct precision for these algorithms since they make different assumptions about the image. For instance, the famous Otsu's method (Otsu, 1979) is based on a linear discriminant analysis and the recent Kwon's threshold selection method is another technique based on a clustering criterion (Kwon, 2004). These aforementioned typical, simple and relatively effective methods based on criteria pay attention to both the foreground object(s) and the background, and they are affected greatly by proportion of the foreground account in the entire image. At the same time, these methods fail to partially remove noise existing in the background (Chen & Li, 2006).

A new method - the edge weighting method is developed in this study. Normally, the image threshold is supposed to exist in the transition region from the target object to the background. If the gray value in the edge area is obtained, it would become easy to find a suitable threshold according to these gray values. As the edge detective operators are based on differential, they are easily affected by noise or point features (such as outlier). Sometimes the result contains pseudo edges (Li et al., 2006; Yi & Du, 2005), which have a further influence on binarization processing. The fundamental ideas of edge weighting method are as follows: the optimal threshold is supposed to subjectively exist. The average of all gray values obtained by edge detection is set as the critical threshold. Pixels with distinct gray values in the image make different contribution to the optimal threshold: the greater the value of $|\theta - \theta_i|$, the smaller its weight. Therefore, we took the inverse of $|\theta - \theta_i|$ as the coefficient of weight to obtain the binarization threshold of the entire image. The steps can be described as following:

First, edge detection is implemented by using different non-directional operators to obtain the intermediate image. The selected operator is not only helpful for obtaining the position of the edge with easy and good accuracy, but also can largely avoid the loss of interior feature of the objects. Tracking the intermediate image, the position of edge pixels were obtained, and all gray values in the original image of these edge pixels could be found out based on which the mean value marked as θ was calculated. The normalization coefficient can be expressed as:

$$S = \sum_{i=0}^{m} \frac{1}{|\theta_i - \theta|} \tag{1}$$

Where θ_i denotes the gray value on the edge; m represents the number of the different gray values. The weighting coefficient of each pixel is defined as:

$$W_i = \frac{1}{S|\theta_i - \theta|} \tag{2}$$

Finally, add up each different gray value of edge pixels with weighting coefficient and the optimal threshold will be obtained based on statistical characteristic of the image.

4. Oasis reconstruction

4.1 Distribution status of oasis

Using the edge weighting method described above, the oases of sample years were reconstructed. The current oases distribution of the Heihe River Basin is showed in Figure 2. The oases consist of two main parts: the middle reach oases and the low reach oases .They are located in the midst of Hexi Corridor and in Ejin Banner in Inner Mongolia respectively. The oases are distributed in zones along the two sides of the main stream of the Heihe River. According to the administration boundary, the spatial distribution of oases in the Heihe River Basin can be divided into 3 parts: ① Zhangye oasis. The oases are located in the middle of the Heihe River. From the south to the north, the oases include three topographic regions: Qilian Mountain, the central corridor plain and north mountain. The Minle and

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Shandan oasis are in the alluvial and pluvial fan and the natural conditions is relative suitable, hence the oasis is widely distributed with relative large area. The Linze and Gaotai oasis are mainly distributed along the two sides of the Heihe River. ② Jiuquan and Jiayuguan oasis. The oases are located in flat open area in north of Qinlian Mountain, which belong to higher position oasis (Zhang, 2002). ③ Ejin oasis in the low reaches. The oases are located in the west part of Inner Mongolia. It has a transitional zone with desert areas, as a result the distribution of the oasis is scattered. More importantly, it is an important line of ecological defense in the leading edge of West China.

The oases distribution of different years can be seen from Figure3, and it shows the main location of oases changed little since 1986.

