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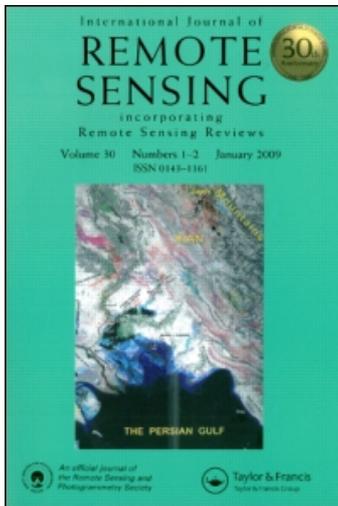
Analysing the forcing mechanisms for net primary productivity changes in the Heihe River Basin, north-west China

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Analysing the forcing mechanisms for net primary productivity changes in the Heihe River Basin, north-west China

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Most of the inland river basins in north-west China have experienced ecosystem degradation and even desertification in the last few decades. As a case study, we estimated the net primary productivity (NPP) of the Heihe river basin and analysed its difference between 2002 and 1998 by using the C-Fix, a Monteith type parametric NPP model. The data used include the normalized difference vegetation index (NDVI) derived from the 1-km SPOT/VEGETATION sensor and other environmental records. By obtaining the spatiotemporal patterns of NPP change as well as land use changes from higher resolution imagery in the basin, we identified its forcing factors in terms of climate change and human activities. We suggest that a decline in rainfall over the five years was one reason for NPP decrease in the basin. Other factors, such as irrational reclamation upstream and intensive development of irrigated farmland in the midstream play more important roles. They reinforce water competition between artificial and natural ecosystems over the whole basin. It is also found that human activities can produce very different NPP changes in a short time in mountainous regions. The NPP decreased in the east Qilian Mountains due to farmland reclamation and overgrazing but increased in the west, according to the ecosystem preserve project.

1. Introduction

Net primary productivity (NPP) determines the rate of atmospheric carbon absorbed by vegetation and is a measure of plant growth. It is a major component of the terrestrial carbon cycle. Accurate estimation of NPP at regional and global scales is of great importance for understanding the response of terrestrial ecosystems to climate warming (Myneni *et al.* 1997, Menzel and Fabian 1999, Nemani *et al.* 2003) and to land use change induced by human activities (DeFries *et al.* 1999, Houghton *et al.* 1999). Recently, a number of NPP models have been developed. They can be categorized into three groups (Cramer *et al.* 1999, Ruimy *et al.* 1999, Matsushita *et al.* 2004): statistical models (Lieth 1975), process models (Liu *et al.* 1997, Hunt *et al.* 1996), and parametric models (Potter *et al.* 1993, Prince and Goward 1995, Goetz *et al.* 1999). The parametric NPP models, taking advantage of remote sensing data, can generate NPP maps in different spatiotemporal resolutions. They are therefore capable of monitoring NPP at regional and global scales in real time.

Assessment of the impacts of climate warming and human activities on NPP evolution has been focused on the tropical forest region (Asner *et al.* 2000, Nemani

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et al. 2003, Ichii et al. 2005) and developed countries (Caspersen et al. 2000, Hicke et al. 2002, Milesi et al. 2003). Fewer studies have been carried out in arid regions in the developing world so far. Realizing that many ecosystems in these areas are deteriorating, we draw attention to inland river basins of China's north-west arid region, where ecosystems are very sensitive to climate and human activities. Many investigations have shown that the oases in the inland river basins of north-west China are experiencing ecosystem degradation (Wang and Chang 1999, Wang et al. 2003). The mechanism behind this was explained qualitatively by statistical analysis (Wang and Chang 1999, Liu and Chen 2001, Li et al. 2002). The landscape evolution was also analysed using land use maps derived from remote sensing data (Li et al. 2001, Lu et al. 2003).

Since NPP is a more quantitative indicator, in this study we estimated NPP of the Heihe river basin by using C-Fix, a Monteith type parametric NPP model (Veroustraete et al. 2002). Our case study area, the Heihe River basin, is the second largest inland watershed in north-west China. By using the normalized difference vegetation index (NDVI) derived from SPOT/VEGETATION, other environmental records, and land-use change maps of two case studies from higher resolution imageries, we obtained spatiotemporal variations of NPP in the region from 1998 to 2002. The main objectives of this paper are to identify areas where NPP significantly changes and to analyse the underlying forcing mechanisms, in terms of climate change and human activities, to bring on the changes.

The paper is organized as follows. In §2, we introduce the study area. §3 describes the C-Fix model, the method for forcing factor analysis, and the datasets including meteorological forcing, NDVI data, coarse resolution land use maps of the whole river basin, and large-scale land use maps of two case study areas. §4 contains a validation of the C-Fix model. In §5, first the NPP pattern and changes are analysed, and then the possible forcing mechanisms for the NPP changes in the upper, middle and lower researches of the Heihe River Basin are discussed. In §6, we summarize the discussion and conclude the paper.

2. Study area

The arid inland area of north-west China (north of $35°$ N, west of $106°$ E) occupies 24.5% of the land area of China. Situated deep in the hinterland of Eurasia, it is one of the driest zones in the world. Unlike many other arid zones in the world, the geomorphologic features of north-west China's dry lands exhibit an alternation of tall mountains (Altay, Tianshan, Qilian, Kulun Mountains, etc.) and inter-mountain depressions. Some 653 inland rivers have their origin in these mountains, consisting of various relatively independent inland river basins (Wang et al. 2004). These basins have both economic and ecological importance in north-west China due to various oasis ecosystems.

The Heihe River basin is the second largest inland river basin in the arid region of north-west China. It is located between $96°42'–102°00'$ E and $37°41'–42°42'$ N and covers an area of approximately $130\,000\,km^2$. It originates from the Qilian Mountains in Qinghai province, runs through the Hexi Corridor of Gansu Province and flows into the western Inner Mongolian Plateau (figure 1).

Geographic differentiation in the basin is evident. From south to north of the basin, there are three major geomorphological units: the southern Qilian Mountains in the upper stream, the Hexi Corridor in the midstream and the northern Alxa High Plain in the down stream. The southern Qilian Mountains, with an elevation of
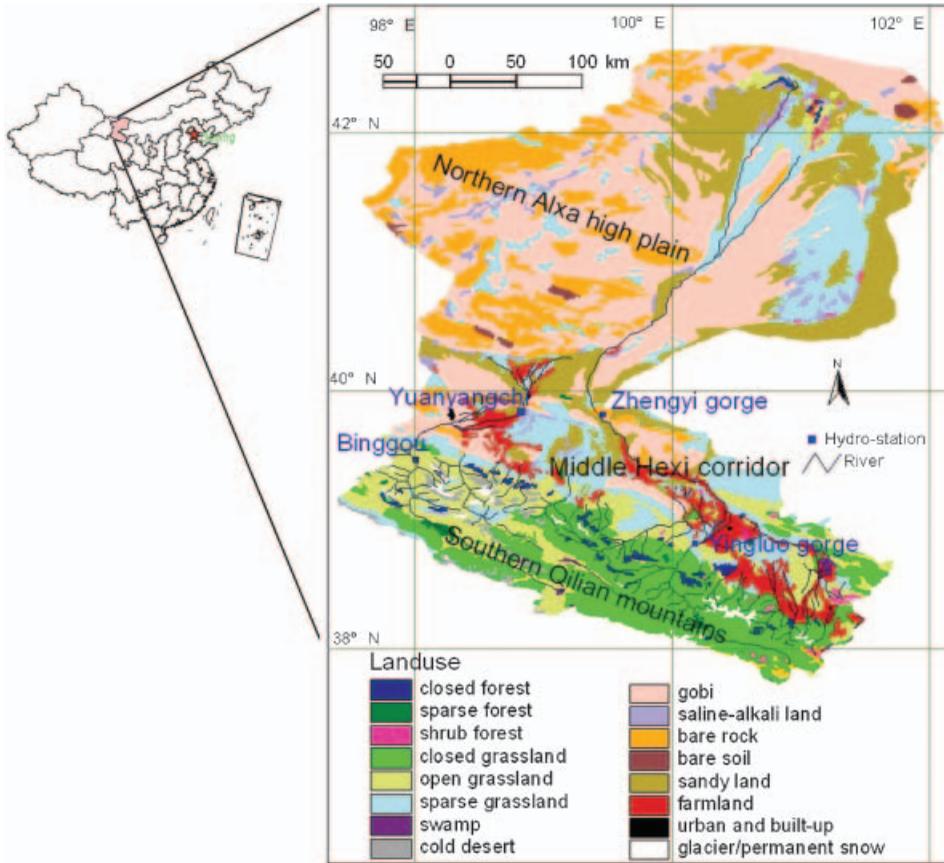
Figure 1.   Land use map and the three major geomorphologic units in the Heihe River basin (data come from Xiao 1999).

2000–5500 m and a mean annual precipitation from about 250 mm in the low-mountain zone to 500 mm in the high-mountain zone, is the area of runoff generation and water resources formation. In addition, the vegetation ecosystems are mainly natural ecosystems, including cold desert, mountain forests and shrubs, alpine meadows and steppe. The middle Hexi Corridor is sandwiched between the southern Qilian Mountains and the northern Mazong Mountains. The elevation of the area decreases from 2000 m to 1000 m, corresponding with a decrease of the mean annual precipitation from 250 mm to less than 100 mm. Here various artificial oases exist, including the counties of Mingle, Shandan, Linze, Gaotai, Zhangye, Jiuquan and Jinta. Irrigated agriculture dominated by farmland vegetation develops very well, but with a high consumption and extensive exploitation of water resources. The northern Alxa High Plain, with a mean elevation of about 1000 m and mean annual precipitation <50 mm, is mainly occupied by gobi (a type of half desertic vegetation with dispersed scleric scrublands) and desert. The downstream area of the Heihe River dissipates into the delta oasis of Ejin Banner. The Ejin Banner oasis is one of the three oases in China that have a natural reserve of river bank forest of diversiform-leaved poplars. The other two oases are located in the Tarim river basin of Xinjiang and Shule river basin of Gansu (Su *et al.* 2003).

