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Effects of human activities on the eco-environment in the middle Heihe River Basin based on an extended environmental Kuznets curve model

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A B S T R A C T

With rapid socio-economic development over the past three decades in China, adverse effects of human activities on the natural ecosystem are particularly serious in arid regions where landscape ecology is fragile due to limited water resources and considerable interannual climate variability. Data on land use, surface and ground water, climate, gross domestic product (GDP) per capita from the middle Heihe River Basin were used to (i) examine changes in water consumption, land use composition, and vegetation cover; (ii) evaluate the effectiveness of short-term management strategies for environmental protection and improvement, and (iii) apply and extend the environmental Kuznets curve (EKC) framework to describe the relationship between economic development and environmental quality in terms of the normalized difference vegetation index (NDVI). The results showed that with rapid development of agriculture and economy, land use change for the period 1986–2000 was characterized by the expansion of constructed oases, considerable contraction of oasis-desert transitional zone and natural oases. This has led to a decrease in ecosystem stability. Since 2001, effective basin management has brought about improved environment conditions, with a more optimal hierarchical structure of vegetation cover. The original EKC model could not explain most of the observed variation in NDVI ($R^2 = 0.37$). Including additional climate variables, the extended EKC model to explain the observed NDVI was much improved ($R^2 = 0.78$), suggesting that inclusion of biophysical factors is a necessary additional dimension in the relationship between economic development and environmental quality for arid regions with great climate variability. The relationship between GDP per capita and NDVI, with the effect of precipitation and temperature taken into consideration, was adequately described by an N-shaped curve, suggesting that the relationship between society and the environment followed a process of promotion, contradiction, and coordination.

1. Introduction

The human activities and climate change have interacted synergistically to impact the relationship between social and ecological systems in the late twentieth century (Steffen et al., 2005). The complex interactions between social and ecological systems have fundamentally changed in China during the past several decades. The impacts of human activities on natural ecosystem are especially serious in arid areas where landscape ecology is very fragile due to limited water resources (Luo and Zhang, 2006). The Heihe River Basin is one of the largest arid inland river basins in northwest China, where oases evolve as a result of opposite processes of oasification and desertification (Zhang et al., 2003; Su et al., 2007). The landscape composition, the spatial pattern or distribution of oases, desert and oasis-desert transitional zone are known as the 'eco-circle level structure', and this notion of a structure of ecological relevance at a large scale can be used as an indicator of ecosystem stability to identify the processes of oasification and desertification based on the relative abundance of oases, desert and oasis-desert transitional zone at the basin or regional scales (Zhang, 2009, 2010). During the period from the 1970s to the 1990s, the ecosystem changed greatly in the Heihe River Basin because of over-exploitation of water and land resources for agricultural and economic development, leading to changes in the eco-circle level

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structure, with decreased ecosystem stability (Chen et al., 2004), and serious eco-environmental problems (Wang and Cheng, 1999). In 2001, short-term management programs were implemented to cease any new land reclamation for agricultural use, improve agricultural water use efficiency, and convert some farmland back to forest and grassland. This integrated water resources management and regulation system has so far brought about positive environmental outcomes for the region (Wu and Tang, 2007). Therefore, it is very important to recognize the impacts of human activities on the eco-circle level structure at a basin scale and the environmental quality at a local scale in different periods, to identify and explain factors and processes that drive the environmental change in the Heihe River Basin, and to provide support for decision making in terms of long-term strategies for environmental protection.

Much research has been undertaken to investigate the eco-circle level structure, land use/cover and environmental change, and the impacts of natural factors and human activities in arid regions based on remote sensing and GIS technology (e.g. Shoshany, 2000; Ayad, 2005), especially since the Implementation Strategy of the Land-Use and Land-Cover Change (LUCC) project was published in 1995 (Nunes and Auge, 1999). In China, research has been concentrated in the inland arid area of northwest China (e.g. Lu et al., 2003; Zhao et al., 2011). Using a model for inland eco-circle level structure with water as the critical input, Chen et al. (2004) analyzed mechanism for and characteristics of changes in ecosystems in arid regions, indicating that use of water and land resources would significantly impact the ecosystem stability. The significant positive correlation between NDVI (normalized difference vegetation index) and precipitation demonstrated that climate variability and change could play an important role in the environment variability in arid and semi-arid regions (Li et al., 2003). However, Kong et al. (2010) investigated vegetation change and environmental drivers in the Tarim River Basin, and the results indicated that environmental factors only contributed to a small proportion of vegetation-related land cover change and the influences of expanding agricultural activities were the main causes of land cover change in arid regions. Dai et al. (2010) also showed that the natural vegetation change was influenced not only by climate change, but also human activities which significantly changed the planted vegetation based on correlation analysis of NDVI and driving factors over northwest China.

All the research has contributed to ecological system study in arid regions of northwest China. However, there were few comprehensive studies in the Heihe River Basin, especially in the middle Heihe River Basin, where advanced irrigation agriculture and intensive human activities have resulted in an over-exploitation of water and land resources, leading to serious eco-environmental problems in the Middle and Lower Basin. To improve the environmental quality, short-term management programs were first implemented in the middle Heihe River Basin. Thus, the middle Heihe River is one of the ideal regions in the inland arid area to demonstrate the relationship between society and the environment. The impacts of human activities on the ecosystem in the middle Heihe River Basin are still largely unclear and there is a lack of quantitative analysis of the interactions between socioeconomic and biophysical processes at the basin scale. Acceleration of urbanization process has led to serious deterioration of the ecosystem in the Heihe River Basin in the late twentieth century (Meng et al., 2005) and the eco-environment has been greatly improved with implementation of short-term management programs since 2001 (Ding et al., 2011). Therefore, it is important to quantify the effectiveness of management strategies to ameliorate the adverse effects of human activities on the ecosystem in the middle Heihe River Basin.

The environmental Kuznets curve (EKC) presents a hypothetical relationship between economic development and environmental outcome (Grossman and Kreuger, 1991, 1995; Chowdhury and Moran, 2012). While the economic development is commonly measured in terms of the income per capita, a multiple of indicators of environmental degradation such as the level of air or water pollution have been used as a measure of the environment outcome from economic development (Shafik and Bandhopadhyay, 1992; Grossman and Kreuger, 1995). The relationship between economic growth and environmental quality can be very complicated, and has been a source of great controversy (Shafik, 1994). Moreover, the EKC model may represent an N-shaped, an inverse N-shaped, a U-shaped, an inverse U-shaped or even a linear relationship (Canas et al., 2003), showing multiple relationships at different stages of economic development and at different spatial scales (Chowdhury and Moran, 2012). There is broad empirical support for the existence of EKC for various pollution indicators or vegetation cover to explain the development–environment relationship (Foster and Rosenzweig, 2003; Shen, 2006; Jalil and Mahmud, 2009). Li et al. (2013) tested the relationship between population growth and vegetation cover in 21 cities in Guangdong Province, China, the results show that there is a long-term inverted N-shaped relationship between population growth and vegetation cover, indicating that population increase with urbanization may have a negative or positive impact on the vegetation cover at different stages of development because of the intensive human activities. However, the current EKC model has not considered natural factors in determining vegetation change as a measure of environmental quality. As the human activities have multiple effects on the environment in the middle Heihe River Basin in different stages of economic development, and climate variability and change are strongly correlated with vegetation variability in the arid region (Zhao et al., 2011), we propose an extended EKC model to include anthropogenic and natural factors for a general explanation of the dynamic relationship between regional development and environmental quality for the middle Heihe River Basin.

Our research had three objectives. The first objective was to analyze the changes in the ecosystem under the influence of intense human activities based on changes of land use and the eco-circle level structure between 1986 and 2000 in the middle Heihe River Basin; the second objective was to assess the effects of short-term management strategies in terms of the spatiotemporal variations of vegetation cover in the Zhangye–Linze–Gaotai basin as an example; and the third objective was to develop an extended EKC model to explore the driving mechanism of the environmental changes for possible future projections, taking into consideration both natural and social-economic factors.