4.2 Validation on reconstruction of oasis

The results of oasis reconstruction need to be validated after the work have been finished. According to related studies, different methods were used to verify the accuracy of the interpretation of remote sensing. In this study, field validation was used to verify the oasis reconstruction. The specific process is as following: 1) based on the extracted oasis in 2009, the uncertainty regions of 10%-20% were chosen to validate in the fields; 2) according to the results of the validation, the results of reconstruction were further modified. The points of verification in the Heihe River Basin are shown as Figure 2.
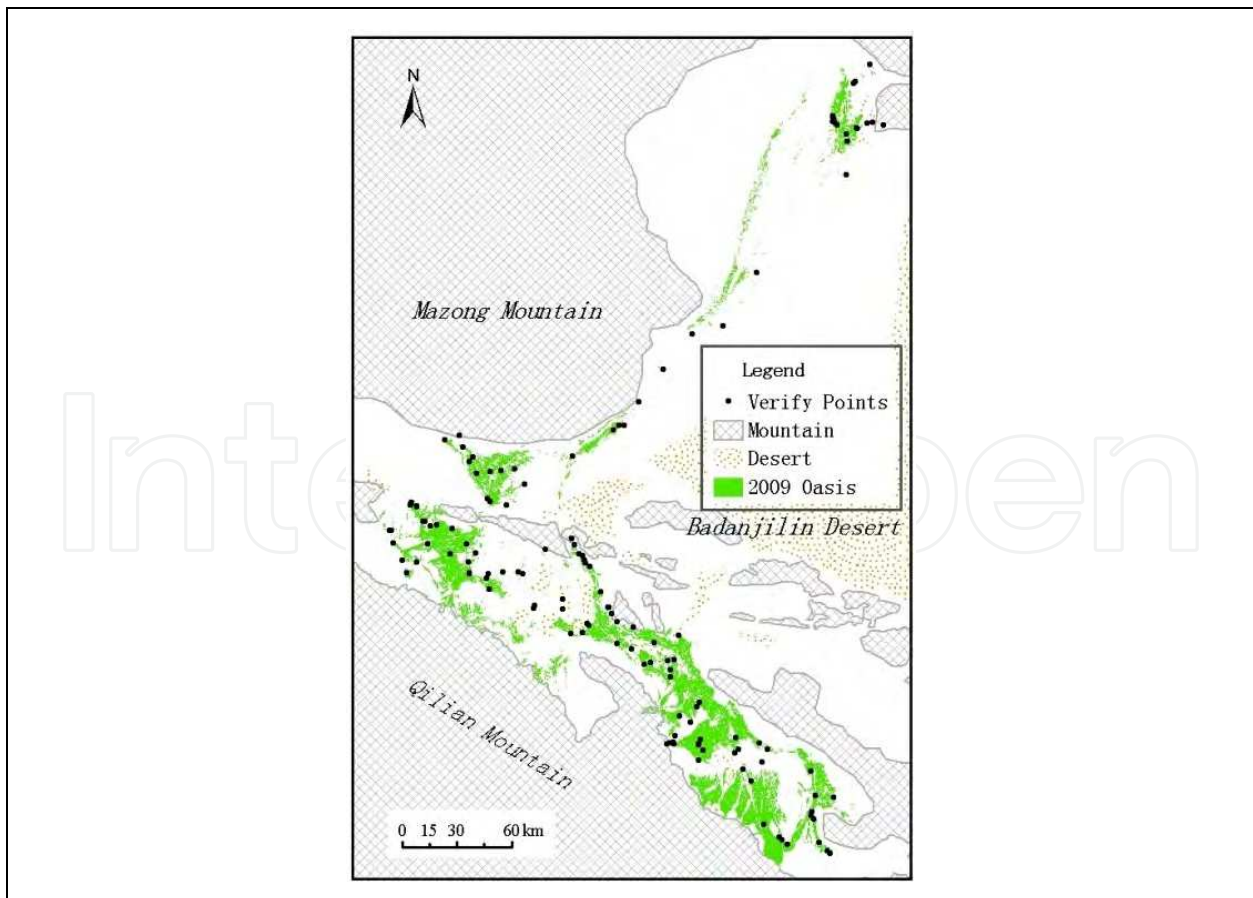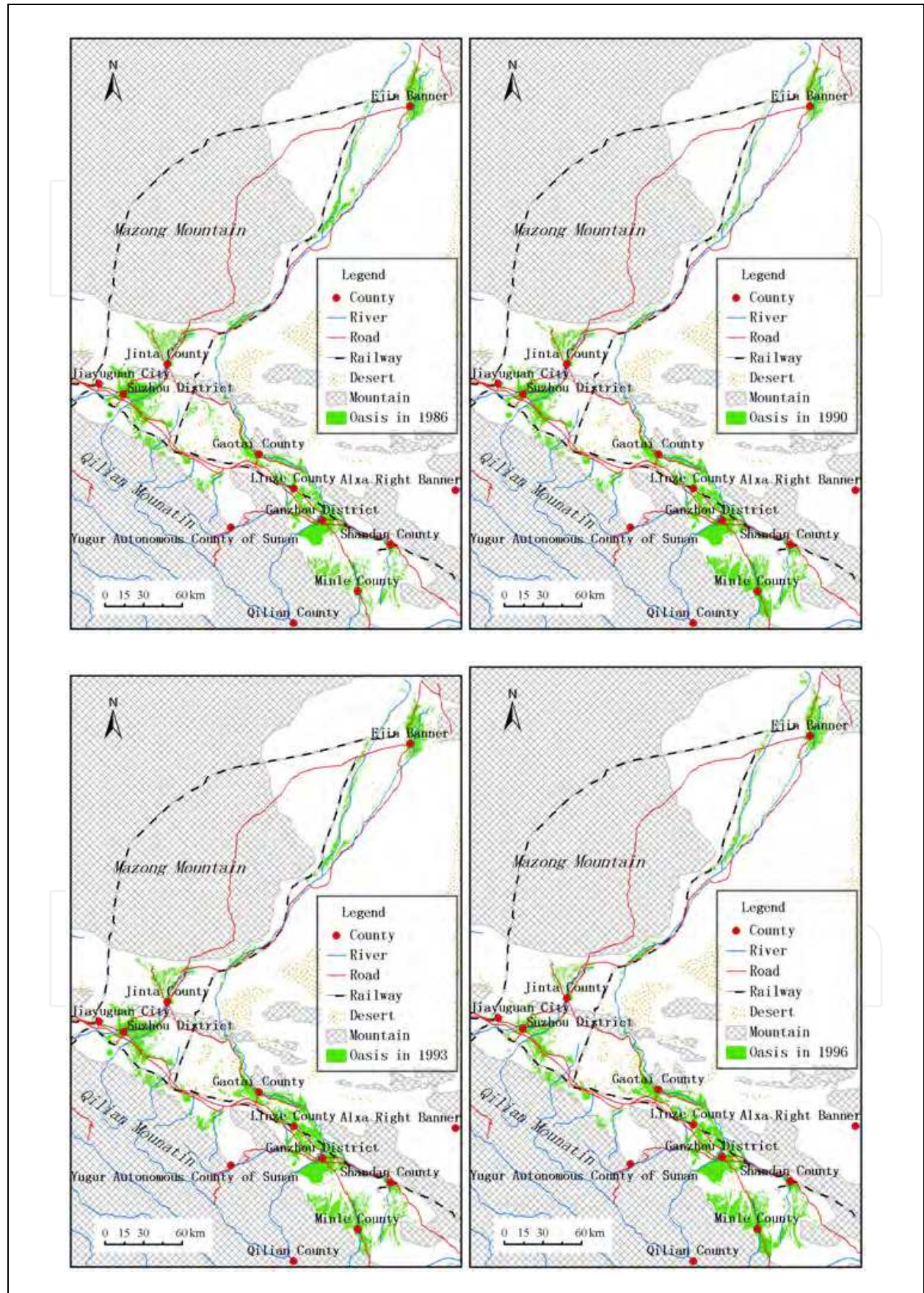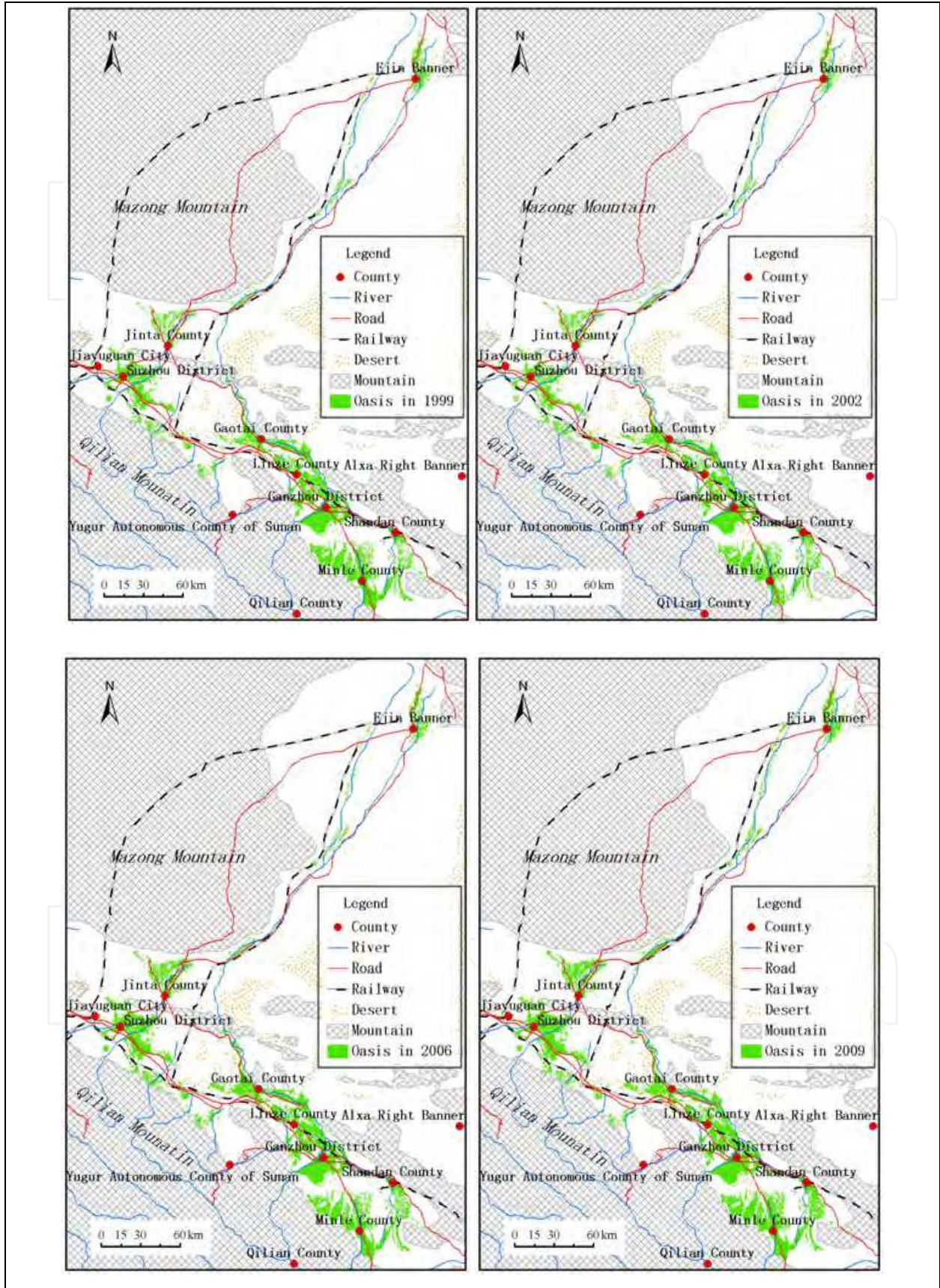