3.   Methodology and datasets

3.1   The C-Fix model

The C-Fix model, as described by Veroustraete et al. (2002), is a Monteith type parametric model to estimate carbon mass fluxes on a regional basis by integrating satellite observations. It is driven by temperature, radiation and the fraction of absorbed photosynthetically active radiation (fAPAR). As the key variable in this approach, fAPAR is directly retrieved from remote sensing data. By now, The C-Fix model has been successfully applied in estimating NPP over the European continent, Africa and west China (Sabbe and Veroustraete 1999, Veroustraete et al. 2002, Lu 2003, Lu et al., 2005).

The model uses equation (1) to estimate NPP measured in $(gC\,m^{-2}\,d^{-1})$ on a daily basis, NPP_d. Here, C refers to carbon.

$$NPP_d = \left(p(T_{atm}) \times CO_2fert \times \varepsilon \times fAPAR \times c \times S_{g,d}\right) \times (1 - A_d), \qquad (1)$$

where $p(T_{atm})$ is a normalized temperature dependency factor for daily mean air temperature T_{atm}, which indicates the constraint of air temperature to GPP (gross primary productivity) and takes [0, 1] (Wang 1996).

CO_2fert is a normalized CO_2 fertilization factor defined as the increase in carbon assimilation due to CO_2 levels above an atmospheric background level (or reference level) (Veroustraete 1994).

ε is radiation use efficiency (RUE) at GPP state. Its value is approximated with $1.1\,gC\,MJ^{-1}$(APAR, absorbed photosynthetically active radiation) on which climatic conditions have only slight influence (Wofsy et al. 1993). The value $1.1\,gC\,MJ^{-1}$(APAR) is equal to $2.45\,gDM\,MJ^{-1}$(APAR), enabling conversion from DM (dry matter) to C. Nouvellon et al. (1998) measured the time variation of ε in a semi-arid grass and shrubland in Arizona from 1990 to 1992. They obtained a mean value of ε of $2.48\,gDM\,MJ^{-1}$(APAR). In addition, Ruimy (1995) also estimated ε, which is equal to $2.45\,gDM\,MJ^{-1}$(APAR), when simulating the global NPP for wide range of global ecosystems. Therefore, ε is set to $2.45\,gDM\,MJ^{-1}$(APAR) in this study. It needs to be clarified that the ε defined here is different from that in many other papers (Allen et al. 2005, Pineiro et al. 2006, Tesfaye et al. 2006, Linderson et al. 2007), where the RUE is defined as the ratio of energy output to energy input (Monteith 1977). But in our paper, the effects of temperature and nutrition constraints are partially given by $p(T_{atm})$ and CO_2fert, respectively (equation (1)). The introduction of these two terms makes ε a more constant parameter. Despite this, the value of $1.1\,gC\,MJ^{-1}$ is an approximation. The water stress, which is seasonally important for arid and semi-arid region, needs to be further considered when more observation is available.

Myneni and Williams (1994) established a linear relationship between fAPAR and NDVI by means of a radiative transfer model. The relationship (equation (2)) was widely validated for a large set of different vegetation-soil-atmosphere observation conditions with $R^2 = 0.919$. It is also independent on the vegetation heterogeneity within pixel.

$$fAPAR = 1.1638*NDVI_{toc} - 0.1426 \qquad (2)$$

The determination of the $NDVI_{toc}$ (NDVI on top of the canopy) can be performed with satellite observations. When the value of $NDVI_{toc}$ is equal to or less than 0.1225, fAPAR will be calculated as zero to reduce the uncertainty in pixels with a high proportion of bare land.

Let c be the ratio of photosynthetically active radiation (0.4–0.7 μm) to global radiation. Its value varies between 0.45 and 0.5. In this study it is set fixed by a mean value of 0.48, according to McCree (1972). $S_{g,d}$ is daily incoming global solar radiation measured in $MJ\,m^{-2}\,d^{-1}$. A_d is the autotrophic respiratory ratio of vegetation indicating the ratio of assimilating carbon by autotrophic respiration to GPP. It is modelled as a simple linear function of daily mean air temperature T_{atm}, according to the parameterization of Goward and Dye (1987).

3.2 *Forcing mechanism analysis method*

The forcing mechanisms for NPP changes are spatially variable in different parts of an inland river basin in China. Typically, in the mountainous area upstream, climatic factors are dominating but human activities such as reclamation, grazing, deforestation and afforestation can exceed if they are intensive. In the midstream area, artificial oasis (farmland) is the preponderant landscape so human activities dominate. In the downstream area, human activities are less, but the water use in upper and midstream areas has great impact on the ecosystems, which depend on the water resource allocated downstream.

Therefore, both climate change and human activities must be considered to analyse the NPP change. For climatic factors, the air temperature and precipitation data from 12 stations (four in the Southern Qilian Mountainous, six in the middle Hexi Corridor and two in the northern Alxa High Plain) from 1998 to 2002 were collected. The long-term air temperature and precipitation data from four mountain stations from 1987 to 2002 were also used to help illustrate the different climatic change patterns in the Qilian Mountains. For human activities, land use is a representative factor which has a close relationship with NPP, so we compiled some large-scale land use maps using remote sensing. We selected two case study areas. One is located in the east Qilian Mountains and the other in the Linze County of the middle Heihe River basin. The land use maps and land use changes in the two case areas will be introduced in the next subsection.

In arid regions limited water supply is a controlling factor for NPP. In upstream areas, the water flow represents the natural discharge. The agriculture has some influence but it is not significant. In the midstream oases, the amount of water is equal to the difference between the discharge from mountainous area and the water allocated for downstream areas. To analyse the relationship between available water resources and NPP, we selected data from four hydrological stations. Two of them are in the west part of Heihe River Basin, i.e. Binggou station in the west Qilian Mountains, which controls the mountain discharge, and the Yuanyangchi reservoir downstream. Another two are in the east part, i.e. Yingluo Gorge in the east Qilian Mountains to measure mountain discharge, and Zhengyi Gorge, which controls the amount of water allocated for natural oasis downstream.

3.3 *Datasets*

3.3.1 Meteorological forcing and NDVI data. Meteo France provided datasets of daily air temperature and incoming global radiation from 1998 to 2002. The data were estimated by means of the ARPEGE model (http://www.meteo.fr/meteonet-en/decourvr/dossier/previsionmeteo/pre.htm). The resolution of the Meteo raster of ARPEGE is $1.5° \times 1.5°$. The data over the study region were extracted from the global dataset and re-sampled by the cubic convolution method to a grid resolution of 0.25° closer to C-Fix spatial resolution.

We used standard 1-km VGT-S10 products from the SPOT4/VEGETATION sensor, which is the 10-day MVC (maximal value composite) $NDVI_{toc}$ dataset to minimize the effect of cloud cover and BRDF by strict atmospheric correction (http://free.vgt.vito.be). The series of $NDVI_{toc}$ composites over the study area from 1998 to 2002 were processed as inputs for the C-Fix model.

3.3.2 Land use map. The newest 1-km land use map of the Heihe river basin was used to evaluate the NPP of different ecosystems. Based on 11 TM images acquired in the summer of 1997, topographic maps, and ground truth investigations, Xiao (1999) compiled a land use map of the Heihe River basin scaled at 1 : 500 000, which was recompiled to the geographic projection with a resolution of 1 km to match the remote sensing data. The land use map of the Heihe River basin (figure 1) was categorized into 16 types according to the classification system formulated by the second nationwide land cover and land use project (Liu, J.Y. *et al.* 2005).

3.3.3 Large-scale land use maps of the two case study areas. Large scale land use maps of two case study areas in 1999 and 2002 were compiled from LANDSAT-7 Enhanced Thematic Mapper Plus (ETM +) images through interactively manual interpretation via GIS platform. The same classification system in figure 2 was used. The ETM + images were downloaded from the Earth Science Data Interface (ESDI) at the Global Land Cover Facility (http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp). The acquired dates are 7 July 1999 and 13 June 2002, respectively. The Path-Row number is 133/33.

The land use maps of the two cases used the Albers equal-area projection. The total accuracy of geometric rectification was within 1 pixel. The interpretation accuracy of the land use classification for the 16 types was more than 90% compared to intensive field surveys. The land use changes between 1999 and 2002 in the two case study areas were then derived from the land use maps with the help of GIS software. The change types were identified using the cross-classification function of GIS software. There are 16×16 possible transitions for each pixel. Obviously, it was difficult to display and analyse this very complex transition map, so we generalized the possible transitions into some major and important transitions, as illustrated in figures 2 and 3 in accordance with two principles: (a) the change map should illustrate the pronounced differentiation of three dominant land classes, the nature ecosystems, the farmland and the desert; (b) it should be favourable to analyse the change of two basic contradiction processes, i.e. expansion of oases and desertification.