2. Materials and methods

2.1. Study area

The middle Heihe River Basin, between the Yingluo Gorge and Zhengyi Gorge stream gauging stations, is located in the central part of the Hexi Corridor, between 98°20′–102°12′E and 37°57′-40°03′N (Fig. 1), with a total area of 2.61×10^4 km^2. The middle Heihe River Basin has a number of administrative districts, including Ganzhou District, Gaotai County, Linze County, Shandan County, Minle County, a part of Sunan County of Zhangye City, Jiayuguan City, and Suzhou District of Jiuquan City. The study area has a temperate continental arid climate with adequate sunlight and infrequent occurrence of precipitation. The mean annual precipitation is only 140 mm and more than half of it occurs in summer months (May–September). The mean potential evapotranspiration in the region is about 1000–2000 mm yr^{-1} (Wang et al., 2007). The area has an unbroken irrigation agricultural history since the

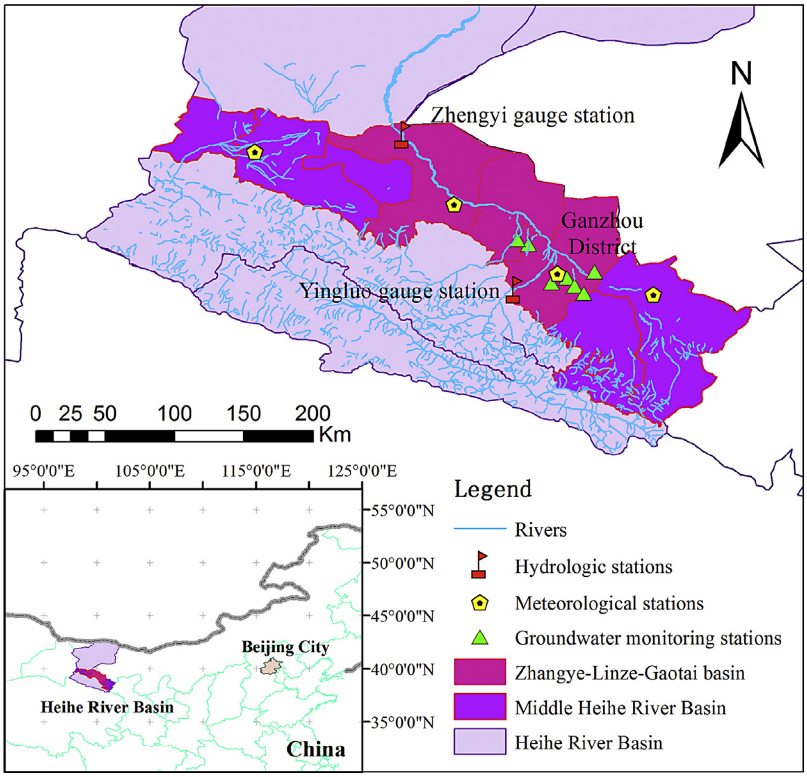

Fig. 1. Location map of the study area, including the Heihe River Basin, the middle Heihe River Basin and the Zhangye–Linze–Gaotai basin.

Han dynasty, and is the main commodity grain base in the Hexi Corridor. Zhangye City has been widely known as the "Golden Zhangye" since ancient times (Meng et al., 2003). However, the past 30 years have witnessed the most rapid development of agriculture and economy in the middle Heihe River Basin, accompanying with significant eco-environmental changes. From 1980 to 2010, the population increased from 1.37million to 1.92 million, and GDP increased enormously from 0.49 billion RMB per annum to 51.87 billion, an increase of more than 100 times (Editorial Board of Gansu Yearbook, 1981, 2011).

2.2. Data sources and processing

In this study, most of the data sets were provided by Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn), including the GIMMS AVHRR NDVI (Normalized difference vegetation index) (1982–2006), SPOT VEGETATION NDVI (1998–2008), land use/cover data of the Heihe River Basin in 1986 and 2000, daily streamflow data of the Yingluo and Zhengyi Gorge gauging stations, groundwater data in the middle Heihe River Basin. In addition, meteorological data (precipitation and temperature) were downloaded from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn), and economic data (GDP and population) in Gansu province were derived from "Comprehensive Statistical Data and Materials on 60 Years of New China".

The GIMMS AVHRR NDVI products, at 15-day interval with 8 km ground resolution, were processed to obtain an annual time series of NDVI, which were used to develop the extended EKC model. The SPOT VEGETATION NDVI products, at 10-day interval with 1 km ground resolution, were transformed into vegetation cover, using the method of vegetation fraction estimation (Li, 2003). Then, the maximum, average, and growth season average vegetation cover was calculated to analyze the eco-environmental changes in the 2000s.

The land use/land cover data were processed using GIS to analyze land use patterns in 1986 and 2000. Moreover, the eco-circle level structure was analyzed on the basis of the land use data. Natural oases include forest land, shrubbery, sparse woodlot, high cover grassland, medium cover grassland, lake, permanent glaciers, beaches and flats, and wet land; constructed oases include other woodland, irrigation canals and ditches, reservoirs, pond, urban land, rural settlement and other land for construction; oasis-desert transitional zone mainly refers to low cover grassland; and the desert includes sandy land, Gobi, saline-alkali land, bare land, exposed rock, shingle land.

The annual streamflows of the Yingluo Gorge and Zhengyi Gorge gauging stations were accumulated from daily data. The annual precipitation data were derived from daily precipitation data and averaged from four meteorological stations (Zhangye, Gaotai, Jiuquan, Shandan), the annual temperature data were spatial and temporal averages processed from the downloaded temperature data. The annual GDP data were accumulated from GDP data for individual administrative districts in the middle Heihe River Basin.

2.3. The EKC model and its extension

The relationship between GDP per capita and some measure of environmental quality is known as the environmental Kuznets curve (EKC). As previously explained, this relationship between economic growth and environmental quality is not monotonic and may present different shapes. A cubic function can be applied to describe the complicated relationship, and the parameter values associated with the cubic function define the shape of the curve (Martı′nez-Zarzoso and Bengochea-Morancho, 2004). Generally, GDP per capita is the independent variable, as a measure of economic growth, and the dependent variable can be diverse, including

Table 1
Parameter values of the environmental Kuznets curve and the implied relationship between environmental quality and economic growth.

β_1	β_2	β_3	Interpretation
>0	=0	=0	A monotonically increasing linear relationship
<0	=0	=0	A monotonically decreasing linear relationship
<0	>0	=0	A U-shaped relationship
>0	<0	=0	An inverse U-shaped relationship
>0	<0	>0	An N-shaped relationship
<0	>0	<0	An inverse N-shaped relationship
=0	=0	=0	A level relationship

indicators of environmental pollution or vegetation status, such as pollution emissions or vegetation cover. Moreover, the variables can be pretreated with linear or natural logarithm transformations (Stern et al., 1996), they are all effective in supporting the existence of the EKC between economic development and environmental quality. The original EKC model is given by:

$$E_{it} = \alpha_i + \beta_1\left(\frac{GDP}{P}\right)_{it} + \beta_2\left(\frac{GDP}{P}\right)^2_{it} + \beta_3\left(\frac{GDP}{P}\right)^3_{it} + u_{it} \qquad (1.a)$$

or

$$\ln E_{it} = \alpha_i + \beta_1 \ln\left(\frac{GDP}{P}\right)_{it} + \beta_2\left(\ln\left(\frac{GDP}{P}\right)\right)^2_{it} + \beta_3\left(\ln\left(\frac{GDP}{P}\right)\right)^3_{it} + u_{it} \qquad (1.b)$$