Fig. 2. The validation points in the Heihe River Basin

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Fig. 3. The oases distribution in the Heihe River Basin from 1986 to 2009

5. Analysis of the oasis changes in the Heihe River Basin

5.1 Analysis of the area changes

Based on the results of oasis reconstruction, oasis areas of the total watershed and each county or district were counted using GIS in each period as shown in Table2, and the change curve of area was drawn according to data in Table2 as shown in figure4. As illustrated in Table 2 and Figure 4, oasis expansion is the main trend from 1986 to 2009 in this area, except 1996 and 2002 that had two periods of short-term oasis atrophy. The smallest oasis area was 4526.16 km² in 2002, while the oasis area reached the maximum value of 5581.44 km² in 2009. The change trend of area presented slow decline from 1986 to 2002 in this area, during which a decrease was followed by a trend of increase. The oasis area increased rapidly since 2002, reaching a maximum in 2009.

According to Table 2 and Figure 4, the oasis areas are large in Ganzhou district and Suzhou district, but small in Minle County, Jiayuguan City and Sunan County, and the oasis areas of the rest counties is at an intermediate level. The changes trend is not exactly the same between oasis area in each county / district and total area. The changes of area are acute in Ejin oasis. Overall, the trend of decreasing, shrinking and expansion of oases run concurrently. There is slight change of oasis area in Minle County, Jiayuguan city and Sunan County. The oasis areas in other counties have some fluctuations in some years, but generally the trend of change is consistent with the overall trends.