Case 1 (figure 2) is a square area of 33 km × 37 km, where one of the best pastures in China named 'the big horse camp' is located. It is noticeable that from 1999 to 2002 the land use change was 3.5% (43 km^2) of the total study area. From north to south, three dominating transitions occurred. The first is the extension of residential area—about 1.5 km^2 of farmland was converted into urban and built-up land, implying extensive construction. The second transition is agriculture expansion onto the grasslands. The study area had a distribution of about 187 km^2 closed grassland and 101 km^2 open grassland in 1999, but about 10% of the closed grassland and 2.1% of open grasslands were turned into farmland by 2002. The third is a remarkable desertification that occurred in the transitional zone between cold desert and other natural mountain ecosystems, where cold desert area increased about 16.1 km^2 and was converted from forest, shrub and grassland.
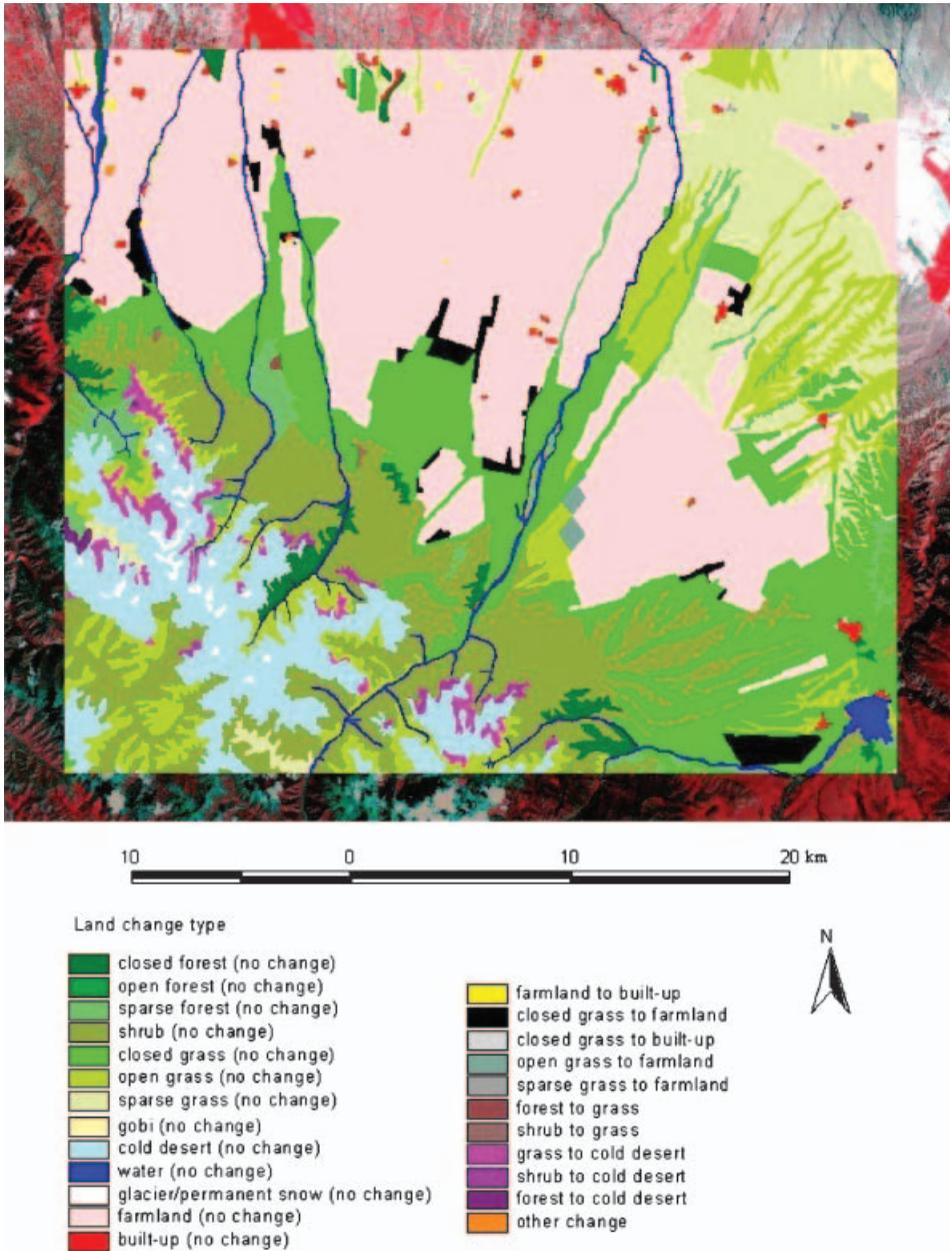
Figure 2. Land use change in the case study area in the upstream area of the east Qilian Mountains between 2002 and 1999. From north to south in the map, three dominating transitions occur, including built-up extension from farmlands, agriculture reclamation on the closed grassland and ecosystem degradation in terms of grass, shrub and forest to cold desert in the high mountain areas, indicating human disturbance might be a cause of the remarkable NPP decrease in the eastern part of the Qilian Mountains.

Case 2 (figure 3) is a square area of $36 \, \text{km} \times 36 \, \text{km}$, where desert and farmland have highest predominance. From 1999 to 2002 the land use change was 1.8% ($23 \, \text{km}^2$) of the total study area. Most of the land use changes occurred in the transitional zone between desert and farmland and along the banks of the Heihe
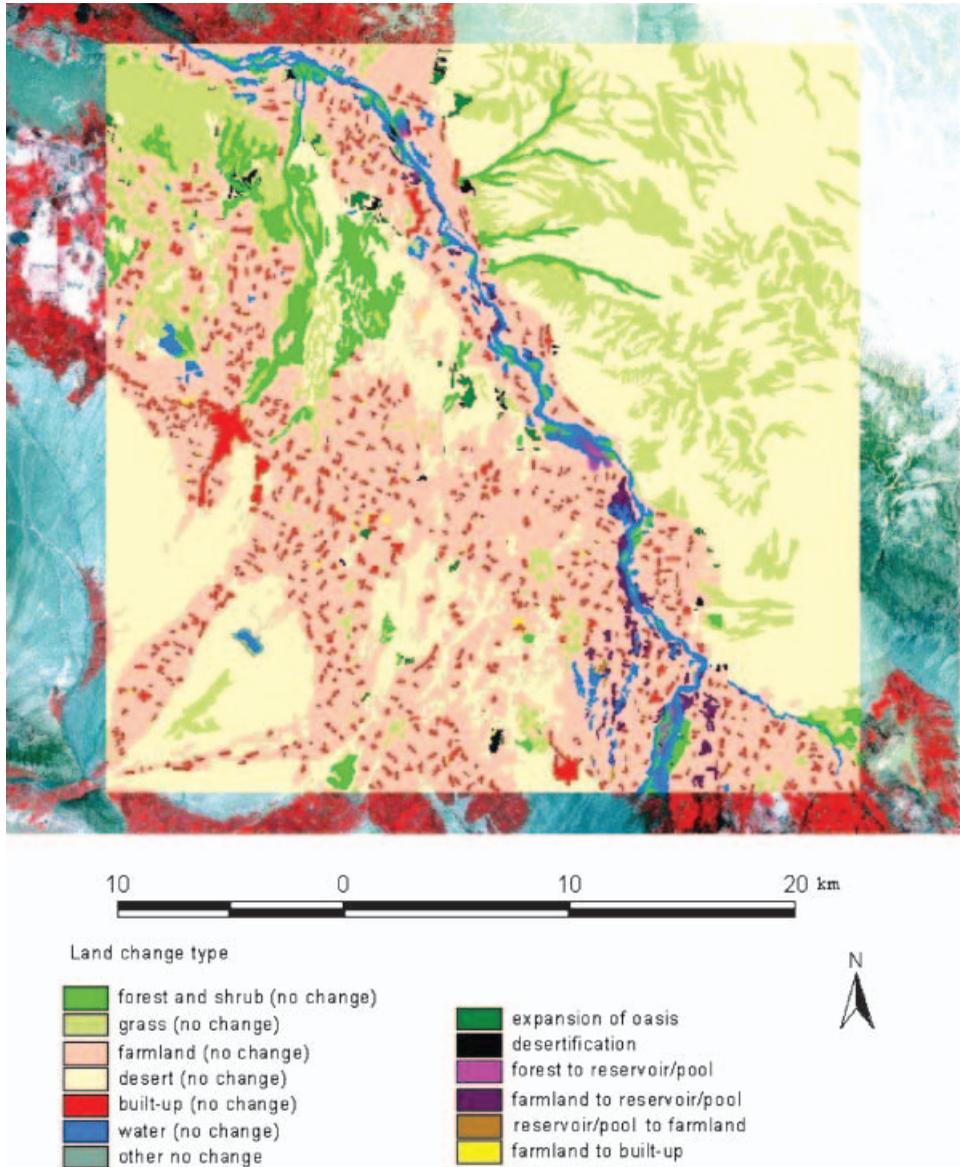
Figure 3. Land use change in the case study area in Linze County of the middle Heihe River basin between 2002 and 1999. Desert and farmland are the types with highest predominance and most of the land use changes occurred in the transitional zone between desert and farmland and along the banks of the Heihe River, implying a strong competition of water between irrigated farmland and natural ecosystems the middle basin.

River. Oasis expansion (about 3.58 km^2 of desert converted into irrigated farmland, and about 0.87 km^2 of desert converted into artificial grassland and forest) and desertification (1.87 km^2 of irrigated farmland and 0.85 km^2 of closed grassland turned back into desert) co-existed. In addition, about 1.62 km^2 of urban and built-up area was formed from farmland between 1999 and 2002. There is also a remarkable land use change along the river stream. In particular, a large area of land was converted into temporary reservoirs or pools between 1999 and 2002. For

instance, $1.7\,\text{km}^2$ of forest and $8.5\,\text{km}^2$ of farmland were submerged by reservoirs or pools. Meanwhile, only $0.56\,\text{km}^2$ of reservoirs and pools were turned back into farmland.