where E represents the pollution emissions (e.g. atmospheric CO_2, SO_2, NO_x emissions and waste water discharge) per capita or vegetation cover; P stands for the total population and GDP is the gross domestic product. The specification is usually estimated on panel data with i refers to the different regions and t refers to the different time, α_i is the individual specific intercept of region i, and u_{it} is a stochastic error term (Auci and Becchetti, 2006). The parameters β_1, β_2 and β_3 define the shape of the functional relationship between economic growth and environmental quality (Table 1) (Song et al., 2008), and the shape can vary depending on selection of the study period, the study area, and indicators of the environmental quality. The 3 shape factors depend on the effect of GDP/P on environmental equality during a certain period. We may expect that the sign of β_1, β_3 to be positive and β_2 to be negative when the EKC exists. However, the eco-environment in the study area was affected by both social and biophysical factors, and the model above only considers social factors, i.e. the GDP per capita, but does not include any biophysical factors. We hypothesized that in this arid environment, biophysical variables, such as the temperature, precipitation, streamflow could be just as important in determining the environmental quality as measured by NDVI in this paper. Thus, we extended the EKC model to include climate and water resources variables. These variables are assumed to affect the growth of vegetation, NDVI, hence the environmental quality. The extended EKC model for the middle Heihe River Basin can thus be written as:

$$NDVI_t = \alpha + \beta_1\left(\frac{GDP}{P}\right)_t + \beta_2\left(\frac{GDP}{P}\right)^2_t + \beta_3\left(\frac{GDP}{P}\right)^3_t + \beta_4 CLM_t + \beta_5 WR_t + u_t \qquad (2)$$

where CLM_t is a proxy for climate factors, such as annual average temperature; WR_t is a proxy for water resources, such as annual precipitation or streamflow; and the other parameters are the same as described above. As we considered the middle Heihe River Basin as a single region for the purpose of EKC modeling, the subscript, i, is no longer required.

Furthermore, we may highlight the effects of human activities on the variation in NDVI by removing the effects of natural factors from Eq. (2). We can then derive an adjusted $NDVI^{(-)}$ as follow:

$$NDVI^{(-)}_t = NDVI_t - \beta_4 CLM_t - \beta_5 WR_t = \alpha + \beta_1\left(\frac{GDP}{P}\right)_t + \beta_2\left(\frac{GDP}{P}\right)^2_t + \beta_3\left(\frac{GDP}{P}\right)^3_t + u_t \qquad (3)$$

The turning points of economic development in terms of GDP per capita can be computed as:

$$\phi_1 = \frac{-\beta_2 - \sqrt{\beta_2^2 - 3\beta_1\beta_3}}{3\beta_3}, \quad \phi_2 = \frac{-\beta_2 + \sqrt{\beta_2^2 - 3\beta_1\beta_3}}{3\beta_3}$$

If the parameters satisfy $\beta_1 > 0$, $\beta_2 < 0$, $\beta_3 > 0$, the EKC reveals an N-shaped relationship (Table 1), and ϕ_1 is the turning point of local maximum NDVI, ϕ_2 the turning point of local minimum NDVI. The three stages separated by ϕ_1 and ϕ_2 describe the periods when GDP per capita changes have different effects on how NDVI varies with economic development with the adjusted $NDVI^{(-)}$. As a result, the eco-environmental changes and their driving mechanism from human activities could be accentuated and examined specifically for different periods of development.

3. Results and discussion

3.1. Spatiotemporal distribution of water resources

Characteristics of and trends in the annual flows of the Heihe River were analyzed using the streamflow data recorded at the Yingluo Gorge and Zhengyi Gorge gauging stations over a 54-year period (1957–2009). The two stations separate the middle Heihe Basin from its upper part and lower part, respectively (Fig. 1). As the precipitation over the middle part of the Heihe River Basin is very low, the reduction in the annual flow between the two locations is broadly related to the annual water abstraction and consumption along the middle reach of the Heihe River (Nian et al., 2013). In this paper, the difference in the annual runoff volume was taken to approximate the annual water extraction from surface runoff for consumption in the middle Heihe River Basin.

The long-term average surface water consumption was 6.02×10^8 m^3 per annum over the 54 years, or 37% of the mean annual streamflow at the Yingluo Gorge. As can be seen in Fig. 2, there was a significant increase (p-value <0.01) of surface water consumption in the middle Heihe River Basin in the 1980s, averaging 6.9×10^8 m^3 per annum, or about twice as high as in the 1970s. The increasing trend continued into the 1990s, up to 8.0×10^8 m^3 per annum. In the 2000s, the surface water consumption started to level off with some variations at about 6.9–9.3 $\times 10^8$ m^3 annually. Correlation between the streamflows at the Yingluo Gorge

Table 2
Changes in the eco-circle level structure from 1986 to 2000. (Ecological area includes total oases and oasis-desert transitional zone).

	Natural oases (km^2)	Constructed oases (km^2)	Total oases (km^2)	Oasis-desert transitional zone (km^2)	Desert (km^2)	Ecological area/total area	Oases/ecological area	Constructed oases/oases
1986	2384	4593	6977	3205	11,438	0.471	0.685	0.658
2000	2294	4868	7162	3029	11,429	0.471	0.703	0.680
Change between 1986 and 2000	−3.8%	6.0%	2.7%	−5.5%	<0.1%	–	–	–

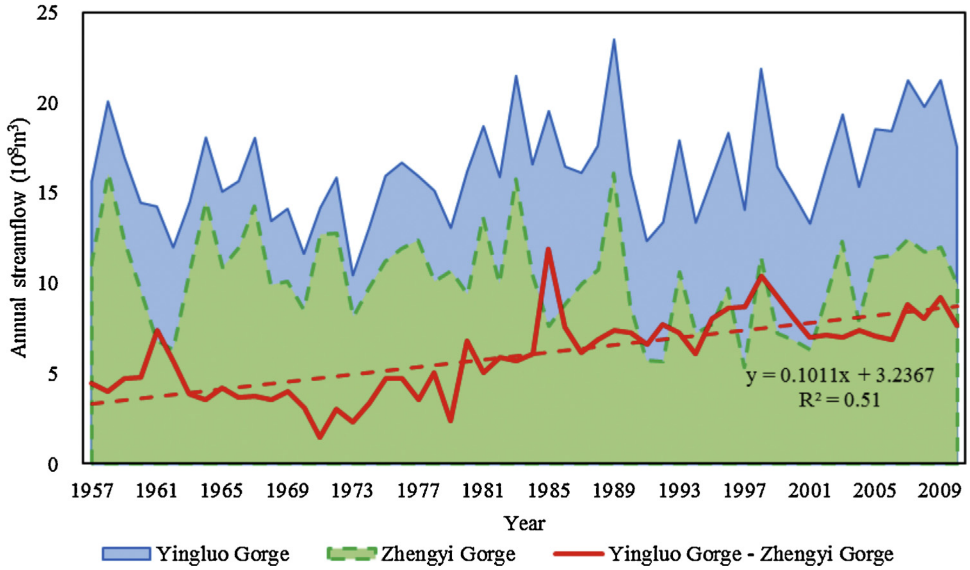

Fig. 2. Time series of annual streamflow of the Heihe at Yingluo Gorge (upstream) and Zhengyi Gorge (downstream), and the difference to approximate the transmission loss and water abstraction in the middle Heihe River Basin (1957–2010).

and the Zhengyi Gorge shows that the streamflow at the Zhengyi Gorge has decreased steadily as a result of extraction of surface runoff for consumptive water use. For the same annual streamflow at the Yingluo Gorge, the annual flow at the Zhengyi Gorge decreased by about 2.5×10^8 m^3 from 1957–1979 to the 1980s, and by about 1.5×10^8 m^3 from the 1980s to the 1990s (Fig. 3). However, not only has the streamflow at the Zhengyi Gorge increased in the 2000s compared to that in the 1990s, but also the correlation between annual streamflows at the two gauge stations became stronger ($R^2 = 0.92$ for the 2000s, and $R^2 = 0.83$ for the 1990s) (Fig. 3). Stronger correlation and tighter relationship between these two streamflow stations indicate a more regulated and managed system for water abstraction in the 2000s. This occurred largely because of a short-term management strategy for water resources planning and allocation for the middle Heihe River in the 2000s (Wang et al., 2004).