In order to understand the rate of regional oasis changes and their characteristic differences, the dynamic degree is calculated for each county and district. The dynamic degree model could be mathematically expressed as the following function (Liu, 2000b):

$$k = \frac{U_b - U_a}{U_a} * \frac{1}{T} * 100\% \tag{3}$$

City	County/District	1986	1990	1993	1996	1999	2002	2006	2009
Zhangye	Shandan	243.87	339.78	289.64	341.90	380.67	359.86	383.92	444.76
	Minle	410.57	784.06	636.41	771.92	836.87	734.02	783.09	899.14
	Ganzhou District	890.74	996.12	1019.75	1004.38	1052.66	997.25	1079.18	1113.93
	Linze	325.96	386.27	457.36	411.01	453.93	407.68	486.25	467.21
	Gaotai	402.31	375.58	451.92	405.60	390.52	415.41	487.18	454.08
	Sunan	67.29	17.33	28.77	24.07	19.61	25.38	45.35	52.74
Jiuquan	Suzhou District	973.27	876.18	920.48	717.37	814.45	760.90	926.12	970.01
	Jinta	480.23	408.09	402.40	309.67	368.94	410.06	506.67	586.28
Jiayuguan	Jiayuguan	101.03	80.43	91.17	35.40	70.51	65.60	87.58	102.78
Inner Mongolia	Ejin Banner	770.59	538.67	714.33	689.47	383.67	339.97	342.04	480.37
Total Area		4665.85	4802.50	5012.23	4710.78	4771.82	4516.15	5127.39	5571.28

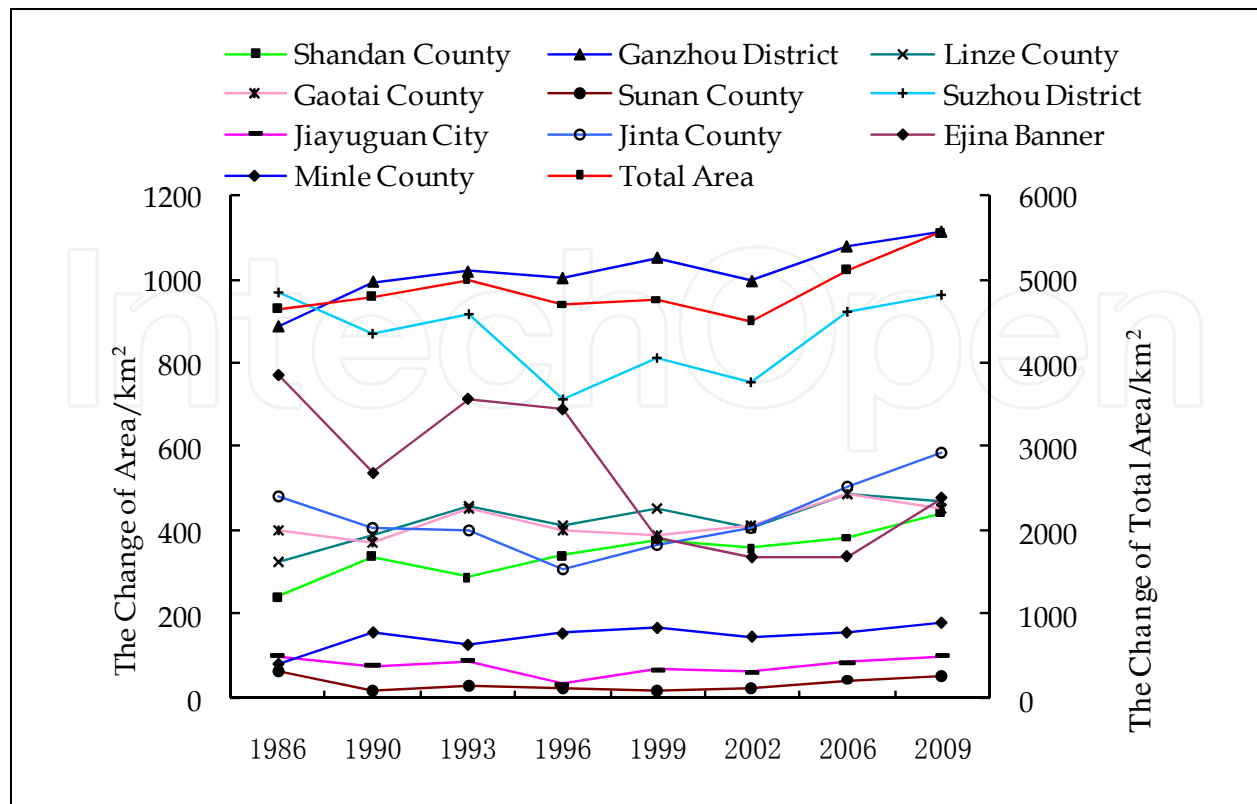Table 2. The oasis area in the Heihe River Basin (unit: km²)

Fig. 4. The oasis area in the Heihe River Basin from 1986 to 2009

Where K is the oasis change rate over time T, U_a is the oasis area at the beginning of the monitoring period, and U_b is the oasis area at the end of the monitoring period .The dynamic degree is thus defined as the time rate of the oasis change that oasis is converted into the desert and that part of the oasis area at the beginning of the monitoring period subjects to change. The dynamic degree represents, in a comprehensive manner, the change of oasis in a given region. The oasis dynamic degree is shown in Table3 and Figure5.