4.   Validation of the C-Fix model

To validate the C-Fix model, we collected some measured NPP data in the forest area of west China during 1989–1994 from the Oak Ridge National Laboratory Distributed Active Archive Center (Ni *et al.* 2001) and the Forestry Bureau of China. In total 82 measurements in the cold and temperate mountain forest area in west China ($78°$–$113°\,\text{E}$, $26°$–$49°\,\text{N}$) were selected. The NPP values from 1998 to 2002 at these measurement points were simulated by the C-Fix model. The relationship between the measured NPP and the simulated NPP averaged over five years is shown in figure 4. The correlation coefficient R is 0.53 and the statistical test is significant. The mean NPP value is $464\,\text{gC}\,\text{m}^{-2}\,\text{yr}^{-1}$ for all measurements and $448\,\text{gC}\,\text{m}^{-2}\,\text{yr}^{-1}$ for the simulation. The deviations may be due to the fact that the measurements are in a small ground-plot but the model simulations are in a $1\,\text{km}^2$ pixel scale, on which mixed land types coexist. They may also be due to the different periods of time.

   NPP measurements of other ecosystems were also collected in the vicinity of the Heihe River basin (table 1). The C-Fix simulated NPP value in each site was the averaged value from 1998 to 2002. As showed in figure 4 and table 1, the simulated
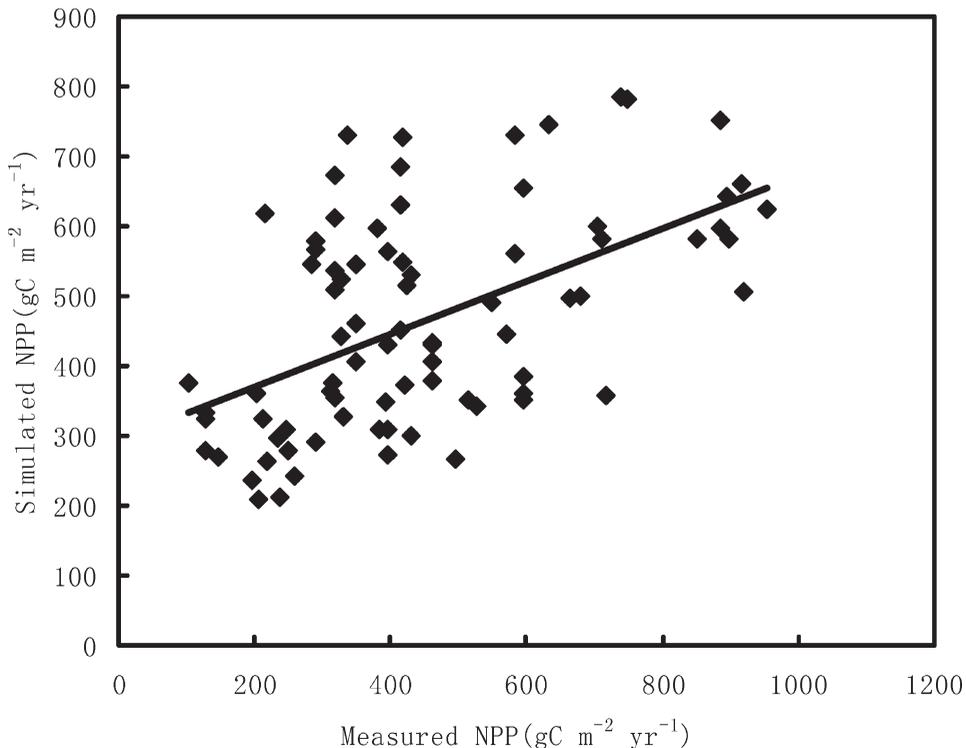

Figure 4.   Correlation of simulated and measured NPP values in the forest area of west China. The correlation equation of simulated NPP (denoted as *SN*) to measured NPP (denoted as *MN*) is: $SN = 0.38\,MN + 296.17$, $R = 0.53$, $n = 82$ points, $p < 0.01$.

Table 1. Comparison of simulated and measured NPP values of different ecosystems in the vicinity of the Heihe River basin.

Ecosystem type	Site	Position	Simulated NPP (gC m^{-2} yr^{-1})	Measured NPP (gC m^{-2} yr^{-1})	Error	Reference
Mixed alpine grassland	Tianzhu	102°26′ E, 37°37′ N	612.5	508.5	−20%	Hu *et al.* 1988, 1994
Typical alpine meadow	Haibei	101°19′ E, 37°12′ N	433.6	436.5	0.6%	Yang *et al.* 1988
Typical sandy grassland	Ordos plateau	108° E, 40° N	240.0	261.0	8%	Wang and Li 1994

NPP values are in agreement with the measured ones in different vegetation types, proving that the C-Fix model is appropriate for simulating NPP of the study area.

5. Results and discussion

5.1 *Spatial pattern of annual NPP in the Heihe River basin*

The annual accumulated NPP of the Heihe River basin from 1998 to 2002 was estimated with the C-Fix model. Figure 5 is an example of the estimated annual NPP in 2002. The spatial resolution of the model output is 1 km.

The control of temperature and water by NPP is clearly illustrated in the southern mountainous area. In the Qilian Mountains, the spatial pattern of annual NPP displays two zonalities, i.e. altitudinal zonal characteristics and longitudinal zonal characteristics. In the altitudinal zone, elevation plays a role, as both air temperature and precipitation depend on it. Air temperature deceases with a lapse rate of 0.6° per 100 m, while precipitation increases by about 15–22 mm per 100 m in the Qilian Mountains (figure 6(a); Chen *et al.* 1992). At elevations of 2500–3400 m, a combination of modest temperatures, precipitation and potential evaporation (figure 6(b)) makes this zone a favourable place for forest, shrub and grass to grow. The NPP values are between 250 and 450 gC m^{-2} yr^{-1}, which are the highest in the mountainous area. Below this zone, at elevations of 2000–2500 m, vegetation becomes sparser because of less precipitation and more evaporation. The NPP values are <200 gC m^{-2} yr^{-1}. Above this zone (from 2500 to 3400 m), at elevations of 3400–3900 m, the NPP values decrease to about 150–250 gC m^{-2} yr^{-1} because of lower temperatures. The vegetation is dominated by alpine meadow and swamp. At elevations of 3900–4200 m, air temperature is even lower, and the ecosystem becomes cold desert. The NPP values decrease to <100 gC m^{-2} yr^{-1}, which is the lowest in the mountainous area.

NPP distribution also displays longitudinal zonal characteristics in the Qilian Mountains, with its value decreasing from east to west. One reason might be the precipitation gradient, which reaches–67 mm per 1° E from the eastern part to the western part of the Qilian Mountains (figure 6(c); Chen *et al.* 1992). The other reason is that the elevation in the western mountains is higher than that in the east. Therefore, less precipitation and lower temperatures result in lower NPP values in the west Qilian Mountains, where glaciers and perennial snow are dominant landscapes.