In addition to the increased water abstraction from surface runoff, concurrent extraction of groundwater resources has also been increasing since the 1980s. The declining trend of groundwater levels in the Ganzhou district is clear, where the depth to groundwater at 7 monitoring stations shows persistent increase ranging from 5.32–12.85 m (Fig. 4). Groundwater resources are depleting, and the rate of depletion has accelerated in recent years. For the period from 1980 to 1992, the rate of depletion varied from

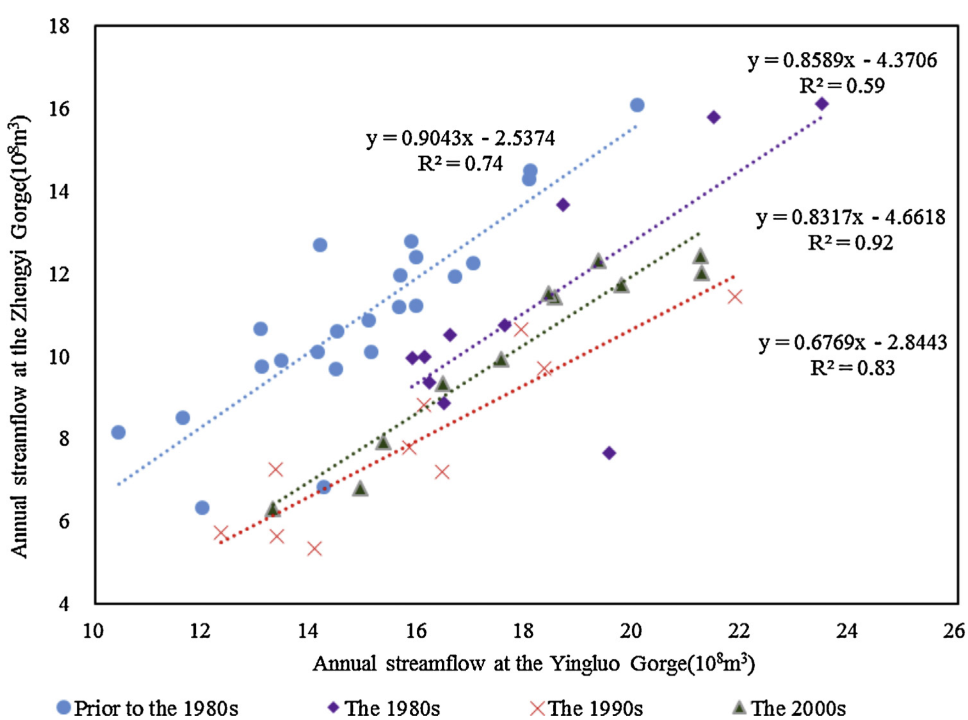

Fig. 3. Relationship between annual streamflows of the Heihe at Yingluo Gorge (upstream) and Zhengyi Gorge (downstream) (1957–2010).

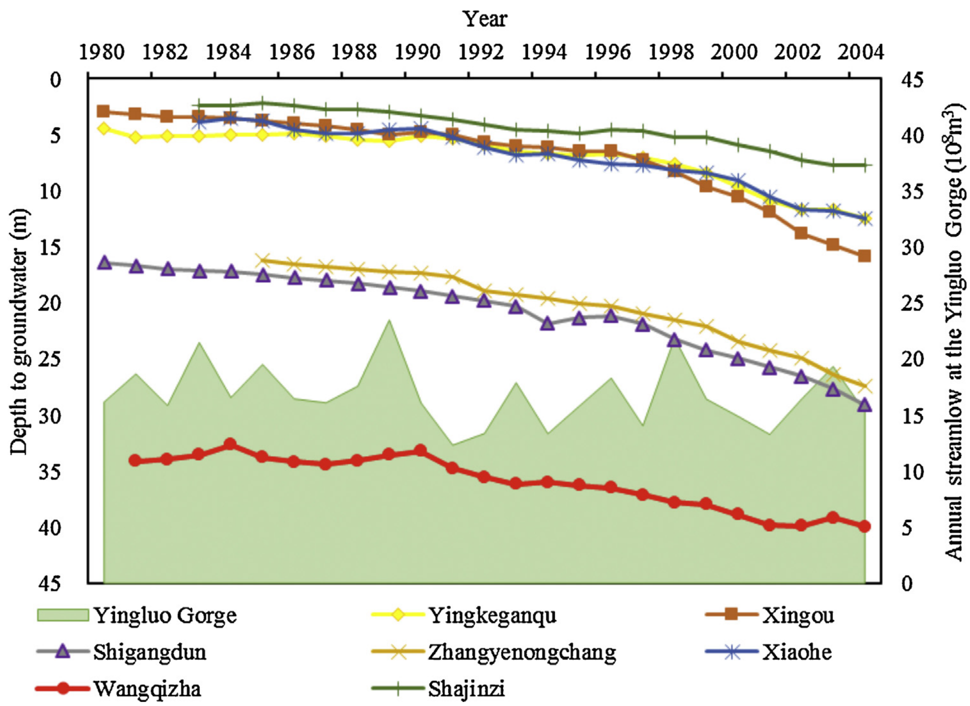

Fig. 4. Annual depth to groundwater at 7 monitoring stations in the Ganzhou district, and the annual streamflow at the Yingluo Gorge (upstream).

0.09 m yr^{-1} to 0.31 m yr^{-1} among these 7 stations; for the 13 years since (1992–2004), the rate depletion has increased to 0.31 m yr^{-1} to 0.89 m yr^{-1}.

In the 1990s, traditional flood irrigation was the main irrigation method, water was delivered mostly through main canals, branch canals, tertiary canals, the water delivery efficiency was 0.65 and the water use efficiency was 35% (Feng et al., 2000), meaning that much of the irrigated water was lost from the delivery system, because of poor construction and maintenance. There were so many water storages whose utilization efficiency were only 40–60%, and half of the water in water storages was lost due to leakage and high rate of evaporation. Thus, accelerated development of agriculture and social economy had led to a continued increase of water consumption in the middle Heihe River Basin, and concurrent decrease in the available water resources for the lower reaches of the Heihe River. The short-term management programs were implemented in 2001 when modern canal-lining techniques were introduced, advanced water-saving irrigation methods adopted, such as sprinkler irrigation and drip irrigation. The use of modern technology, the integrated planning and allocation of water resources have significantly increased water use efficiency, and ensured appropriate water allocation between the middle and the lower reaches.

3.2. Land use change from 1986 to 2000

The intensive human activities in the middle Heihe River Basin are clearly evident not only from the water resources utilization, but also from the exploitation of land resources. The total area of the study area is 2.16×10^4 km^2. Following the area ratio from large to small, land-use types in the middle Heihe River Basin were unused land, grassland, arable land, forest land, aquatorium, and residential area (residential land, industry and mining) in 1986, and the proportions of the first three were 53.0%, 20.4%, 18.7%. From 1986 to 2000, the arable land area increased by 247.5 km^2, from 18.7% to 19.9%; at the same time, the grassland declined by 195.9 km^2, from 20.4% to 19.5%. Analyzing the land use conversion between the six land use types (Fig. 5), the transfer from grassland to arable land was the largest, about 226.4 km^2, accounting for 90% of the loss of grassland and 75% of the increase in arable land. In addition, there was 40.6 km^2 from aquatorium to arable land, accounting for 99% of the loss of aquatorium (41.0 km^2). Apart from the expansion of arable land, there was a sharp increase of 20.9 km^2 in the residential area from 387.2 km^2 to 408.1 km^2, and about 70% of this increase came from arable land.

The land use conversion caused changes in the eco-circle level structure, which includes the following land uses: natural oases, constructed oases, oasis-desert transitional zone and desert. Ecological area in this study includes all the above except the desert, and the ratio of ecological area to total study area indicates the frangibility of the ecosystem, i.e. the smaller this ratio, the more fragile and vulnerable the eco-environment is. The oases to ecological area ratio and the constructed oases to oases ratio represent the relative stability of oases and constructed oases, respectively. During the period 1986–2000, constructed oases increased by 275 km^2 (6.0%), and transitional zone, natural oases decreased by 176 km^2 (5.5%), 90 km^2 (3.8%), respectively (Table 2). The eco-environment showed a decline trend in the relative stability due to the significant expansion of constructed oases and a noticeable decline of the transitional zone, with the constructed oases to oases ratio increased from 0.658 to 0.680 and the oases to ecological area ratio rised from 0.685 to 0.703.