Table 3 and Figure5 indicate that the oasis dynamic degrees are greatly different in different periods. The oasis dynamic degree of Jiayuguan City was the largest compared with that of other counties or districts, which had been increased from -20.39 in 1993-1996 to 33.06 in 1996-1999, indicating that the oasis had severely decreased and increased in these periods respectively. In addition, the oasis dynamic degree was larger in Sunan County, which was -18.56 in 1986-1990 with severe decreasing, and 22.02 in 1990-1993 with severe increase. On the whole, the oasis dynamic degree kept at an intermediate level in other counties, but larger in individual periods. For the whole basin, the oasis dynamic degree maintained a less difference in the Heihe River Basin in all periods, with a gently increase or decrease. Taking the oasis as a complete system, not only the whole oasis system but also part of the oasis should be concerned, because the individual changes which constitute oasis system, could be researched to understand exactly the inner factors of the oasis change. On the other hand, the oasis dynamic degree in the same period remained great difference in all counties. The oasis dynamic degree was up to 22.74 with an extreme increase in Minle County, and -18.56 in Sunan County with an extreme decrease in 1986-1990. The oasis dynamic degree reached the maximum of 22.02 with extreme increase in Sunan County in 1993-1996. The oasis dynamic degree in Jiayuguan city was the largest among all counties in 1996-1999. In

City	County/District	1986-1990	1990-1993	1993-1996	1996-1999	1999-2002	2002-2006	2006-2009
Zhangye	Shandan	9.83	-4.92	6.01	3.78	-1.82	1.67	5.28
	Minle	22.74	-6.28	7.10	2.80	-4.10	1.67	4.94
	Ganzhou District	2.96	0.79	-0.50	1.60	-1.75	2.05	1.07
	Linze	4.63	6.13	-3.38	3.48	-3.4	4.82	-1.31
	Gaotai	-1.66	6.77	-3.42	-1.24	2.12	4.32	-2.26
	Sunan	-18.56	22.02	-5.45	-6.17	9.81	19.67	5.43
Jiuquan	Suzhou Districr	-2.49	1.69	-7.36	4.51	-2.19	5.43	1.58
	Jinta	-3.76	-0.46	-7.68	6.38	3.72	5.89	5.24
Jiayuguan	Jiayuguan	-5.10	4.45	-20.39	33.06	-2.32	8.37	5.79
Inner Mongolia	Ejin Banner	-7.52	10.87	-1.16	-14.78	-3.80	0.15	13.48
Total Dynamic Degree		0.73	1.45	-2.00	0.43	-1.78	3.38	2.88

Table 3. The dynamic degree of the oasis change in the Heihe River Basin from 1986 to 2009 (unit:%)
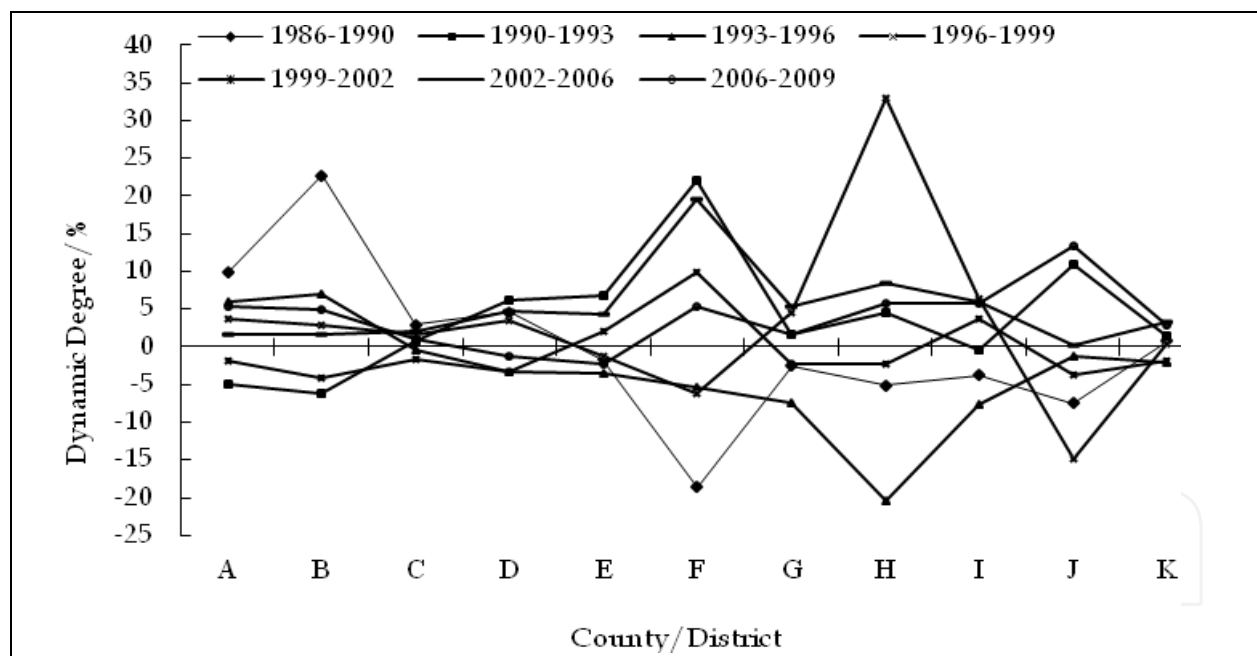
A: Shandan County; B: Minle County; C: Ganzhou District; D: Linze County; E: Gaotai County; F: Sunan County; G: Suzhou District; H: Jiayuguan City; I: Jinta County; J: Ejin Banner; K: Total Dynamic Degree