In the middle reaches of the Heihe River basin, many artificial oases exist. Almost all farmlands are irrigated by a complex channel system, which draws away most
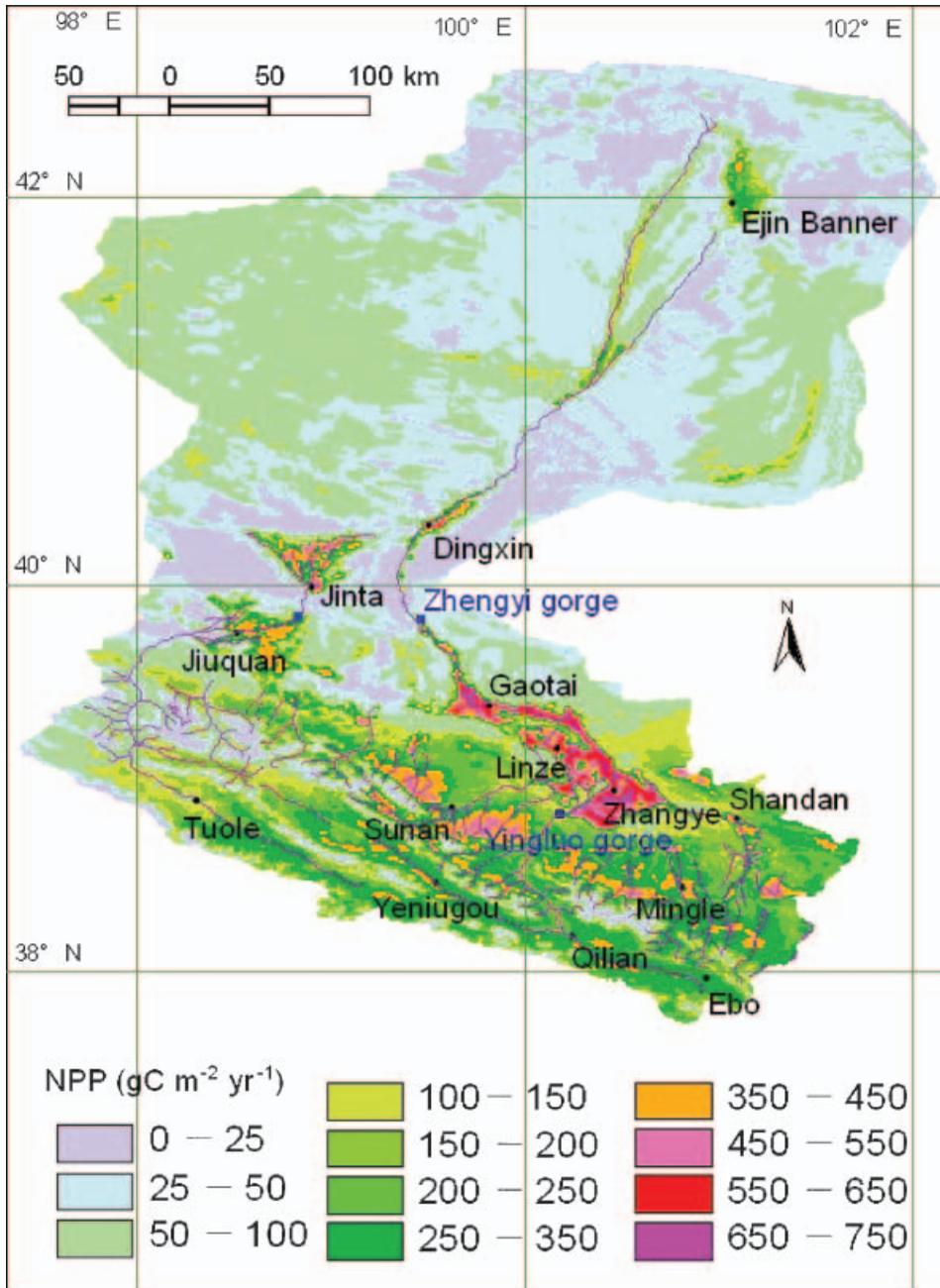
Figure 5.   The spatial pattern of annual NPP in the Heihe River basin in 2002. In the Qilian Mountains, the spatial pattern of annual NPP displays two zonalities. For altitudinal zonality, the NPP values are highest for forest (2500 to 3400 m) and decrease both in higher and lower altitudes. It reaches the lowest value in the cold desert and glacier areas. For longitudinal zonality, the NPP values are higher in the east than in the west. In the middle reaches, the NPP values of agriculture are generally high. The maximum NPP value appears in the irrigated farmland of Zhangye. The NPP values of surrounding desert and gobi are low. In the downstream river bank, the NPP of natural oasis presents a moderate level but away from the river channel the NPP values decrease to very low.
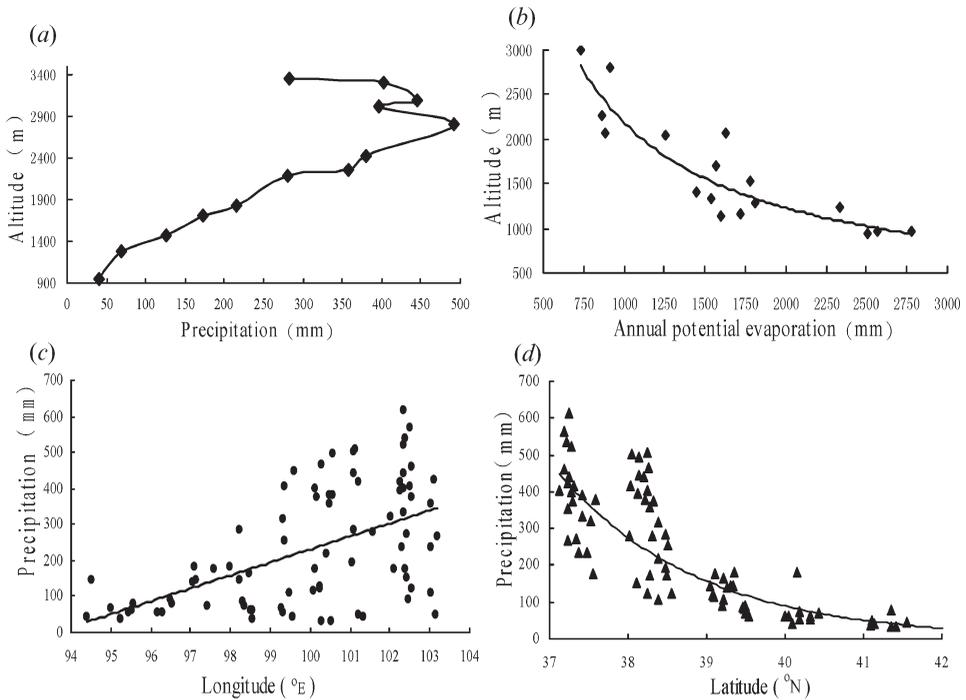
Figure 6.   The gradients of the environmental variables in the Heihe River basin. (*a*) relation between precipitation and altitude ($y=4.8x+957$, $R=0.87$, $n=13$ points, $p<0.01$); (*b*) relation between annual potential evaporation and altitude ($y=668254^{x-0.83}$, $R=0.9$, $n=17$ points); (*c*) relation between longitude and precipitation ($y=36.054x-3374.3$, $R=0.53$, $n=84$ points, $p<0.01$); (*d*) relation between latitude and precipitation ($y=5E+11e^{-0.5622x}$, $R=0.89$, $n=84$ points, $p<0.01$).

natural run-offs generated in the mountainous area for agriculture usage. Therefore, although a small amount of precipitation and large evaporation capacity occur (figure 6(*a*, *b*)), agriculture is well developed. The NPP values are generally high, reaching $350\,\mathrm{gC\,m^{-2}\,yr^{-1}}$ and more. The maximum NPP value of $720\,\mathrm{gC\,m^{-2}\,yr^{-1}}$ appears in the irrigated farmland of Zhangye, the most developed oasis in the basin.

The vast northern Alxa High Plain downstream occupies more than half the area of the whole basin. Climate is extremely dry here due to very low precipitation ($<50\,\mathrm{mm}$) but high evaporation potential (figure 6(*b*, *d*)). Along the downstream river bank, the NPP of natural oases presents a moderate level between 150 and $250\,\mathrm{gC\,m^{-2}\,yr^{-1}}$, contributing to relative abundant surface and ground water. Away from the river channel, NPP values decrease to $<50\,\mathrm{gC\,m^{-2}\,yr^{-1}}$ in the wide areas of desert and gobi. The annual NPP in the downstream area is closely related with the distance from the river. Closer to the main river and its tributaries the NPP level of the ecosystem is higher. This suggests that the response of natural vegetation downstream is very sensitive to water availability and its variations.

5.2   *NPP change from 1998 to 2002 in the Heihe River basin*

Table 2 reports total and mean NPP estimates for each land use type in 1998 and 2002. The total NPP of the Heihe River basin in 1998 is estimated to be 20.86 Tg (Teragrams, i.e. 10^{12}g) of carbon per year, but only 18.16 Tg in 2002. The lost

Table 2. Estimates of mean and total annual NPP of different land use types in the Heihe River basin in 1998 and 2002.

Land use type	Percentage of area in 1998 (%)	Mean NPP in 1998 (gC m^{-2} yr^{-1})	Mean NPP in 2002 (gC m^{-2} yr^{-1})	Difference between 2002-1998 (gC m^{-2} yr^{-1})	Total NPP in 1998 (Tg C yr^{-1})	Total NPP in 2002 (Tg C yr^{-1})
Closed forest	0.83	258.79	266.30	7.51	0.37	0.38
Sparse forest	0.30	181.87	184.41	2.54	0.09	0.10
Cold desert	1.03	78.44	84.00	5.56	0.14	0.15
Swamp	0.13	238.05	248.33	10.27	0.05	0.06
Farm land	3.95	349.73	364.18	14.45	2.36	2.46
Urban and built-up	0.04	122.44	126.65	4.22	0.01	0.01
Closed grassland	11.16	252.23	244.12	−8.11	4.81	4.65
Open grassland	8.31	165.73	174.16	8.44	2.35	2.47
Sparse grassland	14.82	115.15	97.73	−17.42	2.92	2.48
Shrub forest	0.48	313.90	268.14	−45.76	0.26	0.22
Water bodies	0.87	152.36	143.92	−8.44	0.23	0.21
Saline-alkali land	2.50	98.37	69.96	−28.41	0.42	0.30
Gobi	30.12	69.72	46.77	−22.95	3.59	2.41
Bare rock	11.29	80.56	57.18	−23.37	1.55	1.10
Sandy land	13.04	73.19	50.15	−23.03	1.63	1.12
Bare soil	0.49	94.91	70.97	−23.94	0.08	0.06
Total/mean	100.00	122	106	−12.85	20.86	18.18

amount is 2.7 Tg over five years, with 85% of the loss due to the NPP decrease in the desert ecosystems including saline-alkaline land, gobi, bare rock, sandy land, and bare soil; another 15% NPP loss is related to the closed and sparse grassland ecosystems.

The NPP changes of different land use types in the basin are diverse. As shown in table 2, increases took place in closed forest, sparse forest, cold desert, and swamps. These are natural ecosystems distributed in the upstream area. Farmland, urban and built-up areas also presented an increase in mean and total NPP. The three types of grassland displayed an inconsistent change, as NPP increased for the open grassland but decreased in the closed and sparse grass. Meanwhile, there were many ecosystems with a decrease in NPP. The largest decrease is for the shrub forest, where the mean NPP decreased by 45.76 gC m^{-2} from 1998 to 2002. Aquatic and riparian ecosystems (water bodies) also demonstrated a decrease with regard to the mean NPP values of 8.44 gC m^{-2}. The ecosystems with an NPP decrease were mainly distributed downstream along the river banks, alluvial fans, and terminal lakes. Additionally, a generally pronounced decrease in mean NPP (from −23 gC m^{-2} to −28 gC m^{-2}) occurred in the saline-alkaline land, gobi, bare rock, sandy land and bare soil, which are dominant land use types in the downstream area.

