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Article

Land Use/Land Cover Change Induced Impacts on Water Supply Service in the Upper Reach of Heihe River Basin

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Abstract: Heihe River Basin is the second largest inland river basin in China, where water supply service in the upper reach has greater influence on the sustainable development of middle and lower reaches. This study analyzed the influence of land use/land cover change (LUCC) on the water supply service in the upper reach by carrying out scenario simulation. Firstly, we analyzed the LUCC and climate change in the upper reach during 1990–2005; then the water supply service, which was represented by the annual water yield, was estimated with the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. Thereafter three scenarios (precipitation change and LUCC change combined, LUCC change only, and precipitation change only) were established to analyze the impacts of LUCC and precipitation change on the water yield. The results show that the LUCC exerted great influence on water yield, while the impact of precipitation change is even more significant than that of LUCC. Although there are still some uncertainties, the results of this study can still provide valuable reference information for ecological conservation and water resource management in the upper reach of the Heihe River Basin.

Keywords: LUCC; water supply service; water yield; InVEST model; upper reach of Heihe River Basin

1. Introduction

Ecosystem services are benefits that humans derive from ecosystems, which include provisioning, regulatory, supporting and cultural services [1,2]. The ecosystem services are the basis of human survival and are closely associated with the human well-being [3]. There is a crucial need to manage locations that are important for maintaining provision of ecosystem services, and it is necessary to consider climate change as well as land use/land cover change (LUCC) in the relevant ecosystem service assessments, especially when analyzing the water-related ecosystem services [4,5]. Along with the socio-economic development and all kinds of emerging ecological environmental problems, ecosystem services are becoming a research hotspot [6]. A good number of studies have been carried out on the provision of ecosystem services, their influencing factors, management measures, *etc.* LUCC is the main approach through which human beings influence the ecosystem and contains plentiful information of human activities [7,8]. LUCC is an important driving factor of ecosystem services, it can alter the spatial pattern of ecosystems, influence the biological processes, and consequently alter the provision of ecosystem services [9]. Besides, as LUCC becomes the focus of research in global change, more and more attention has to be paid to the influence of LUCC on ecosystem services [9], and quantitative assessment of the relationship between LUCC and ecosystem services has also become a hotspot in the ecological field. Moreover, water supply service is one of the most important ecosystem services, since adequate freshwater supply is fundamental for ensuring the sustainability of agriculture, industry and the natural environment [1]. The increasing water demand due to economic and demographic growth has led to intensive water usage among all economic sectors in many regions [10], and water scarcity has become one of the most serious worldwide problems. The water supply service and its driving mechanism have received more and more attention [11,12], and analysis of influence of LUCC and climate change on the water supply service is essential for formulating adaptive management strategies [13].

Although ecosystem services have been identified to be declining over the previous decades, there is no clear methodology of evaluating the impacts of LUCC on ecosystem services [14]. Several methods have been presented to assess ecosystem services, but these methods vary widely, and quantitative comparative studies with these methods have been lacking [15]. The Integrated Valuation of Environmental Services and Tradeoffs (InVEST), which is developed by the Natural Capital Project [16], offers a standardized approach to evaluate scenarios based on parameterization with LUCC, and it has been widely used to assess a variety of ecosystem services. Besides, scenario analysis as a method of evaluating possible futures has been advocated as an important research and planning tool in environmental studies [17,18]. There have been some studies that combined scenario analyses with the InVEST model, which use LUCC as the driver of ecosystem services [2]. However, there are only a few studies that have incorporated climate change when assessing ecosystem services [19].

LUCC is a dominant factor in influencing the heterogeneity of ecosystem services on the landscape [20]. For example, recent studies have shown that increase in agricultural land use has direct consequences on ecosystem services [17,21]; LUCC also plays an important role in influencing the climate system, such as atmospheric temperature, humidity, cloud cover, circulation, and precipitation, and these impacts range from the local and regional scales to sub-continental and global scales [7,22–24]. In particular, the supply of freshwater flows and water-related ecosystem services are closely related to land use management [1]. Besides, it is important to notice that climate change has greater influence on the water supply service in arid and semi-arid regions. For example, climate change will intensify the hydrological cycle in semi-arid areas through increases in global temperature, rainfall concentration in short periods of the year, and more frequent droughts [1]. Climate change will also shift the amount and timing of water movement through the landscape, which can alter the water yield [25].