Fig. 5. The net changes of oasis in the Heihe River Basin from 1986 to 2009

1999-2002, the oasis dynamic degree kept at lower level in all counties, which indicates that the degree of increase or decrease was more gently, and the oasis remained a steady state in a short period. The oasis dynamic degree also kept at lower level in the counties except Sunan County in 2002-2006. From 2006 to 2009, the oasis dynamic degree reached 13.48 with abrupt increase in Ejin oases, while it remained at lower level in other counties or districts.
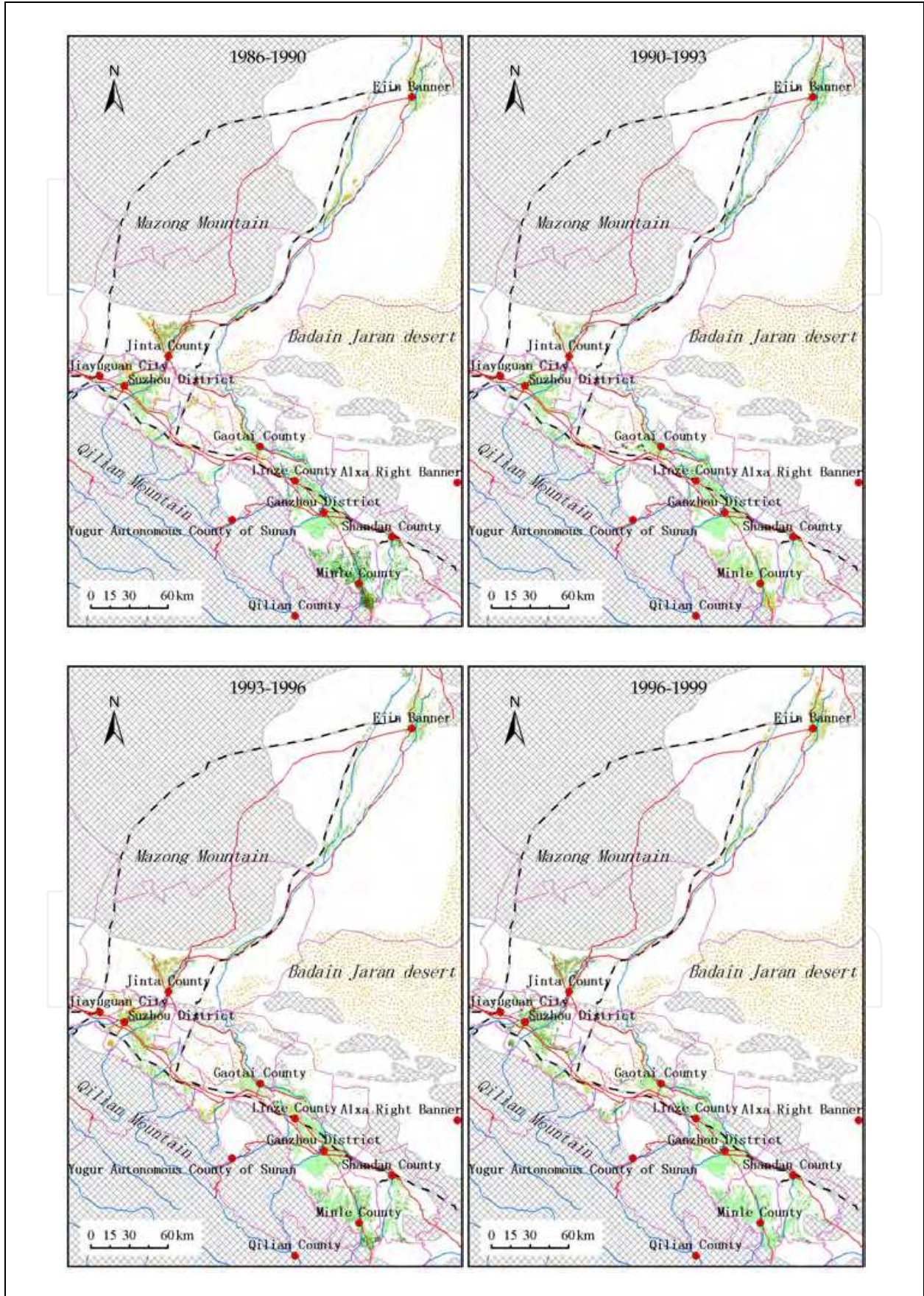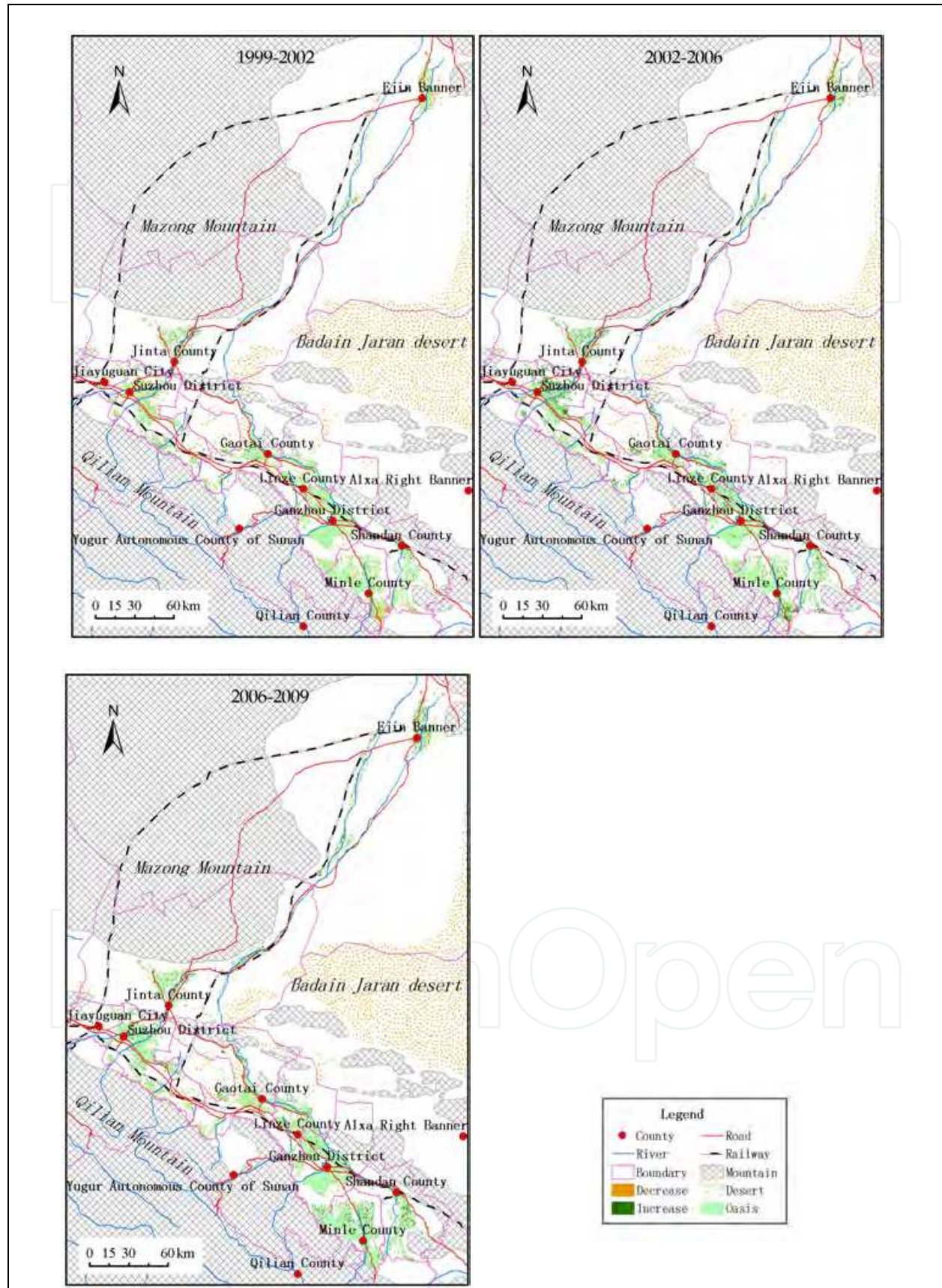
Fig. 6. The maps of oasis change in the Heihe River Basin from 1986 to 2009