However, why is the total annual NPP in 2002 lower than that in 1998? Why does the NPP of some ecosystems increase but the others decrease? Is there a relationship between increase of NPP and decrease? What are the forcing mechanisms? To address these questions, we compiled a spatially explicit NPP difference map between 2002 and 1998 by subtracting the 2002 map from the 1998 map (figure 7). Other ancillary information, including climatic data (figures 8, 9, 10), water management data (figure 11), and the land use change maps of two case areas (figure 2 and figure 3) were also used for this analysis.
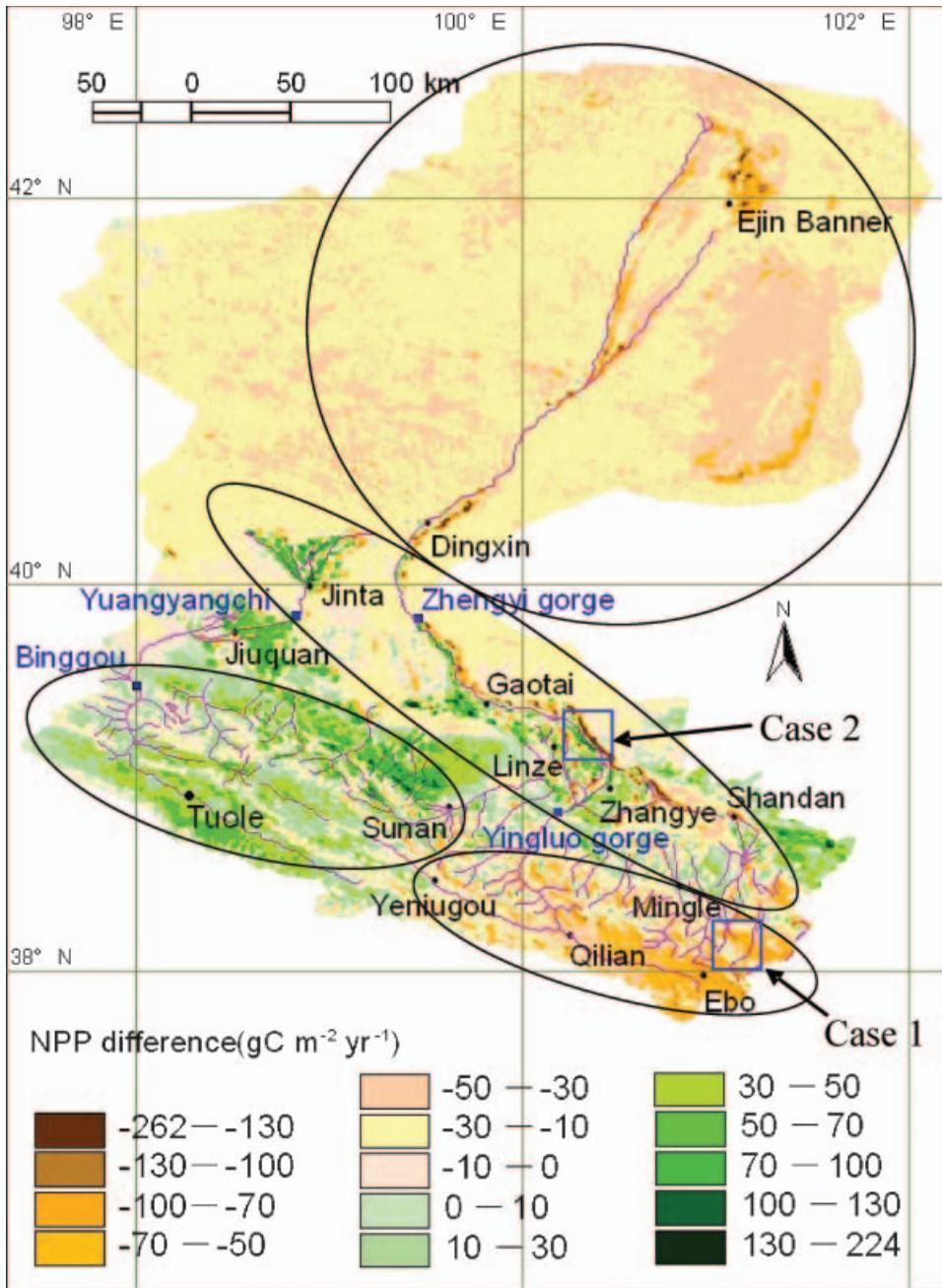
Figure 7. NPP difference in the Heihe River basin between 2002 and 1998. The changes were not uniform over the Heihe river basin, implying that the forcing mechanisms might be spatially quite variable. In the eastern part of the Qilian Mountains, NPP decreases due to the irrational reclamation and a warm and dry trend. In the western part of the Qilian Mountains, NPP increase due to the preserve activities and a warm and wet trend. In the middle reaches, NPP changes inconsistently based on the water competition between farmland and desert ecosystems. In the downstream area, NPP decreases due to a continual shortage of the down stream inflow and extremely arid climate.
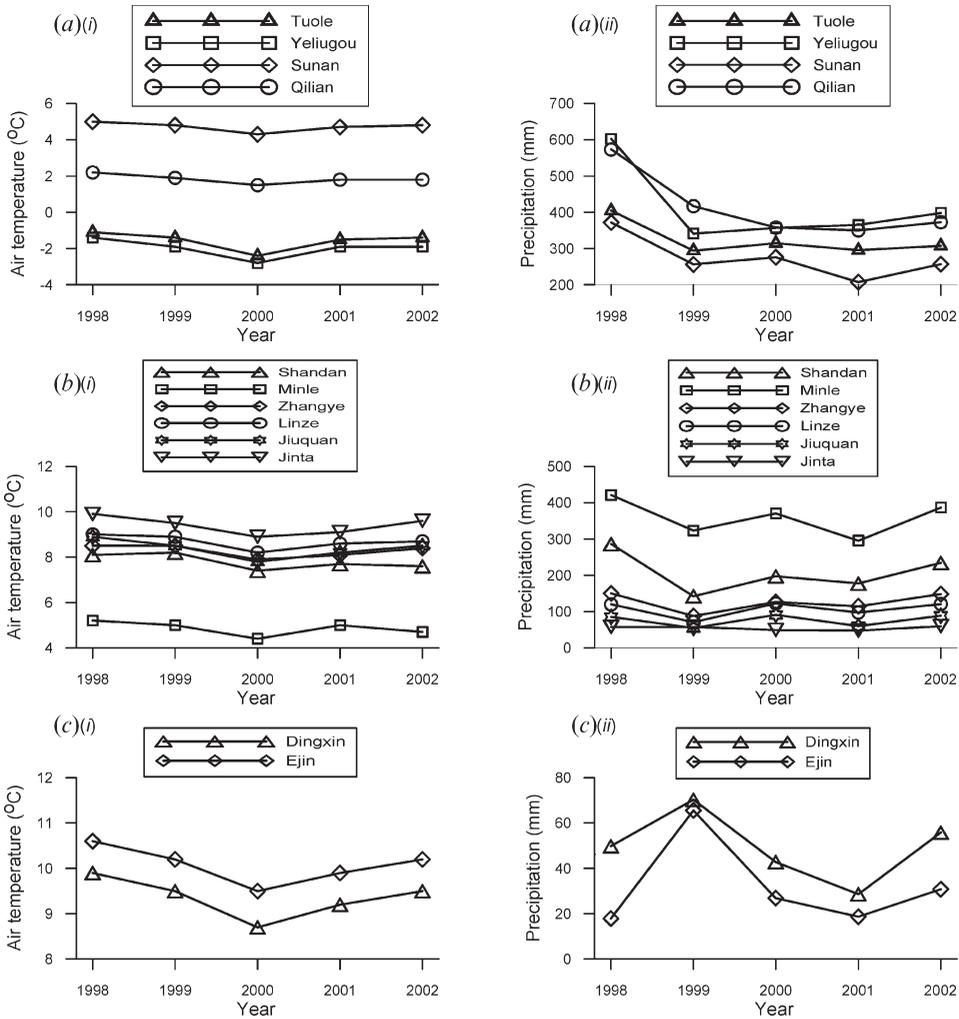
Figure 8. Mean annual temperature and precipitation in different parts of the Heihe River basin from 1998 to 2002. (*a*)(*i*) and (*a*)(*ii*) are the temperature and precipitation, respectively, in the Southern Qilian Mountains from 1998 to 2002; (*b*)(*i*) and (*b*)(*ii*) are the temperature and precipitation, respectively, in the middle Hexi corridor from 1998 to 2002; (*c*)(*i*) and (*c*)(*ii*) are the temperature and precipitation, respectively, in the northern Alxa High Plain downstream from 1998 to 2002.

5.3 *Possible forcing factors on the NPP change*

As shown in figure 7, there were a wide range of NPP changes in the whole basin between 2002 and 1998. The spatial heterogeneity of changes was significant. In the Qilian Mountains, the NPP decline occurred in the eastern part, whereas increases appeared in the western part. In the middle Hexi Corridor, the NPP change seems to elicit a large inconsistency. In the northern Alxa High Plain downstream, a negative trend of NPP was apparent. Therefore, the changes were not uniform over the Heihe river basin, implying that the forcing mechanisms were spatially quite variable.

