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Vegetation and carbon sequestration and their relation to water resources in an inland river basin of Northwest China

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Abstract

In the Heihe River Basin in the arid inland area of northwest China, the distribution of water resources in vegetation landscape zones controls the ecosystems. The carbon sequestration capacity of vegetation is analyzed in relation to water resources and vegetation growing conditions. During the last 20 years, the vegetation ecosystems have degenerated in the Heihe River Basin. Simulation using the C-FIX model indicates that, at present, the total amount of *NPP* of vegetation accounts for about 18.16 TgC, and the average value is 106 gC/m^2/yr over the whole basin. *NPP* has generally the highest value in the upperstream mountain area, middlestream artificial oases area, downstream river bank area, alluvial fan and the terminal lake depression where vegetation grows relatively well. The lowest value is found in the vast downstream desert and Gobi area. Protection of vegetation ecosystems and enhancement of carbon sequestration require such inland river basins as the Heihe River Basin to be brought under management in a comprehensive way, taking water as a key, to carry out a rational and efficient allocation and utilization of water resources.

Keywords: Inland river basins; Vegetation; Carbon sequestration; Water resources; Management

1. Introduction

The arid inland area of northwest China is located from north of 35°N and from west of 106°E in China, accounting for 24.5% of the land area of the country. The very arid continental climate, low precipitation and low runoff coefficient, and the topography of high mountains alternating with plains and basins, all make the ecosystems very vulnerable and they possess marked vertical zonal characteristics. Water is the key controlling factor for vegetation distribution in the arid area of northwest China. The vegetation ecosystems are characterized by small forest covered areas in the mountains and desert vegetation distribution in the plains and basins, and by very sparse vegetation distribution in the area as a whole. Moreover, the limited water resources are collectively utilized in the artificial oases in the middlebasin plain area, where irrigation agriculture is very well developed, forming a farmland vegetation ecosystem, frequently causing over-exploitation of water resources and degradation of natural ecosystems in the downstream area. To date, the carbon cycle and sequestration function of terrestrial ecosystems in the arid inland area of northwest China has not been investigated.

The arid area of northwest China consists of various relatively independent inland river basins. Each inland river basin contains clear vertical zonation of vegetation, namely high mountain glaciers, a snow and permafrost zone, a mountain vegetation zone, an artificial oases zone in the middlestream area and natural oases and desert zone in the downstream area (Kang et al., 1999). In the inland river basins, water resources are generated in the mountains in the upperstream area and consumed and distributed in the plain and basins in the middle and downstream areas. The advance and retreat of oases, ecological degradation and desertification are closely related to allocation and utilization of water resources.

In order to investigate the carbon cycle and carbon sequestration of the vegetation ecosystems in the arid inland river basins of northwest China, the Heihe River

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Basin in the Hexi area was chosen as a representative. The Hexi area is located at 37°17′–42°48′N, 93°23′–104°12′E, to the west of the Yellow River in Gansu Province, covering an area of $33.9 \times 10^4\,km^2$. Administratively, the Hexi area belongs to three prefectures of Gansu Province (from east to west: Wuwei, Zhangye and Jiuquan mainly in the three inland river basins respectively). The three inland river basins are from east to west: the Shiyang River Basin, the Heihe River Basin and the Shule River Basin. In the Hexi area, some areas in the south belong to Qinghai Province and some in the north to the Inner Mongolia Autonomous Region. The Hexi area is bordered by the Wuqiaoling on the east, the Xinjiang Uigur Autonomous Region on the west, the Qilian Mountains and Aljin Mountains on the south and Inner Mongolia to the borders of the Mongolian Peoples Republic to the north.

Based on field investigations of vegetation ecosystems, water resources and *NPP* simulation by the C-FIX model, this paper is intended to analyze the relationship among water resources, the vegetation landscape zones, ecosystems and carbon sequestration in the Heihe River Basin. Distribution of *NPP* and the factors that impact it are studied. Comprehensive countermeasures for enhancing the carbon sequestration capacity in the three basins are also discussed.