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5.2 Analysis of spatial pattern change of the Heihe oasis

Eight maps of oasis distribution between 1986 and 2009 were made using change detection in ArcMap (Figure 6). The areas of changed part were calculated as shown in Table 4 and Figure 7. Table 4 shows that the most outstanding increase of area occurred in 1986-1990 as much as 968.84 km². The most outstanding decreasing area of 935.96 km² occurred in 1993-1996. From 1999 to 2002, the increased area is the smallest (389.38 km²), and between 2002 and 2006 the decreased area is the smallest (313.99 km²). From the point of change trends of the oasis area in the study period, the increase and decrease of area are alternately present as undulate. The decreased area is much larger than the increased oasis area between 1993-1996 and 1999-2002, indicating that the oasis shrunk in both periods. It is clear that the shrinking regions are far more than the expanding regions from the change maps of oasis. The increased areas are greater than the decreased area in other periods, indicating that the oasis expanded in these periods.

	1986-1990	1990-1993	1993-1996	1996-1999	1999-2002	2002-2006	2006-2009
Increase of Area	968.84	735.41	634.52	757.65	389.38	925.23	772.45
Decrease of Area	832.20	525.68	935.96	696.62	645.05	313.99	328.54

Table 4. The change of oasis area in each periods in the Heihe River Basin (unit:km²)
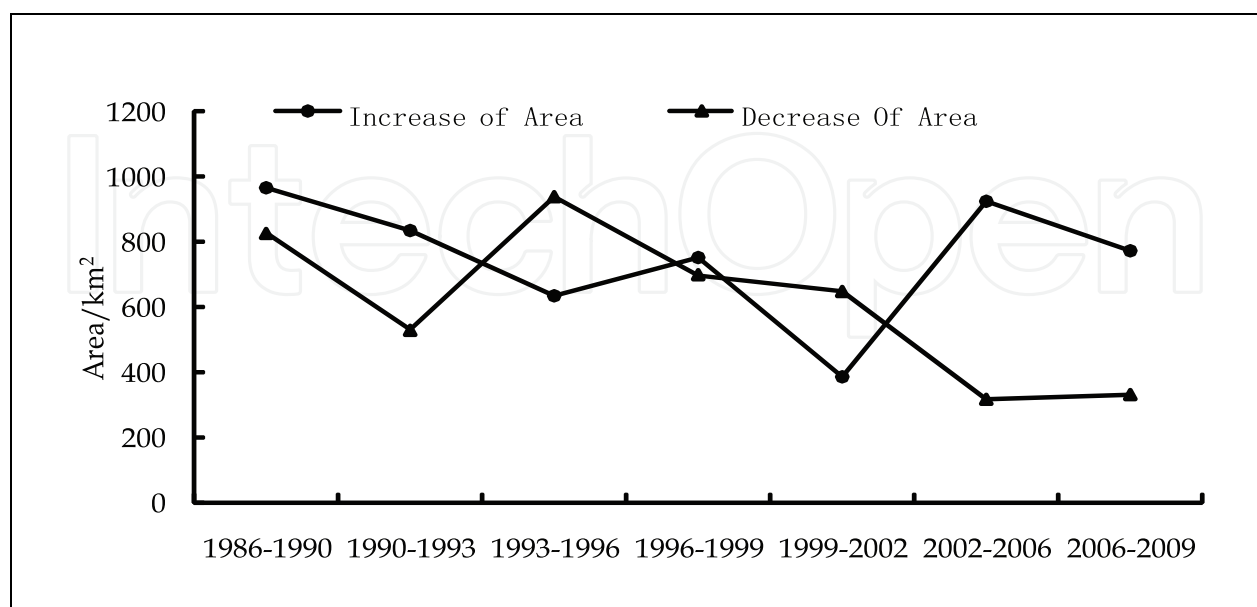