5.3.1 NPP changes in the Qilian Mountains. Figure 8 (*a*) shows that the climate variations in the west and east Qilian Mountains from 1998 to 2002 had a similar
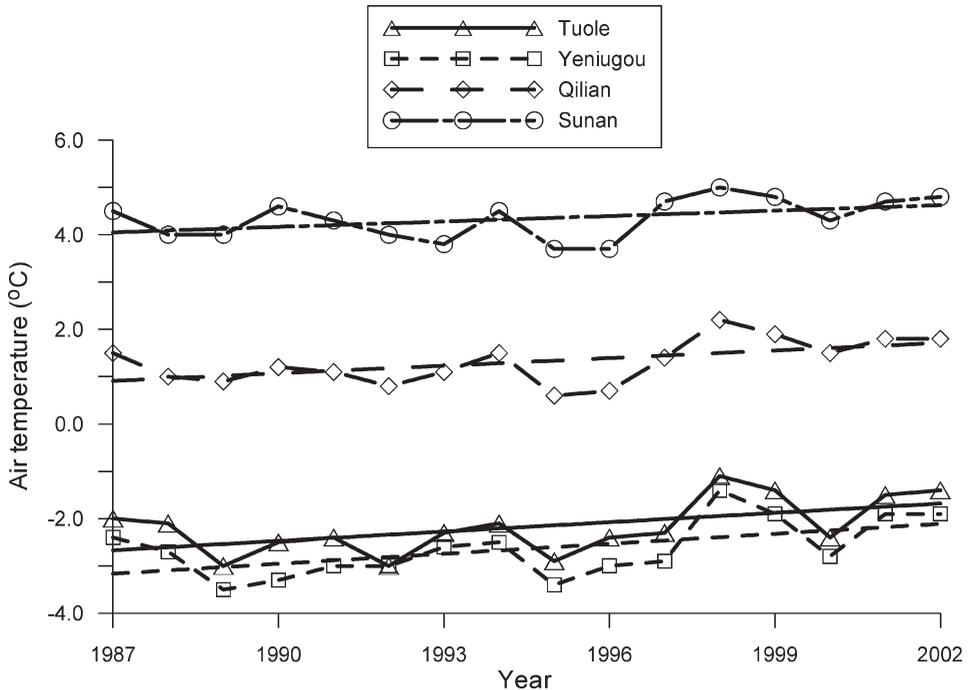
Figure 9.   Trends of mean annual temperature in different parts of the Qilian Mountains (West: Tuole and Sunan; East: Yeniuguo and Qilian) from 1987 to 2002. Statistical tests: Tuole, $n=16$, $p=0.03$; Sunan, $n=16$, $p=0.10$; Yeniugou, $n=16$, $p=0.03$; Qilian, $n=16$, $p=0.03$. This figure profiles a climate warming trend in the Qilian Mountains over the 16-year period.

trend. At all the meteorological stations, annual air temperature was constant and annual precipitation declined. However, in contrast NPP increased in the west but decreased in the east. So, what are the potential causes?

Shi *et al.* (2003) suggested that since 1987 the west Qilian Mountains has experienced a climatic shift from warm-dry to warm-wet conditions, whereas the east Qilian Mountains is still under the warm-dry climate due to less benefit from the westerly atmospheric circulation and less glacial and snow melt than in the west. Figure 9 profiles a pronounced climate warming in the Qilian Mountains during the last 16 years. In addition, figure 10 suggests a slight increase trend in annual precipitation in the west Qilian Mountains (as shown in the Tuole station) but a slight decrease in the east Qilian Mountains (as shown in the Yeniugou and Qilian stations). Climate warming accelerates glacier and snow melt, which has been observed in many of the high mountains of north-west China during the last decades (Shi *et al.* 2003). According to the Glacier Inventory of China (Shi *et al.* 2005), there are 1078 glaciers covering 420.55 km^2 in the Qilian Mountains. The water storage of the glaciers accounts for 137.7×10^8 m^3, and the annual glacial meltwater accounts for 2.98×10^8 m^3. The ratio of the glacial meltwater to the total river run-off is averaged at 8% and is larger in the west part than in the east part. In particular, most of the big glaciers distribute in the western part of the Qilian Mountains, so they make more significant contribution to the total river run-off in these regions. Additionally, human usage of water in the west Qilian Mountains is negligible. Consequently, as figure 11 indicates, an obvious run-off increase from 1987 to 2002 was measured at the Binggou hydrological station in the west Qilian Mountains,
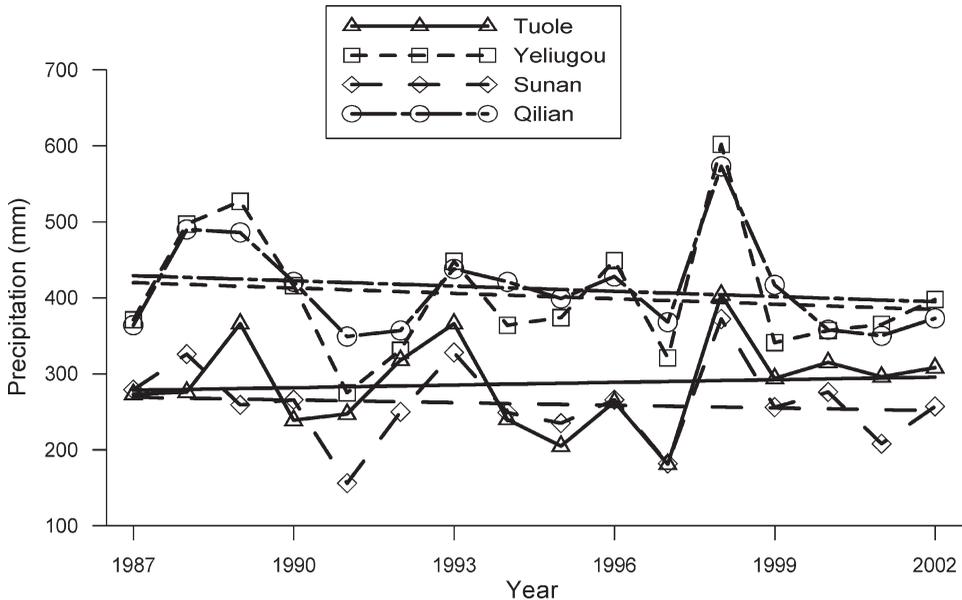
Figure 10. Trends of mean annual precipitation in different parts of the Qilian Mountains from 1987 to 2002 (West: Tuole and Sunan; East: Yeniuguo and Qilian). Statistical tests: Tuole, $n=16$, $p=0.73$; Sunan, $n=16$, $p=0.70$; Yeniugou, $n=16$, $p=0.62$; Qilian, $n=16$, $p=0.52$. This figure suggests a slight increase trend in annual precipitation in the west Qilian Mountains (as shown in the Tuole station) but a slight decrease in the east Qilian Mountains (as shown in the Yeniugou and Qilian stations) over the 16-year period.

whereas run-off decline in the same period was found at the Yingluo Gorge in the east Qilian Mountains. The western part of the Qilian Mountains contains large areas of natural ecosystems, including forest, shrub, alpine meadow and cold desert, but few farmlands (figure 1), suggesting that human disturbance is slight here. Therefore, better climatic conditions in the form of climate warming and wetting are in favour of an NPP increase in the western part of the Qilian Mountains. In addition, the national 'Tian Bao' (Natural Forest Preserve) project has been intensively executed in this region since 1998 (http://www.tianbao.net). According to field investigations (Li 2006), more than 52% of forest area in the Heihe River basin is distributed in the Sunan County of the western and middle Qilian Mountains, which is the county with the largest area of preserved forest since the 'Tian Bao' project initialized. Figure 7 shows that the highest NPP increase of closed forest mainly occurred in Dahe town and Qifeng town in the western part of Sunan County, with about 80–100 $gC m^{-2}$ absolute NPP increase over the five years. As the Statistical Annals reported, about 7.8 km^2 afforestation area was expanded and 130 000 trees were planted around the two towns over the five years. Therefore, it is suggested that the large positive NPP trend in the western part of the Qilian Mountains is driven by both conservation practices and a warmer and wetter climate.

In contrast, although the same climate warming occurs in the eastern part of the Qilian Mountains, NPP is observed to decrease. The decline in rainfall (figure 8(*a*ii)) and run-off from the Yingluo Gorge (figure 11) could partly explain the NPP decrease, but not adequately. Human activities may play a more important role. As reported by many investigators, continuous grassland degradation and land desertification occurred in these areas due to agricultural expansion and overgrazing in the last few
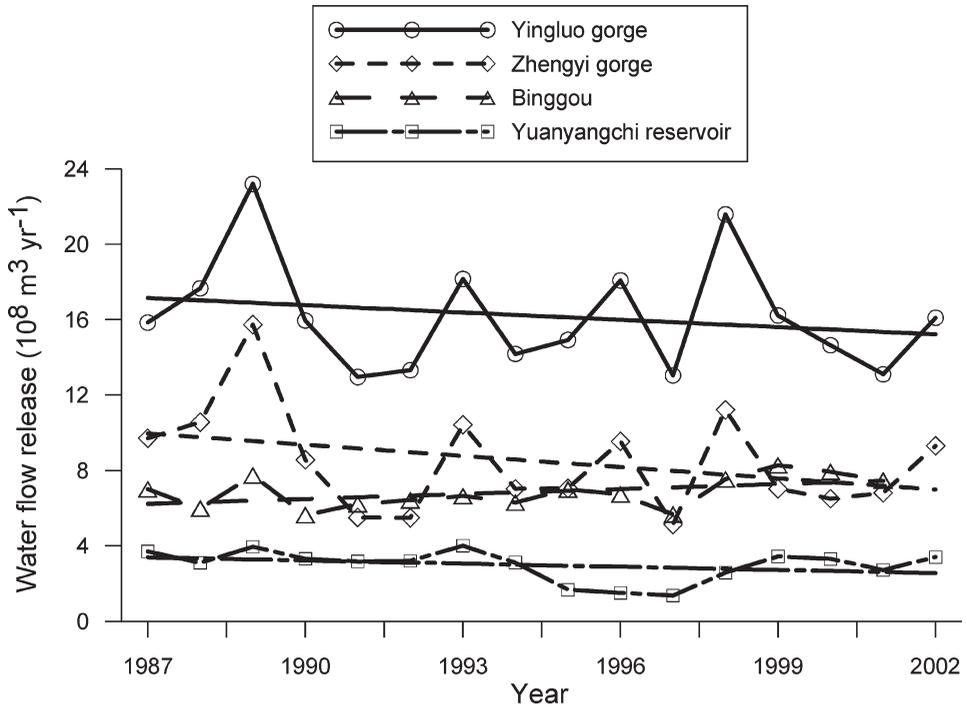
Figure 11.   Run-off flows released between the Bingou and Yuangyangchi reservoirs and the Yingluo and Zhengyi gorges between 1987 and 2002. Statistical tests: Yingluo, $n=16$, $p=0.45$; Zhengyi, $n=16$, $p=0.19$; Binggou, $n=15$, $p=0.07$; Yuangyangchi, $n=16$, $p=0.22$.