2. Arid environment and vertical zonal vegetation ecosystems

2.1. Characteristics of the water cycle

The Heihe River Basin is one of the relatively large inland river basins in the arid regions of northwest China. The drainage area of the Heihe River Basin ranges from 37°45′ to 42°40′N and from 96°42′ to 102°04′E, covering an area of $13 \times 10^4\,km^2$ (Fig. 1). The Heihe River originates in the Qilian Mountains in Qinghai province, and flows through the Hexi Corridor of Gansu Province and enters

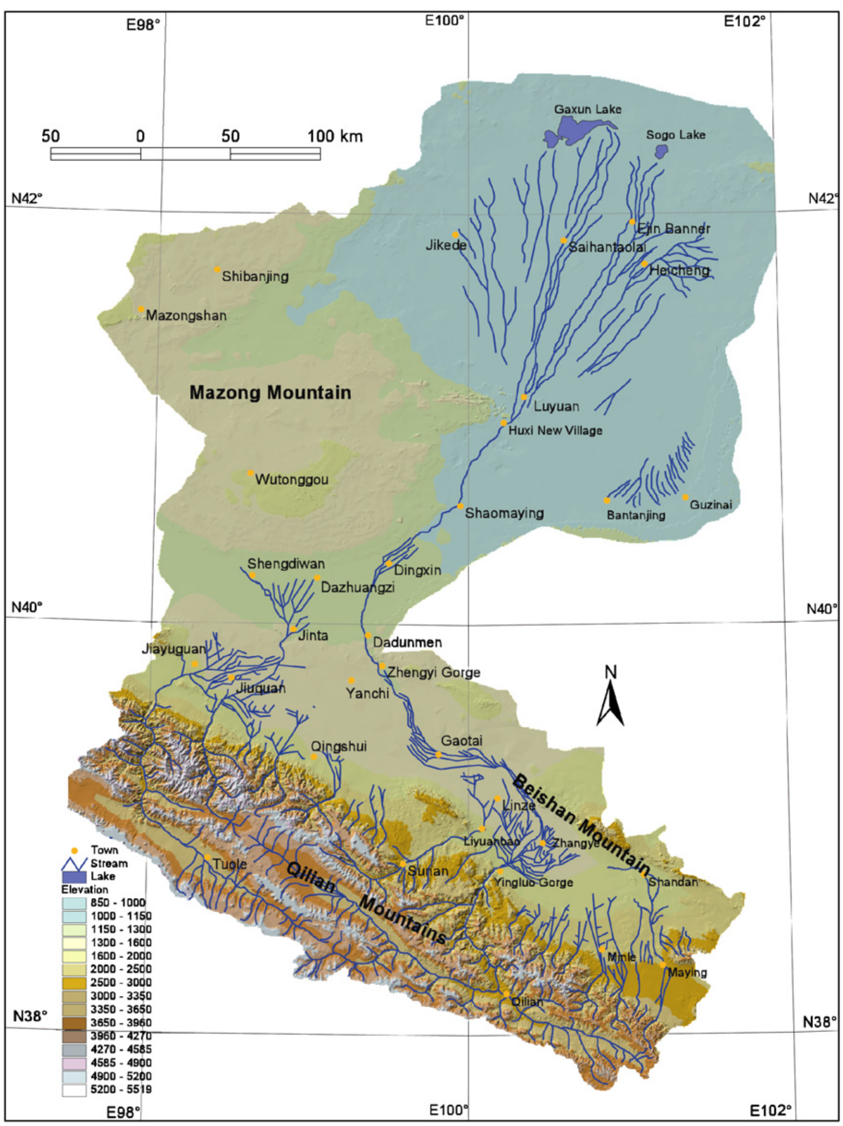

Fig. 1. Sketch map of the Heihe River Basin (drawn by Li Xin).

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the western part of the Inner Mongolian Plateau (Gao and Li, 1990).

The Heihe River Basin is situated in the inland area of Eurasia, far from the oceans. The water vapor originates mainly from the summer southeast monsoon from the Pacific Ocean and the summer southwest monsoon from the Indian Ocean (Zhou, 1983; Sun, 1978) and also from westerly air flows (Yang, 1992). In winter, it is extremely cold and dry because of the dominant control over the area by the Mongolian and Siberian High Pressure system. The highest air temperature in summer can reach about 40 °C in the plains and downstream area, while the lowest air temperature in winter falls to about −40 °C in the high mountain upper basin area. The annual precipitation is generally 50–200 mm in the plains and basin area, and about 200–500 mm in the mountain areas. About 70–80% of the annual precipitation is concentrated in the months from June to September, while less than 5% occurs in the winter months from December to February (Chen and Qu, 1992; Li et al., 1999). Therefore, the Heihe River Basin has an extreme continental dry climate and is short of water resources.

The Heihe River drainage system consists of 35 rivers, which can be divided into three sub-drainage systems: the east sub-drainage system, the middle sub-drainage system and the west sub-drainage system (Fig. 1). The water balance of Heihe River Basin is characterized by low precipitation, rapid evaporation and low runoff ratio (Table 1). Because of the increasing utilization of the water resources, the three sub-drainage systems have been separated from their surface water hydraulic connections, forming three relatively independent drainage systems. However, there may be some sub- surface hydraulic connections, but this point needs further investigation.