With the rapid agricultural and economic development, arable land expanded at the expense of surrounding grassland, and part of the arable land encroached for construction and residential development, resulting in an expansion of constructed oases and considerable contraction of the oasis-desert transitional zone. During the same period, forest land and aquatorium decreased because of mechanized operations for filling ditch and reclaiming land from lake marshes on a large scale, thus, natural oases were affected. As a result of intense human activities, the evolution of land use patterns can be summarized as the expansion of constructed oases, considerable contraction of the oasis-desert transitional zone and natural

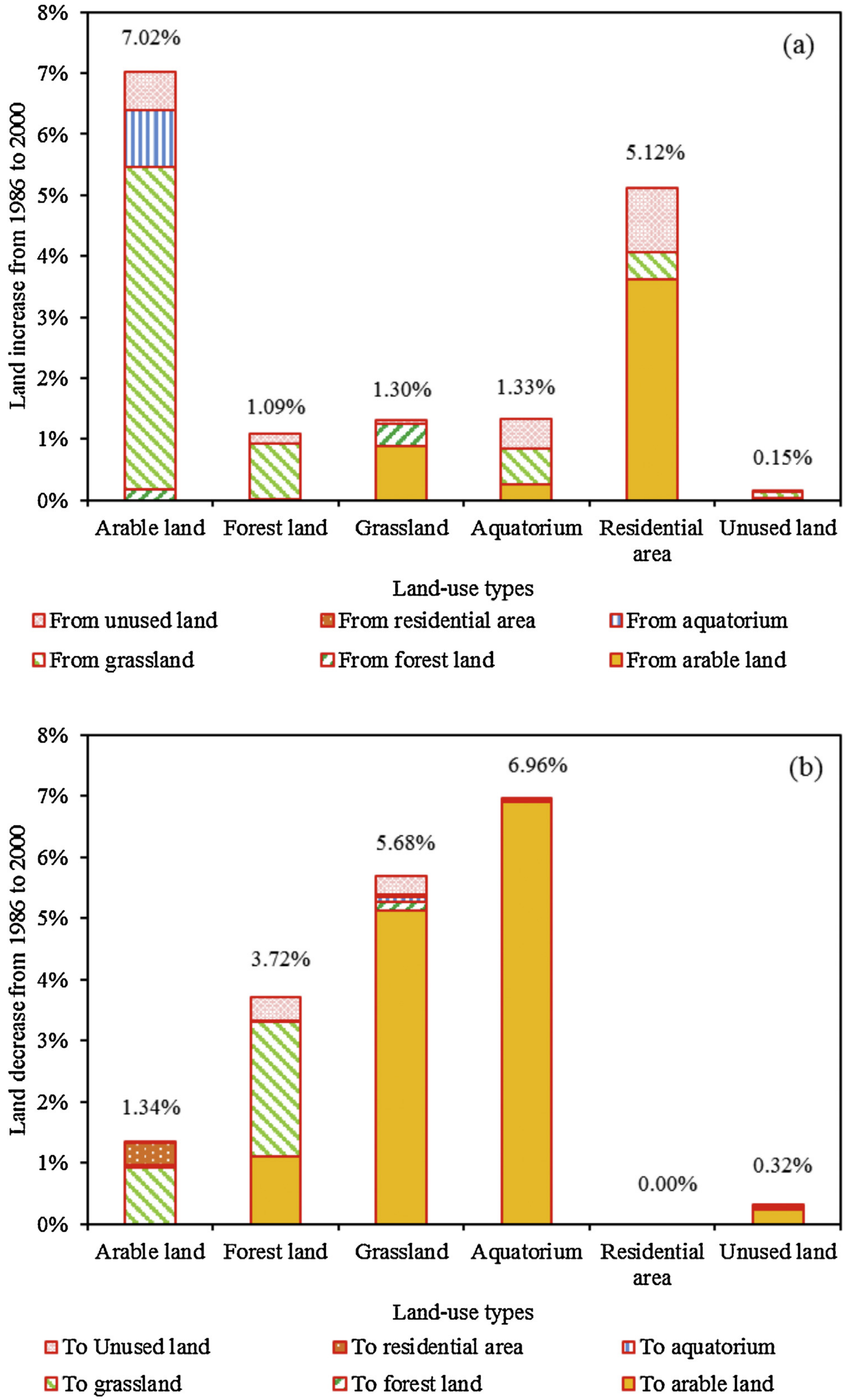

Fig. 5. Land use change from 1986 to 2000 in the middle Heihe River Basin.

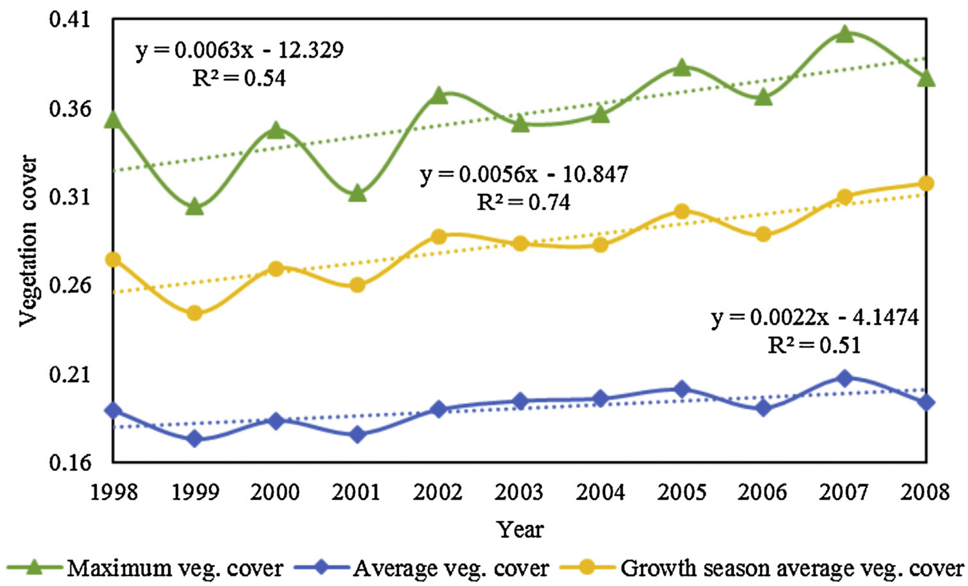

Fig. 6. Time series of the vegetation cover from 1998 to 2008 in the Zhangye–Linze–Gaotai basin.

oases, and there was a general decrease in the overall eco-system stability.

3.3. Eco-environmental changes in 2000s

As short-term management programs were first implemented in the Zhangye–Linze–Gaotai basin in the earlier 2000s, and the vegetation cover can be used an indicator of the eco-environmental quality in the arid area, we considered a number of changes of the vegetation cover to measure the improvement in the eco-environmental quality in the Zhangye–Linze–Gaotai basin. The maximum vegetation cover has increased steadily by 0.0063 per annum, and the average vegetation cover during the growth season shows a parallel increase at 0.0056 per annum ($R^2 = 0.74$) (Fig. 6). The spatiotemporal changes in the vegetation cover showed that the environment improved most notably in the Ganzhou District (Fig. 7), where the changes of vegetation cover during the growth season were 0.03–0.3 in most regions, and the vegetation cover increased by 5–60%. However, the vegetation cover of some area in the north (transitional zones) and along the Heihe River (arable land) decreased by 0.1–0.3, or 5–60%.