decades (Lu *et al.* 2003, Zhao and Dang 2003, Zhao *et al.* 2004). For example, local farmers have converted many closed grasslands into rape oil farmlands. Rape oil farmland has high economic benefit but consumes large water resources due to its high evapotranspiration, therefore further enhances the drought and degradation of the adjacent closed grasslands (by personal communication from local farmers). According to the results in figure 9, an absolute decrease of 50–70 $\mathrm{g\,C\,m^{-2}}$, i.e. a 10–25% relative decrease in NPP, is present in the large area of closed grasslands in the east Qilian mountains. In order to identify the magnitude and direction of the impacts of human activities, a case study of land use change in this region was performed (figure 2 and §3.3.3). There were two kinds of unfavourable land use changes. The first was the transformation of perennial grassland (alpine meadow) into non-irrigated farmland by manual technologies in the upstream area. This led to increased exposure of topsoil to wind, decline in soil fertility and reduced edible biomass, which in turn accelerate overgrazing of vicinal grasslands to keep the local livestock production (Zhao and Dang 2003). The second change was the transition from forest, shrub and grassland into cold desert. This displays a fragmentary distribution and complex shape (figure 2), indicating the influence of natural phenomena such as water erosion on slopes and wind erosion on fragile soils. According to field investigation and social capital analysis, Li (2006) also reported that local farmers have the lowest awareness of ecological preservation among farmers in the basin. Therefore, we suggest that the remarkable NPP decrease in the eastern part of the Qilian Mountains is derived from a mixture of drought and human disturbance in the form of irrational reclamation and overgrazing.

5.3.2 NPP changes in the middle Hexi Corridor. In the middle Hexi Corridor between the Yingluo and Zhengyi Gorges, the NPP change presented a complex spatial pattern, with positive and negative trends coexisting in artificial oases dotted along the river stream (figure 7). Do the increases and declines of NPP in the midstream area respond to the same forcing? To explore this question, we first investigated the climate variability in this region. As shown in figure 8 (*b*), from 1998 to 2002 the annual air temperature declined slightly and annual precipitation remained almost constant in the oases such as Zhangye, Linze, Gaotai, Jiuquan and Jinta. Therefore, it is suggested that climate variability cannot explain the inconsistent NPP changes in the midstream areas of the Heihe River basin. On the other hand, the Hexi Corridor has approximately $5000 \, km^2$ of irrigated farmland. It is due to the water in the Heihe River that these artificial oases are densely populated regions and important commodity grain bases in north-west China. Meanwhile, the available water resources are certainly limited. The amount is equal to the water allocation differences between the Yingluo and Zhengyi Gorges and between Bingou and Yuanyangchi reservoir (figure 11). For the available water resources, about 80% was used for irrigation and economic use, and only 20% for natural ecosystems in the middle region (Liu and Chen 2001).Strong competition for water between irrigated farmland and natural ecosystems exists in the middle Hexi Corridor. In order to test this phenomenon, another case study of land use change in the midstream was also performed in Linze County (figure 3 and §3.3.3). According to the data, the land use change was dominated by two coexisting but opposite processes: expansion of oasis and desertification. They were comparable in terms of transformation areas, making the NPP change diverse in the midstream area of the Heihe River basin.

The NPP decrease along the river stream may be due to the conversion of riparian land into the temporal reservoir/pool between 1999 and 2002. According to the results in figure 9, there was a decline in NPP in these submerged zones, with about $100–200 \, gC \, m^{-2}$ absolute decrease, i.e. 25–50% relative decrease. This is also in accordance with the land use change.

Therefore, due to the water competition between artificial oases and deserts, the NPP changed inconsistently in the middle Hexi Corridor. The growth and decline of NPP is mainly dependent on the availability of water resource, which in turn depends on water policy and management strategies.

5.3.3 NPP changes in the northern Alxa High Plain. The vast northern Alxa High Plain downstream occupies more than half of the total area of the Heihe River basin. From 1998 to 2002, NPP decreases took place everywhere in this region. The NPP change (figure 7) shows a relatively small heterogeneity in the downstream area compared to that in the upper and midstream regions. Many areas, especially the gobi and bare rock, have very homogeneous NPP values, indicating the same forcing factor. Figure 8(*c*) showed a slight decline in both annual air temperature and annual precipitation in Dingxin and Ejin in the downstream area from 1998 to 2002. This suggests that lower rainfall is a forcing factor that results in NPP decrease in the extremely arid area of northern Alxa High Plain.

NPP decrease was stronger along the river stream and in its vicinity. The largest negative NPP trend occurred here, revealing that another forcing factor related to run-off is at work. The landscape along the downstream river and its tributaries is dominated by natural oases. The vegetation is mainly river bank forest, such as diversiform-leaved poplars and saline shrubs as well as meadows and grassland. Their

productivities rely on the in-stream water and ground water, where the ground water is recharged by the surface water flow of the Heihe River. Liu, H. *et al.* (2005) stated that to maintain the habitats of the natural ecosystems downstream, the annual water flow released from the Zhengyi Gorge should not drop below $0.95 \, km^3$, of which about $0.56 \, km^3$ of water resources is to be reserved for the Ejin Banner oasis and terminal lakes. The remaining $0.39 \, km^3$ is used for other oases between the Zhengyi Gorge and Ejin Banner. In recent years, although the water released for downstream areas increased slightly due to a new water management policy, it has not reached $0.95 \, km^3$. Therefore, the long-term water deficit had lowered the groundwater levels by 2–3 m in the centre of Ejin Banner since 1988. From 1982 to 1995 the coverage in the Ejin Banner oasis declined by 31% for diversiform-leaved poplars, by 57% for sand jujube, by 39% for red willows, and by 7% for suosuo willows (Liu, H. *et al.* 2005). Our study also illustrated the strong deterioration of downstream oases in the form of a NPP decline from 1998 to 2002. Therefore, it is suggested that the amount of water allocated to downstream areas of the Heihe River basin is a major control on ecosystem function in this area. If the administrated flow released from the Zhengyi Gorge keeps on declining, the ecological environment in the region will deteriorate and desertification will progress further.

6. Conclusions

The oases in the arid inland river basins are of economical and ecological importance in northwest China. They are usually endowed with a rich ecosystem diversity and high NPP but are undergoing a continuous ecosystem degradation and even desertification in recent decades. Recent advances in the acquisition and interpretation of remotely sensed data offer a valuable tool to characterize and quantify these changes. The integration of the C-Fix NPP model with the high spatiotemporal resolution NDVI data from the SPOT/VEGETATION sensor allows a complete and detailed analysis of the driving forces of NPP changes over the whole basin area.

As a case study, we investigated the NPP changes in the Heihe River basin from 1998 to 2002 and made suggestions for the most important forcing mechanisms related to the NPP change. NPP in the arid inland basin can change dramatically even in a short period. Furthermore, the changes are not uniformly distributed across the whole basin, suggesting that the forcing mechanisms vary spatially. With the help of ancillary information including climate data, water management reports and higher resolution imagery of ETM +, we suggest that the NPP increase in the western part of the Qilian Mountains is by both due to conservation practices and a warmer and wetter climate, while the remarkable NPP decrease in the eastern part of the Qilian Mountains is mainly due to farmland reclamations and overgrazing. Positive and negative trends of NPP change coexist in the artificial oases in the middle Hexi Corridor, revealing intense competition for water between farmland and desert ecosystems. It is suggested that a decline in NPP occurring in the northern Alxa High Plain in the downstream area can be linked with a continuous water shortage, which decreases the plant growth.

The intensive expansion of farmland in the upper and midstream areas is suggested to be a dominating forcing factor for a continuous NPP degradation in the natural ecosystems over the whole basin. If the downstream water flow keeps on declining, the ecosystems in the region will deteriorate further and desertification will be enhanced.

It is noticed that the NPP loss occurs spatially in ecosystems constrained by water availability. Both natural variation of precipitation and human activities play roles in water availability. The latter result in (1) competition for water between agriculture, grazing and natural ecosystems in the eastern part of the Qilian Mountains; (2) competition for water between agriculture and natural ecosystems in the middle reaches, (3) competition for water between middle and downstream areas. Many of the NPP changes presented in this paper are closely related with these water competitions caused by human activities.

Viewed methodologically, NPP models on remote sensing, such as C-Fix, provide a facilitative way to quantify NPP of large areas. Furthermore they can be used to monitor changes like degradation or restoration of land use. These processes are particularly important for arid land river basins under the pressure of water resource shortage. On the other hand, this kind of NPP model relies heavily on the quality of remotely sensed data and parameterization methods. Therefore, two aspects should be given attention in our further study and modelling efforts. One is to analyse whether the effect of water limitation in the arid region can be sufficiently expressed through the use of NDVI only. The other is the determination of model parameters, which vary for different vegetation types rather than remaining constant in the study area. The proper parameter values will lead to an improved estimation of NPP.

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