According to the Glacier Inventory of China (Wang et al., 1981), there are 1078 glaciers covering 420.55 km^2 in the Qilian Mountains of the Heihe River Basin. The water storage of the glaciers amounts to 137.7×10^8 m^3, and the annual glacial melt water produces 2.98×10^8 m^3. The alimentary ratio of the glacial melt water to the total river runoff averages 8% (Yang, 1991).

Fig. 2 shows the significant altitude dependency of annual air temperature, precipitation and pan evaporation measured at the standard meteorological stations distributed throughout the Heihe River Basin (Kang, 2002). Precipitation exceeds evaporation in the mountain area which is the area of runoff generation and water resources formation. In the plain, basins, oases and desert areas, evaporation greatly exceeds precipitation. Consequently, this area is characterized by moisture deficiency and is also the area of salt accumulation (Kang et al., 2002). Basically, the climate of the area to the south of the Qilian Mountains is the cold and temperate semi arid mountain type; while the northern lowland areas of the basin belong to the temperate arid and desert type of climate.

2.2. Vegetation ecosystems

In the inland river basins of the arid area of northwest China, types, distribution and changes in vegetation are

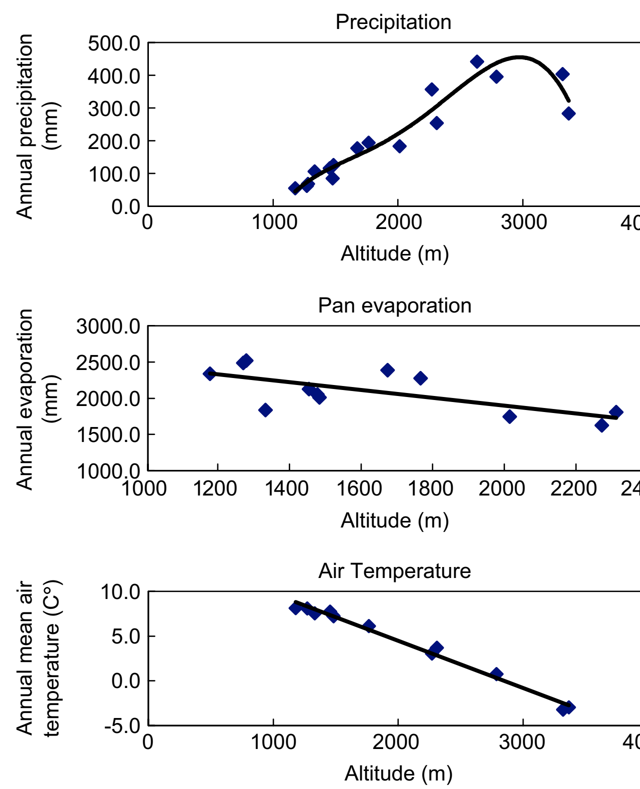

Fig. 2. Altitude dependency of yearly mean air temperature, total precipitation and pan evaporation in the Heihe River basin (averaged values at the standard meteorological stations during 1956–1998) (from Kang, 2002).

Table 1
Precipitation and runoff in the Heihe River Basin (from Kang, 2002)

	Drainege area (km^2)	Precipitation		Runoff		Runoff ratio
		10^8 m^3	mm	10^8 m^3	mm	
East drainage system	105602	122.6	116.1	29.28	27.7	0.24
Middle drainage system	5273	9.8	185.9	2.97	56.3	0.30
West drainage system	19125	33.5	175.2	9.61	50.2	0.29
Whole Heihe River Basin	130000	165.9	127.6	41.85	32.2	0.25

Table 2
Ecological sub-regions of the Heihe River Basin (statistics of 1995) (from Cheng Guodong et al., 1999)

Ecological sub regions	Area (10^4 hm^2)	Description of ecosystems
Forest and grassplot of the Qilian Mountains	242.83	Forest 23.40×10^4hm^2; grassplot 138.19×10^4 hm^2
Piedmont desert steppe	48.35	Forest and farmland 12.69×10^4 hm$^{2;}$ steppe 33.22×10^4 hm^2
Middlestream plain area of irrigation agriculture (artificial oasis)	327.97	Farmland 227.29×10^4 hm^2; grass 78.44×10^4 hm^2; wasteland 23.23×10^4 hm^2
Middlestream plain area of salinization soil	31.45	Located in the central area of the middlestream
Middlestream area of desert and Gobi	135.76	Located in the northwest area of the middlestream
Downstream natural oasis	193.15	River bank forest, shrub, grass and pasture of the Ejin Banner oasis area
Downstream desert	171.42	In the terminal lakes basin
Downstream low hill desert	149.09	West of the downstream area
Total	1300.02	Mountain forest accounts for 1.80% of the basin area, mountain grass 10.63%, piedmont steppe 3.72%, artificial oasis 25.23%, natural oasis 14.86%, desert 43.76%

closely related to water availability. The response of vegetation to water availability is very sensitive. Because of a long history of exploitation and utilization of water and land resources by human activities, the natural vegetation has been converted to artificial vegetation. The vegetation ecosystems have the following characteristics (Li et al., 2002).