Analyzing the vegetation cover changes during the growth season from May to October, the increase in the vegetation cover was notable for all months during the growth season except May, especially after 2001. The increase in the vegetation cover occurred in August and September in the Zhangye–Linze–Gaotai basin was so dramatic that since 2001, the peak vegetation cover alternated between July and August, while, the vegetation cover in July was consistently higher than that in August prior to 2001 (Fig. 8). The maximum monthly vegetation cover reached its peak in July 2007

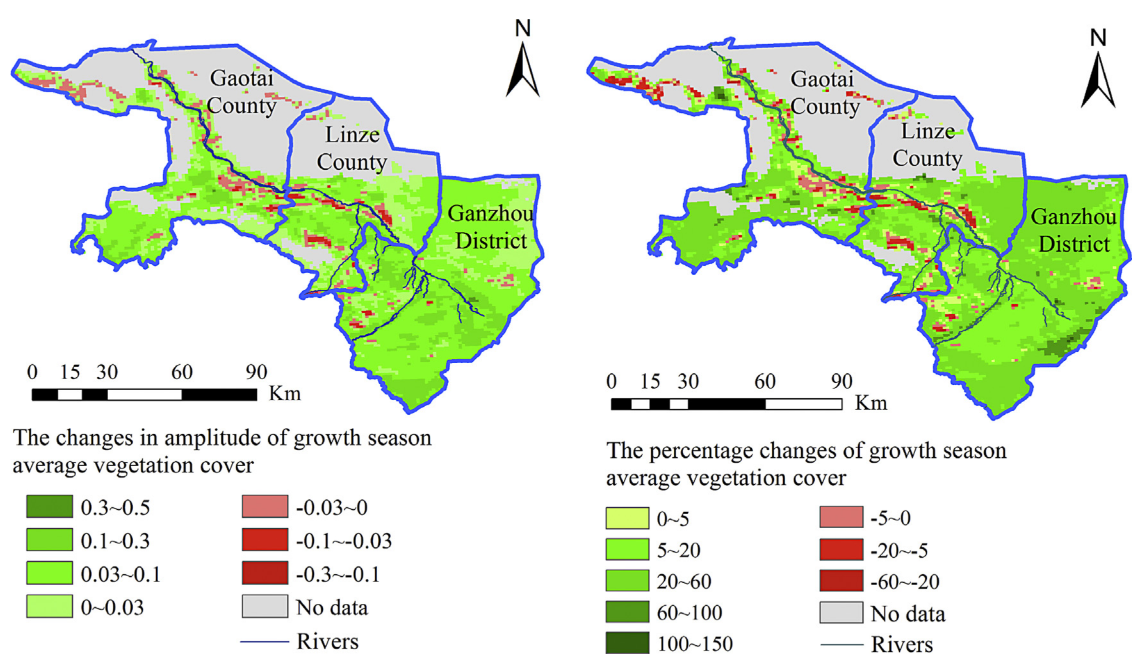

Fig. 7. Spatiotemporal changes in the average vegetation cover from May to October (the growth season) in the Zhangye–Linze–Gaotai basin (1999–2007).

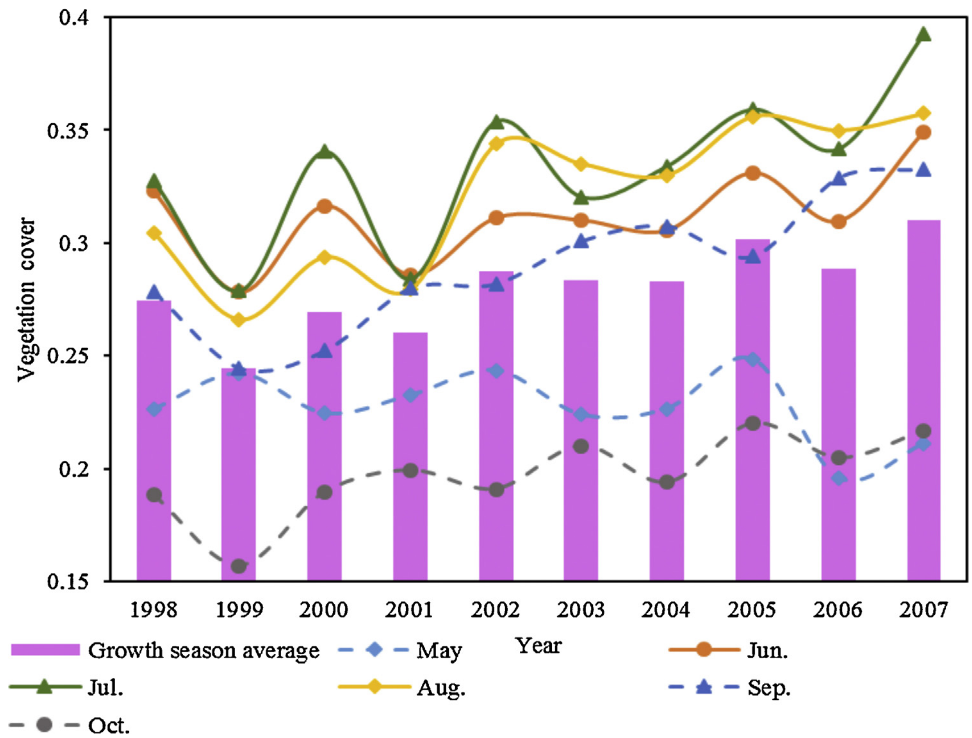

Fig. 8. Time series of the monthly vegetation cover from May to October (the growth season) in the Zhangye–Linze–Gaotai basin (1998–2007).

at 0.39, and this was considerably higher than 0.33 recorded for 1998, and 0.29 for 2001.

The annual maximum vegetation cover was used to classify the degree of vegetation in the study area according to the following scheme:

- Very low—0–15%.
- Low—15–30%.
- Medium to low—30–45%.
- Medium—45–60%.
- Medium to high—60–75%.
- High—75–100%.

As can be seen clearly from Fig. 9, there was a remarkable increase of the high vegetation cover, increasing from less than 1% in 1998 to nearly 17% in 2008. The sudden increase of the high vegetation cover from 1999 to 2000 was attributed to the vegetation cover improvement of forest land and high cover grassland. At the same time, the variations in the low and very low vegetation cover classes seemed to occur in tandem (Fig. 9). Change in the low class had a corresponding, almost equal, and opposite change in the very low class, suggesting that the very low class was regularly transformed to low class and vice versa on a large scale. All in all, the hierarchical structure of the annual maximum vegetation cover improved, and there have been improvements in eco-environment quality.

3.4. The extended EKC model

Fig. 10 shows the annual time series of (a) NDVI; (b) GDP per capita; (c) average temperature; and (d) precipitation in the middle Heihe River Basin. It is clear from Fig. 10 that there has been a huge increase in GDP per capita from 1982 to 2006, especially in recent years. Against this consistent and sustained increase in economic development, we also note from Fig. 10 the considerable interannual fluctuations in NDVI and climate variables. These short-term variations fundamentally necessitated an extension of the EKC model to include some biophysical factors to explain the variations in the eco-environmental quality as indicated by NDVI. Parameters for the original EKC model, i.e. Eq. (1.a) were estimated using NDVI and GDP per capita data for the period 1982–2006. The relationship between NDVI and GDP per capita showed an N-shaped relationship, and the parameters satisfy $\beta_1 > 0$, $\beta_2 < 0$, $\beta_3 > 0$ in the original EKC model (Table 3).

The original EKC model without considering of natural factors failed to fully explain most of the variations in NDVI with a R^2 value of 0.37 only (Fig. 11(a)). The extended EKC model, i.e. Eq. (2), through introducing natural factors could explain the interannual variations in NDVI much better than the original EKC model. The result of linear correlation analysis indicated that precipitation and temperature were significantly correlated with the NDVI ($r = 0.56$ for precipitation; $r = 0.47$ for temperature). Changes in precipitation and temperature are closely related to the water and energy conditions, which are important factors in vegetation growth in arid areas, especially for grass and other vegetation types in the oasis-desert transitional zone, where runoff is rare, and surface water so limited that precipitation dictates the vegetation growth to a great extent. Thus, the extended EKC model below was selected and parameters re-estimated with multiple regression analysis through introducing natural factors as follows:

$$\mathrm{NDVI}_t = \alpha + \beta_1\left(\frac{GDP}{P}\right)_t + \beta_2\left(\frac{GDP}{P}\right)_t^2 + \beta_3\left(\frac{GDP}{P}\right)_t^3 + \beta_4 TEM_t + \beta_5 PRE_t + u_t \quad (4)$$

where TEM_t is the annual average temperature, and PRE_t is the annual precipitation in the middle Heihe River Basin. All other parameters are the same as those in Eq. (2). Estimated parameter values and model performance indicators are presented in Table 3 for both the original and extended EKC models.