Fig. 7. The change of oasis area in each period in the Heihe River Basin (unit:km²)

From the point of spatial distribution of oasis changes during the last 25 years, the expansion and shrink of oasis have occurred alternately in all counties in the Heihe River Basin. In addition, the intensity of expansion and shrink varied sharply in different periods. Both of expansion and shrink had a distinct regional distribution between 1986 and 1990. The expanding regions mainly concentrated in Minle County, Shandan County, yet more or less expansion appeared in other counties. The shrunk regions mainly concentrated in Suzhou District, Jinta County and Ejin Banner. From 1990 to 1993, both expansion and shrink of oasis presented scattered, the expanding regions were located in Linze County, northern of Gaotai County and Ejin Banner, while the shrink regions were located in Minle County, Shandan County and Jinta County. From 1993 to 1996, the most serious decline of the oasis occurred in Linze County, south of Gaotai County, Suzhou District and Ejin Banner, while little expanding regions presented in Minle County and south of Shandan County. From 1996-1999, the expansion of oasis was the smallest, and its distribution was scattered. There was a little expansion of oasis distribution in all counties except Ejin Banner. The shrunk regions distributed in Gaotai County, north of Jinta County and Ejin Banner, and the shrinking of oasis was most severe in Ejin Banner. From 1999-2002, the shrinking of oasis widely occurred in the Heihe River Basin, but the expansion of oasis only sporadically took place in Shandan County, Gaotai County and Jinta County. The expanding area of oasis in 2002-2006 was the largest of all periods, and the expanding regions were widely located in the whole basin; correspondingly, there were few atrophied regions. From 2006-2009, the expanding area of oasis was also larger and the expanded oases widely distributed in Minle County, Shandan County, Jinta County and Ejina Banner, while the shrinking of oasis mainly took place in Linze County, Gaotai County and the south of Sunan County.

In the whole study area, the regions that the oasis area changes greater mainly distributed at the border of the oasis. For instance, through artificial cultivation, improvement of irrigation system, a large number of deserts with relatively good natural conditions were converted into farmland, woodland, etc. Meanwhile, grassland degradation and desert formation occurred as a result of water shortage and other undesirable condition. In addition, some areas that have no or are short of surface water began to pump groundwater to irrigate the reclaimed wasteland. Disorder exploitation led to rapid decline of groundwater level and strengthened the drought of soil, yet increased abandoned land. Furthermore, the grassland severely degraded due to over-grazing. The factors mentioned above recurred in different research periods. As a result, oasis changes dynamically between expansions and shrink in the study area.

6. Conclusion

This study discussed the spatial and temporal processes and characteristics of oasis changes in the Heihe River Basin between 1986 and 2009. The following conclusions can be obtained:

First, expansion was the main trend of oasis change in the Heihe River Basin from 1986 to 2009, except the period from 1996 to 2002 in which the oasis shrunk shortly. From 1986 to 2002, the oasis area experienced a process of gentle increasing and then decreasing

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process. After 2002, an abrupt increase appeared and reached the top in 2009. The oasis area reached the maximum value as 5581.44 km² in 2009 and minimum value as 4526.16 km² in 2002.

Second, the changes of oasis dynamic degree were great different in all counties over the past 23 years. The oasis expanding and shrinking occurred in all counties, and both of them alternatively occurred in each county.

Third, the intensity of expansion and shrinking varied in different periods. It indicates that the all oases in the Heihe River Basin are a whole and there is interrelationship existed. However, there are still questions such as the change reasons remaining unclear and further analysis is expected to be made in the future.

Final, the edge weighting method is an efficient way to reconstruct the oasis changes over past decades, which not only makes the reconstruction easier, quick, automatic, but also the results more objective and accurate.

7. Acknowledgment

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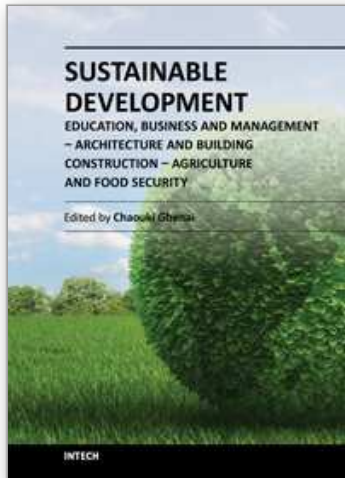
Securing the future of the human race will require an improved understanding of the environment as well as of technological solutions, mindsets and behaviors in line with modes of development that the ecosphere of our planet can support. Some experts see the only solution in a global deflation of the currently unsustainable exploitation of resources. However, sustainable development offers an approach that would be practical to fuse with the managerial strategies and assessment tools for policy and decision makers at the regional planning level. Environmentalists, architects, engineers, policy makers and economists will have to work together in order to ensure that planning and development can meet our society's present needs without compromising the security of future generations. Better planning methods for urban and rural expansion could prevent environmental destruction and imminent crises. Energy, transport, water, environment and food production systems should aim for self-sufficiency and not the rapid depletion of natural resources. Planning for sustainable development must overcome many complex technical and social issues.

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