The natural vegetation is dominated by grass and shrubs. The vegetation has clear vertical zonality because of altitude-dependent climatologic elements (Fig. 2). In the Heihe River Basin, the upper reaches are in the Qilian Mountains. Below the snow line (about 4200 m a.s.l.), the vegetation can be divided into high mountain meadow, brush and meadow, mountain grass and forest (mainly *Picea crassifolia*), mountain grass and finally desert grass in the north. In the middle basin, below the piedmont, the vegetation is based mainly on artificial oases. In the downstream Ejin Banner area, the vegetation belongs to the extreme arid desert-grass type, and desert forest and various saline soil brush and meadows along the river bank and the terminal lakes. As water utilization increases in the upper and middle reaches, the vegetation downstream is easily damaged and degraded. Non-natural vegetation, in addition to farm land, includes planted forests, grass, garden plots and green land. The non-natural forest, including arbor forests and shrubs, comprise shelter belts protecting farmland as windbreaks, and, sand-fixing forests. In addition to vegetation, 44% of the basin is occupied by desert.

On the basis of topography, hydrology, climatology, and ecology and the distribution of land and water resources and their economic utilization patterns, the ecosystems of the Heihe River Basin can be divided into 8 sub-regions (Table 2).

2.3. Problems of water resources and ecosystem change

Water resource problems in the Heihe River Basin can be attributed to the serious shortages produced by over-exploitation. To maintain the stabilization and equilibrium of natural landscape zones and ecosystems, a rational distribution of water resources should be developed to benefit all parts of the river basin. The long history of exploitation and utilization of water and land resources in the inland basins has included the following: forestry and animal husbandry in the southern mountains in the upper basin area, irrigation agriculture in the corridor area of the middlestream, and natural oases and desert pasture in the northern downstream area. If the utilization of water resources in the upper and middle basin area exceeds the natural flow, both the surface runoff and groundwater storage in the downstream areas will be reduced, causing a lowering of the water table. Moreover, to compensate for the reduction of surface runoff in the downstream area, extraction of ground water has greatly increased, causing serious depletion and lowering of the water table, resulting in vegetation degeneration and desertification.

The scarce water resources of these inland basins have to support both economic development and the functioning of ecosystems. During the process of economic development, industry and agriculture seldom consider the needs of the ecological system leading to eventual environmental deterioration. It is important that there should be a balance between the needs of the economy and the needs of ecological system. The present ecological status must be maintained through the provision of adequate water resources. The water required for vegetation refers to the plant consumption required to prevent further deterioration and gradually improve the biotic environment (Liu and Chen, 2001). The ratio of water consumption for economy, artificial ecosystems and natural ecosystems in the Heihe River Basin is listed in Table 3.

The proportions of water consumed by the economy and by natural ecosystems reflect the stress placed on the vegetation system and environment in the inland river basins. There must be limits placed on the exploitation and utilization of water resources for economic purposes. According to the present status of exploitation and utilization of water resources in inland river basins, water use by the economy should be in the range of 30–50% of

Table 3
Ratio of water consumption for economy, artificial and natural ecosystems in the Heihe River Basin (from Liu and Chen, 2001) (Statistics from 1956 to 1995)

Economic water consumption	Ecological water consumption	Artificial oases water consumption	Natural oases water consumption	Artificial oases Economic water consumption	Ecological water consumption
0.60	0.40	0.75	0.25	0.80	0.20

Table 4
Change of vegetation ecosystems in the Heihe River Basin from 1980s to 1990s (from Wang et al., 2003)

Mountain vegetation		Artificial oases		Natural oases		Total oases		Transition area		Desertification area	
Area change	Percent	Area change	Percent	Area change	Percent	Area change	Percent	Area change	Percent	Area change	Percent
−0.9	−28	−0.01	−1	−0.08	−29	− 0.09	−11	−1.18	−37	1.27	26

Area in 10^4 km^2.

the available water resources (Liu and Chen, 2001). In the Heihe River Basin, water use by the economic sector is nearly 80%, while only 20% is available for ecosystems. Economic activities concentrated in the middle basin area cause serious deterioration of the biotic environment and environment in the downstream Ejin Banner area.