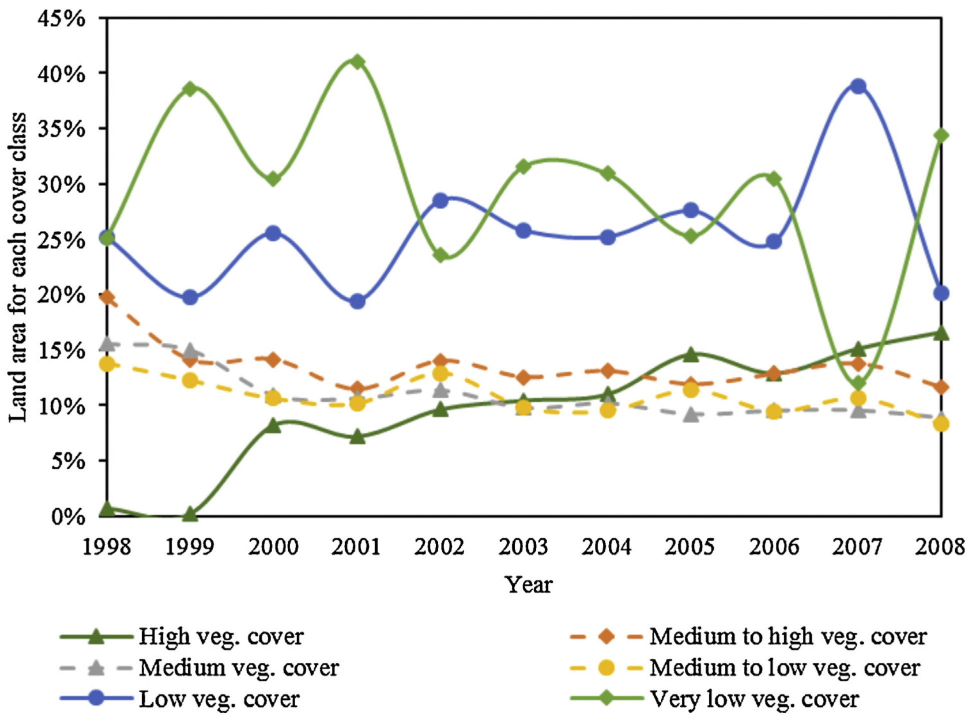

Fig. 9. Changes in the percentage area of the six vegetation cover classes in the Zhangye–Linze–Gaotai basin (1998–2008).

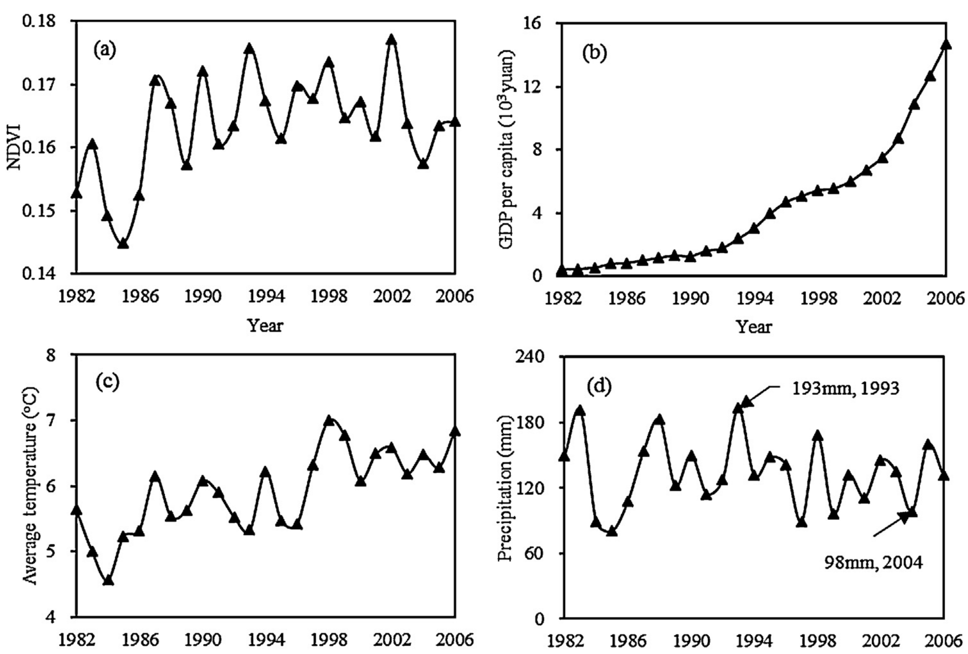

Fig. 10. Time series of the NDVI, GDP per capita, average temperature and precipitation in the middle Heihe River Basin from 1982 to 2006.

Eq. (4) describes the relationship between eco-environment quality and its driving socioeconomic and biophysical factors. Comparing the regression results using the original EKC model, the extended EKC model is able to explain most of the observed variations in NDVI for the study area ($R^2 = 0.78$). The discrepancy between the observed NDVI and the modelled NDVI using the extended EKC model is noticeably smaller than that using the original EKC model (Fig. 12). If considering only the climate factors (precipitation and temperature), the value of R^2 would be reduced to 0.57 with the same multiple linear regression technique. Thus, both human factors, i.e. GDP per capita and natural climate factors are relevant and needed to explain the interannual variations in NDVI in the middle Heihe River Basin. In addition, Eq. (4) is significant at the 1% level, so are the coefficients for individual terms involving *GDP/P*, *PRE*, and *TEM* at the 5% level. Removing the effects of natural factors, the N-shaped relationship becomes stronger and the amount of scatter around the Kuznets curve is smaller (Fig. 11(b)). Turning points in terms of NDVI in the EKC