According to recent research (Liu and Chen, 2001), during the last 20 years, the vegetation systems have been deteriorating in the Heihe River Basin (Table 4). Decreasing mountain vegetation, shrinking natural oases, and the reduction of the transition area between oases and desert indicates the increase of desertification.

3. Carbon sequestration of vegetation

3.1. Net primary productivity (NPP) of vegetation

NPP is defined as the net total organic mass of green vegetation produced by photosynthesis per unit area and unit time and from which the autotrophic mass is deducted. It is expressed in $gC/m^2/yr$. *NPP* indicates the growing status and productivity of vegetation, and is an important factor for estimating the biosphere carbon cycle as well as carbon sources and sinks (Field et al., 1998). In the Heihe River Basin, the photo-energy utilization ratio model C-FIX, high-resolution SPOT/VEGETATION remote sensing data, global grid meteorological data and the land utilization map of the Heihe River Basin have been used to estimate the *NPP* gross amount, its annual accumulation and spatial distribution, in order to assess the carbon sequestration capacity of vegetation ecosystems under different land utilization patterns (Lu, 2003).

3.2. C-FIX model

The C-FIX model (Veroustraete et al., 2002) is based on the Monteith theory (Kumar and Monteith, 1981) of photo-energy utilization and is driven by air temperature, radiation and the effective radiation ratio (*fAPAR*) for photosynthesis of the vegetation canopy. The model can be used to estimate the Gross Primary Productivity (*GPP*), Net Primary Productivity (*NPP*), and Net Ecosystem Productivity (NEP) (Sabbe and Veroustraete, 1999, 2000).

For a given point position or grid, the C-FIX model is based on the following equations to compute the daily *NPP* value:

$$GPP_{\mathrm{d}} = p(T_{\mathrm{atm}})\,\mathrm{CO_2fert}\,\varepsilon fAPAR\,c\,S_{\mathrm{g,d}}, \tag{1}$$

$$NPP_{\mathrm{d}} = GPP_{\mathrm{d}}(1 - A_{\mathrm{d}}). \tag{2}$$

The variables in Eqs. (1) and (2) are explained as follows. GPP_d and NPP_d are daily Gross Primary Productivity and daily Net Primary Productivity ($gC/m^2/d$), respectively; $p(T_{atm})$ is a normalized factor which is dependent on daily air temperature T_{atm}, and indicates the role of air temperature in the photosynthesis efficiency. It has a value between [0, 1] (Wang, 1996); CO_2fert is a normalized CO_2 fertilizer effect factor (Veroustraete et al., 2002); ε is the photo-energy utilization ratio during the *GPP* stage, and its value is approximately 1.1 gC/MJ (Wofsy et al., 1993); *fAPAR* is the fraction of photosynthetically active radiation absorbed by the vegetation canopy, and it is determined based on the vegetation index or leaf area index obtained by remote sensing.

In the present study, the algorithm developed by Myneni and Williams (1994) is used:

$$fAPAR = 1.1638\,NDVI_{\mathrm{toc}} - 0.1426. \tag{3}$$

C is the the ratio of effective photosynthetic radiation (0.4–0.7 μm) to the total incident radiation. Its value varies between 0.45 and 0.5 and a value of 0.48 has been used in the present study; $S_{g,d}$ the incident solar radiation flux ($MJ/m^2/d$). A_d the ratio of carbon for autotrophic respiratoration of vegetation to *GPP* (Goward and Dye, 1987); $NDVI_{toc}$ the Normalized Difference Vegetation Index at the top of the canopy.

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3.3. Data

For computation of *fAPAR*, VGT-S10 *NDVI* (10 days maximized *NDVI*) data from the CTIV of the Belgium VITO institute were applied to 1 km resolution maps of East Asia from April 1st, 1988 to December 31st, 2002. For driving the C-FIX model, the global $1.5^\circ \times 1.5^\circ$ daily grid of meteorological data from Meteo France was applied and interpolated into a $0.25^\circ \times 0.25^\circ$ spatial resolution grid. The land-use map of China on a scale of 1 to 1 million compiled and authorized by the Institute of Geographical Sciences and Natural Resources Research, CAS has also been used as a data base.

3.4. Validation

(1) *NPP simulation against ground data*: To evaluate the C-FIX model simulation, Lu (2003) collected the measured *NPP* data for the forest area of west China from 1989 to 1994 from the Oak Ridge National Laboratory Distributed Active Archive Center (Ni et al., 2001) and from the Forestry Bureau of China. A total of 41 measured points in the forest area have been selected to represent the cold and temperate mountain forest in the area from 90° to 110°E and from 29° to 40°N where the mountain area of Heihe River Basin is situated. The *NPP* values of the 45 points were simulated using the C-FIX model in 1999. The measured and simulated *NPP* values are correlated and shown in Fig. 3.

The correlation coefficient of Fig. 3 is 0.47 and it is statictically significant. The average *NPP* value is 475.9 g/m^2/yr for the measurements and 546.8 g/m^2/yr for the simulation; the relative difference is 14.9%.

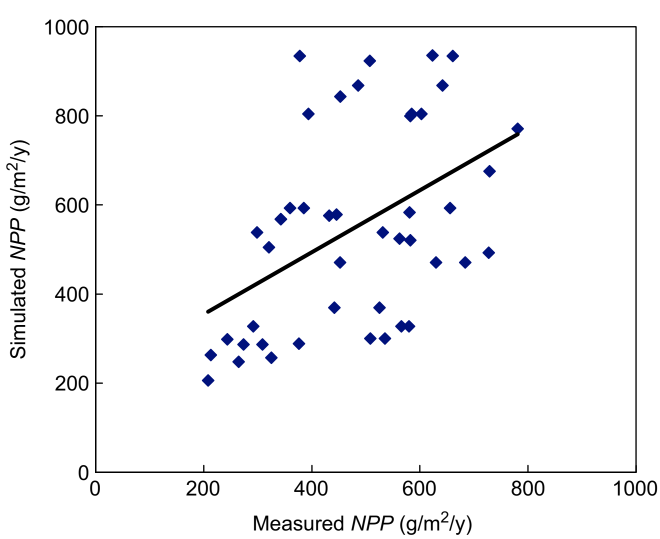

Fig. 3. Correlation of simulated and measured *NPP* values in the forest area of west China (The correlation equation of simulated *NPP* (symbolized as *SN*) to measured *NPP* (symbolized as *MN*) is: $SN = 0.70\ MN + 215.85$, square of correlation coefficient $R^2 = 0.221$).

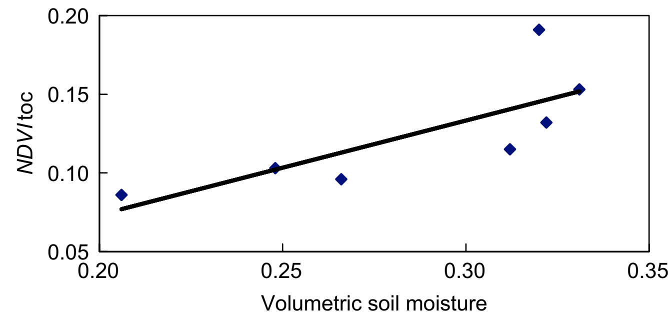

Fig. 4. Correlation between monthly $NDVI_{toc}$ and measured volumetric soil moisture in the downstream area of the Heihe River Basin (42°01′N, 101°14′E, 920.5 m a.s.l., during June to December of 2002, square of correlation coefficient $R^2 = 0.59$).

Lu (2003) also chose Tianzhu (102°26′E–37°37′N) to represent grassland and Haibei (101°19′E–37°12′N) to represent alpine meadow. The measured *NPP* value was 508.5 g/m^2/yr and the simulated value was 612.5 g/m^2/yr averaged for the grass land of Tianzhu from 1998 to 2002, while the measured *NPP* value was 436.5 g/m^2/yr and the simulated value was 433.6 g/m^2/yr averaged for the alpine meadow of Haibei during the same period. The simulated and measured *NPP* values are rather close to each other.

Therefore, we consider that the C-FIX model simulation of *NPP* values is valuable for the Heihe River Basin.

(2) *NDVI and soil moisture*: *NDVI*, the Normalized Difference Vegetation Index, indicates the density and vigor of green vegetation growth. As the plants come under water stress, the *NDVI* value used for the present simulation in the Heihe River Basin should be validated using ground measured soil moisture. Fig. 4 shows the correlation between monthly values of $NDVI_{toc}$ and soil moisture measured by TDR at the natural oases in the downstream area (soil moisture data are from the Linze Inland River Comprehensive Research Station, CAS).

The measured soil moisture was averaged for the following depths below the ground surface: 0.2, 0.4, 0.6, 0.8, 1.2 and 1.6 m. The correlation coefficient is 0.77 in Fig. 4. $NDVI_{toc}$ values from the remote sensing data increase with measured soil moisture in the Heihe River Basin. Therefore, the application of $NDVI_{toc}$ in the C-FIX model to simulate *NPP* values is acceptable.

3.5. Vertical zonal distribution of NPP in the heihe river basin

Simulation of *NPP* was carried out using the C-FIX model in the Heihe River Basin and the results are discussed in this section.