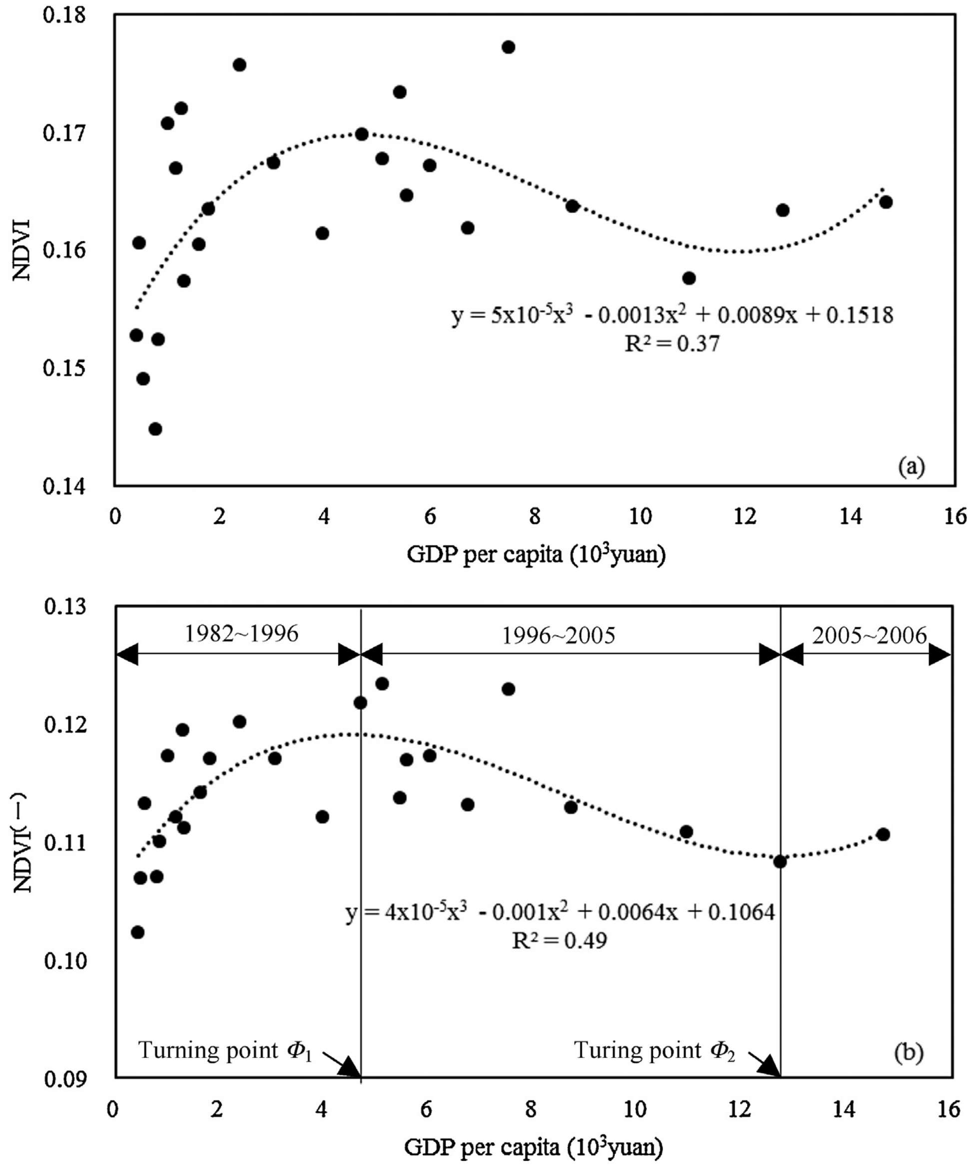

Fig. 11. Relationship between GDP per capita and NDVI from 1982 to 2006, (a) is the original relationship between GDP per capita and NDVI, and (b) is the relationship between GDP per capita and NDVI with the effects of precipitation and temperature removed.

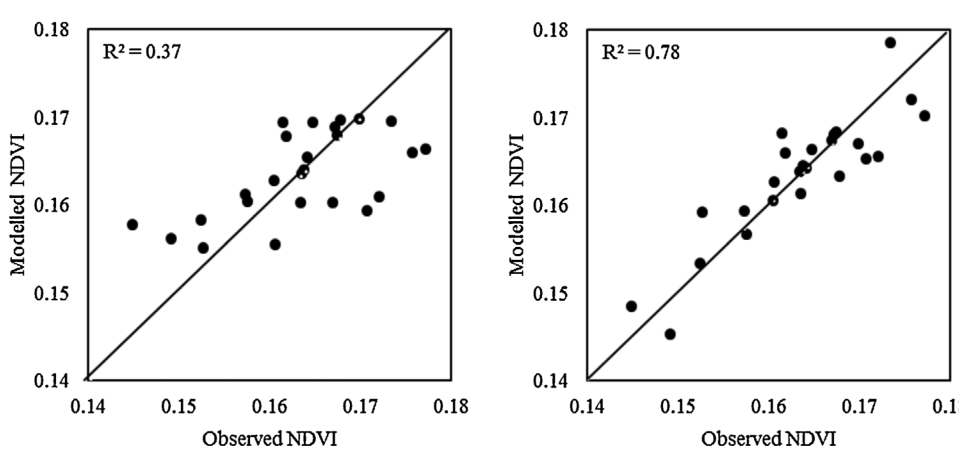

Fig. 12. Relationship between the observed and the modelled NDVI using the original EKC model (left) and the extended EKC model (right).

Table 3
Estimated parameter values of the original Environmental Kuznets Curve (EKC) model and the extended EKC model for the period from 1982 to 2006.

	The original EKC model		The extended EKC model	
	Regression coefficient	*p*-Value	Regression coefficient	*p*-Value
Constant	0.152	≤0.001	0.106	≤0.001
TEM	–	–	4.88×10^{-3}	0.032
PRE	–	–	1.53×10^{-4}	≤0.001
GDP/P	8.85×10^{-3}	0.005	6.40×10^{-3}	0.005
$(GDP/P)^2$	-1.32×10^{-3}	0.012	-9.63×10^{-4}	0.012
$(GDP/P)^3$	5.29×10^{-5}	0.032	3.73×10^{-5}	0.032
F-statistic	4.15	0.019	13.65	≤0.001
R^2	0.37		0.78	
Adjusted R^2	0.28		0.72	

framework occurred in 1996 and 2005. It is interesting to note that the turning points of the Kuznets curve occurred after the peak in NDVI in 1993, and the trough in 2004 since 1986 (Fig. 10(a)). This misalignment between extremes in NDVI and the turning points occurred, because of the critical influence of precipitation which was the highest on record in 1993 (193 mm) and the lowest on record in 2004 (98 mm, see also Fig. 10(d)).

We also note that the minimum vegetation cover occurred much earlier in the Zhangye–Linze–Gaotai basin in 1999 (Fig. 6), than the turning point in 2005. On one hand, the short-term management programs were implemented in the Zhangye–Linze–Gaotai basin in 2001, much earlier than in other counties in the middle Heihe River Basin; on the other hand, the lag between the turning points of vegetation cover in the middle Heihe Basin demonstrated the eco-environment improvement as a result of the short-term management programs in the Zhangye–Linze–Gaotai basin and the management experience can be shared with other districts. Although the turning points of GDP per capita are not completely consistent with the turning points of vegetation because of the impact of climate factors, the results still show the long-term relationship between human activities and the eco-environment, and explain the effects of human activities in different stages and provide support for decision making for long-term environment protection.

Furthermore, the extended EKC model might be improved through using primary industry production (or primary industry production per capita) to replace GDP per capita since farmland activities (irrigation, land reclaim, etc.) might be the main factors to impact the vegetation. The vegetation cover area of the constructed and natural oases in the middle Heihe River Basin are composed of grassland, arable land and forest land. As such, the vegetation growth and deterioration are likely to be directly affected by the primary industry activities. An increase in primary industry production would imply an increase in grazing, cultivation, planting activities, and additional water resources exploitation. These could result in positive or negative impacts on vegetation cover. Instead of NDVI, vegetation cover, NPP (Net Primary Production), LAI (Leaf Area Index) can be other possible indicators of the eco-environmental quality for arid regions, since they are closely related to vegetation growth.

4. Conclusions

The land use change under intensive human activities was characterized by the expansion of constructed oases, considerable contraction of oasis-desert transitional zone and natural oases in the middle Heihe River Basin. With rapid agricultural and economic development in the 1990s, a sharp increase of water consumption resulted in a remarkable decline of ecological flow and groundwater levels. Comparing land use patterns in 1986 and 2000, the transformation from grassland to arable land was as high as $226.36\,km^2$ or 90% of the loss of grassland, forest land and aquatorium suffered losses for expansion of the arable land as well. Thus, the exploitation of water and land resources led to a general decrease in the overall ecosystem stability.

However, the eco-environment has been improved since the implementation of short-term management programs in the earlier 2000s. The hierarchical structure of the annual maximum vegetation cover has improved considerably. The high vegetation cover (>75%) increased from less than 1% in 1998 to nearly 17% in 2008 and the very low vegetation cover (<15%) was transformed to low vegetation cover (15–30%) on a large scale. Moreover, the vegetation cover from July to October showed significant growth trends, and the maximum vegetation cover was increased to 0.39 in 2007.

Effects of human activities on the eco-environment in the middle Heihe River Basin could be aptly described with an extended EKC model, showing an N-shaped relationship between GDP per capita (economic growth) and NDVI (environmental quality), which showed that the relationship between human activities and eco-environment followed a process of promotion, contradiction, and coordination at different stages of social and economic development. In the early stages of social economic development, the improvements of agriculture and eco-environment were synchronous. However, the over-exploitation of water resources and expansion of constructed oases resulted in eco-environment degradation and a decrease of ecosystem stability, indicated by the declining section of the environmental Kuznets curve. The positive ecological effects of human activities refers to the effective application of modern technologies in protection of resources and the environmental protection, and ecological conservation, promoting common development and progress of productivity and the eco-environment.

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