In 2002, the total amount of *NPP* accounted for about 18.16 TgC, and the average value was 106 gC/m^2/yr over the whole basin, which is slightly less than the value of

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116.03 gC/m^2/yr averaged over the grassland of the whole country (Sun and Zhu, 2000). The spatial distribution of annual *NPP* in the Heihe River Basin is shown in Fig. 5. The distribution of *NPP* is obviously restricted by water conditions, and is highly related to the basin drainage system and the water allocation. *NPP* generally has higher values in the upperstream mountain area, middlestream artificial oasis area, downstream river bank area, alluvial fan and terminal lake depressions, while it had the lower values in the vast downstream desert and Gobi areas (Fig. 5).

In the upper basin Qilian Mountains area, precipitation is relatively abundant and natural vegetation predominates in the mountain ecosystem. Controlled by altitude, air temperature and precipitation, the distribution of *NPP* values reflects some characteristics of vertical zonality. At an altitude of 3000–4200 m, the low air temperature of the high mountain cold deserts results in the lowest *NPP* values, generally below 100 gC/m^2/yr. At an altitude of 3400–3900 m, the vegetation consists of alpine meadow and shrub with *NNP* values generally between 150 and 250 gC/m^2/yr. At altitudes of 2500–3400 m, precipitation and air temperature are favorable to growth and the vegetation in this mountain forest and grass zone has the highest *NPP* values of between 250 and 450 gC/m^2/yr and the *NPP* can

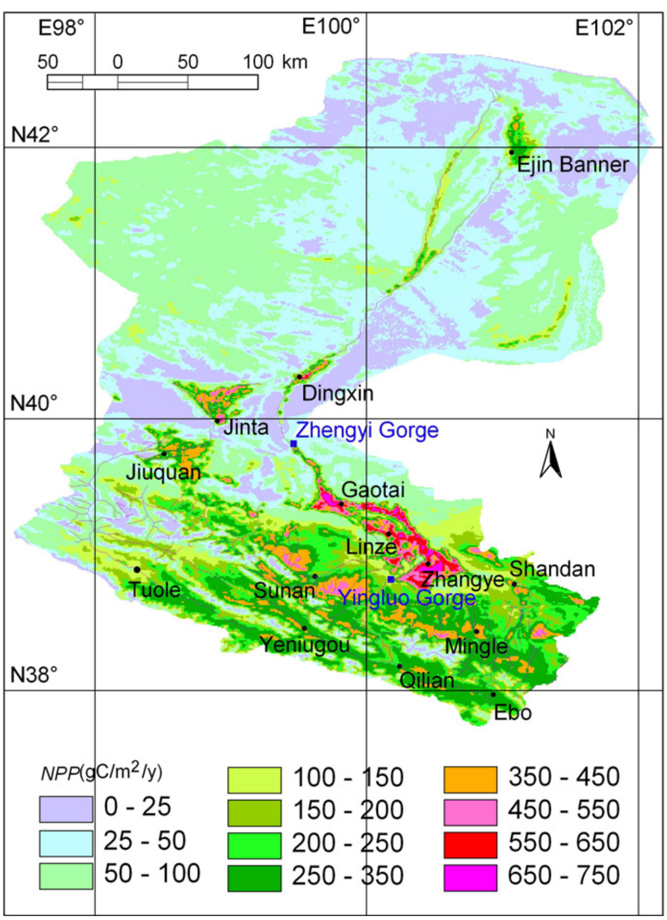

Fig. 5. Spatial distribution of annual *NPP* in the Heihe River Basin in 2002.

reach 500 gC/m^2/yr. From 2300 to 1900 m a.s.l., the *NPP* values are less than 200 gC/m^2/yr because of low precipitation, high evaporation and sparse desert grass vegetation (Fig. 5).

In the middle basin artificial oasis area, flat topography, good photo-thermal conditions, and widespread irrigation systems contribute to very favorable conditions for agricultural development and *NNP* values are high, generally more than 350 gC/m^2/yr, and the maximum can be 720 gC/m^2/yr (Fig. 5).

In the downstream area, climate is extremely arid with high moisture deficits and since irrigation consumes most of the available water resources, runoff is greatly reduced and even non-existent. *NPP* values here are generally less than 100 gC/m^2/yr and in the vast Gobi desert area, the values can reach 0 (Fig. 5).

4. Enhancement of carbon sequestration capacity of vegetation

4.1. Balanced utilization and allocation of water resources

Although the vegetation cover is rather sparse in the Heihe River Basin, the three major vegetation ecosystems described above still play an important role in carbon sequestration and cycling as indicated by the spatial distribution and variation of the simulated *NPP* in the basin. Carbon sequestration depends on land use type and zonal vegetation, which are controlled and limited by available water resources. In the Heihe River Basin, runoff from the mountains has increased slightly over the last few decades due to global warming (Shi et al., 2004). It is assumed, therefore, that the degradation of vegetation ecosystems can be mainly attributed to the impacts of human activities during the last 20 years.

In an attempt to remedy this situation a scheme to allocate water resources rationally has been implemented by the local authority and the Management Bureau of the Heihe River Basin since 2002, and about 5–7 × 10^8 m^3 of water per year has been released from the middlebasin to the downstream area during the last 3 years depending on the water availability during the year. At the same time, efforts are being made to utilize water resources more efficiently.

4.2. Protection of vegetation ecosystems

4.2.1. Protection of mountain forest in the upperstream area

As indicated above, the mountain forest zone has the highest carbon sequestration capacity of the natural vegetation in the basin. This zone in the upperbasin mountain area accounts for 45.2 × 10^4 hm^2, and consists mainly of dragon spruce *Picea crassifolia*. Experimental field studies by the Institute of Water Conservation Forests in the Qilian Mountains on the carbon balance of *Picea crassifolia* in the upper reaches of the Heihe River Basin (Wang et al., 2000) revealed that the biomass of

Picea crassifolia is 203.08 t/hm^2, and its present carbon sequestration capacity is 332.58 t/hm^2, equivalent to 1219.23 t/hm^2 of CO_2. The *Picea crassifolia* ecosystem absorbs 9.85 t/hm^2 of CO_2 from the atmosphere per year. Investigations indicate that waste land is still available for reforestation with *Picea crassifolia* in the mountain area so that the capacity for fixing CO_2 from the atmosphere can be further exploited. Therefore, protection of the mountain forest is not only important for water and soil conservation and runoff regulation, but also for enhancing the carbon sequestration capacity of vegetation. In recent years, forestry and animal husbandry have been controlled or forbidden in these areas but the practice still continues in many localities.

4.2.2. *Comprehensive measures for the whole basin*

An inland river basin is an integrated system of water resources, ecology and economy. In this system, water resources are basic and the key limiting factor for ecosystems health and maintenance of a sustainable economy and society.

It is essential that rational management and allocation of water resources be undertaken by an authorized agency in coordination with different sectors and stakeholders. Water resources management laws for judicious utilization of water resources must be enforced and highly efficient water -saving agriculture must be practiced by developing production sectors with high productivity and low water resource consumption. Well-drilling must be strictly prohibited as well as over-grazing, in order to achieve a balance between exploitation and regeneration of groundwater in the basin. Coordination between economic development and ecological protection is important.

Because of the marked vertical zonality of the basin, different management strategies must be applied to each zone. In the mountain area the chief approach should be protection and planting of new forests. In the middle basin oases and lowlands, more efficient water use strategies must be employed and protection forests must be planted in the artificial oases area. Because most of the water resources in the lower basin are utilized for farm irrigation, the area of farm land must be controlled in a rational manner. To implement this, the national Grain for Green program of returning marginal farmland to the original forest or grass cover has been adopted in the Zhangye area in the middle Heihe basin. During the 3 years prior to 2004, about 5×10^4 hm^2 of agricultural land was converted to forest lands. Moreover, stringent water conservation measures have been implemented in the Zhangye area as a pilot project since 2002. All these measures will enhance the carbon sequestration capacity of the inland basin.

In the downstream Ejin Banner area, the ecosystem of the transition area between the natural oases and the desert must be restored and stabilized. Grazing in these areas has to be strictly prohibited and vegetation degeneration stopped.

5. Discussion and conclusion

In the inland river basins of the arid area of northwest China, the types, distribution and changes of vegetation are closely related to and controlled by the water resource conditions and strong vertical zonal characteristics. The response of vegetation to water availability is very sensitive. The spatial distribution of annual *NPP* values in the Heihe River Basin is closely related to water and vegetation growing conditions. The *NPP* simulation carried out in this study indicates that in the study area, the nature of the vegetation cover plays a significant role in the carbon sequestration of terrestrial ecosystems. The very dry climate in much of the Heihe River Basin and the competition for water resources by the economic sector places a great stress on the natural vegetation systems by lowering the groundwater table and reducing surface runoff. The latter combine to reduce the carbon sequestration potential of the natural vegetation.

In the vast inland arid area of northwest China, enhancing the capacity for carbon sequestration requires scientific management and the rational allocation and utilization of a limited water resource. The Grain for Green program and pilot projects to utilize water more efficiently by the agricultural sector are a useful step in this direction. However, these improved water management strategies have to be carried out in consideration of global warming and increased human activities of every kind. Multidisciplinary research efforts are required to study these new impacts on the Heihe River Basin and to improve our carbon cycle models through field measurements and experiments to determine energy, water and carbon fluxes in the different ecological zones.

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