The Heihe River is the second largest inland river of China, and the water of this river plays a key role in supporting the ecological environment of the whole basin. The water yield in the upper reach of the Heihe River Basin (HRU), which is the main water source region, fluctuated dramatically due to the climate change and intensified human activities, especially the land use change during past decades. Meanwhile the agricultural land in the middle reaches expanded continuously with the rapid socio-economic development, which led to the extraction of a large amount of water from the runoff of the Heihe River for agricultural irrigation and vegetation degradation in the lower reaches due to the intensified water scarcity. It is therefore of great significance to analyze the relationship between LUCC, climate change and water supply service and clarify the driving mechanism of the water yield change in the upper reaches to guaranteeing the sustainable water supply to the middle and lower reaches of the Heihe River Basin. However, previous studies in the upper reach of the Heihe River Basin have generally only focused on the impact of climate change on the water supply service [26,27]. There are only a few studies related to the influence of LUCC on the water supply service in the upper reach of the Heihe River Basin, most of which start from the perspective of the existing policies and only analyze the influence of LUCC under the national policy regulation on the water supply service. Most of these previous studies didn't analyze the influence of LUCC and climate change on the water supply service in the long term, and there is seldom research on the driving mechanism of LUCC on the water supply service.

This study selected the upper reach of the Heihe River Basin as the study area, and analyzed the change in the water supply service due to LUCC and climate change. Using InVEST along with scenarios of LUCC and climate change, this study investigated the driving mechanism of the water yield change. In particular, it was assumed that LUCC and climate change are independent for the whole study period. Scenarios were established for analyzing the influencing mechanism of LUCC and climate change on the water supply service. Results of this study can provide valuable reference information for improving the water resource management and ecological conservation.

2. Study Area

Heihe River Basin is generally divided into three parts according to the landform, including the southern Qilian Mountains, the central Hexi Corridor and northern High Plains Alxa. The upper reach of the Heihe River is mainly in the southern Qilian Mountains, where the major vegetation is the coniferous forest with the *Picea crassifolia* as the constructive species [28]. In the upper reaches, the elevation is between 1665 m and 5271 m; the main landforms include high and middle mountains, intermountain basins; and low mountains and hills. The local climate is influenced by both the continental climate and the Qinghai-Tibet plateau climate.

Heihe River Basin is divided into three parts by the Yingluoxia and Zhengyixia stations. We define the part above Yingluoxia as the "upper reaches", the part below Zhengyixia as the "lower reaches", and the part between these two regions as the "middle reaches". The upper reaches are the major water source regions and the middle reaches are the major water consumption regions, while the lower reaches are ending regions where both rivers and lakes disappear. The upper reach of Heihe River Basin are located in the Hexi Corridor ins Gansu Province, between 98°34'E–101°09'E, 37°43'N–39°06'N. The catchment area of the upper reaches is about 100,000 km^2, and Yingluoxia station is the controlling hydrologic station (Figure 1). The upper reaches cover most of Qilian County of Qinghai Province, and a few parts of Gansu Province, including Mati Township of Sunan County, Mongolian Township of Baiyin City, Dahe Township and Kangle Township. The annual average temperature ranges from −3 °C to 7 °C in the upper reaches, while the annual rainfall ranges from 300 mm to 700 mm, and there is obviously uneven distribution of rainfall throughout the year. The major land use types in the upper reaches include grassland, woodlands, water and bare land. There are various soil types in the upper reaches, e.g., aeolian sandy soil, cold desert soil, alpine meadow soil, mountain swamp chestnut soil and mountain marshy soil.

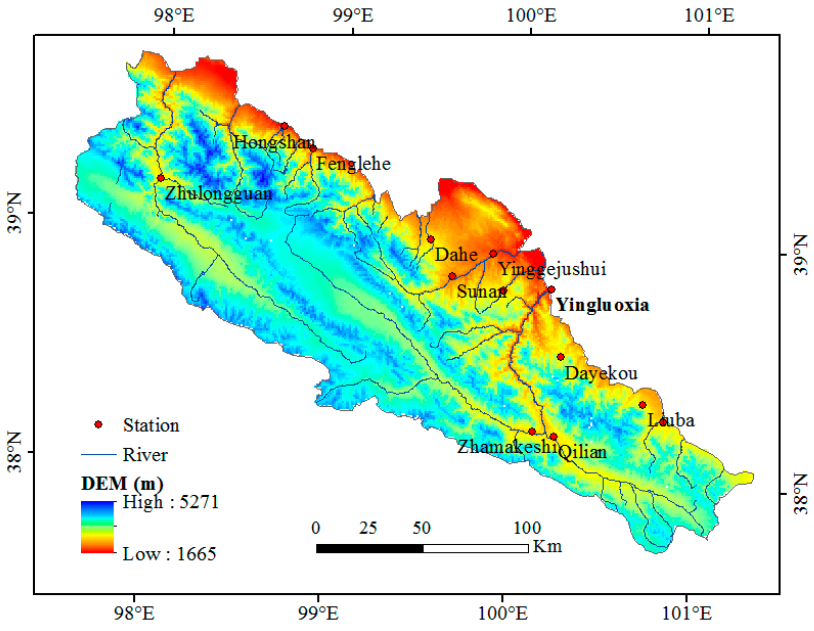

Figure 1. Location and major hydrological stations of the upper reach of Heihe River Basin.

The upper reaches of the Heihe River Basin serve as the major water source region, where the water supply service is of great importance to guaranteeing the sustainable development of the whole basin [29]. However, there has been serious ecological degradation due to changes in temperature and precipitation, and human activities in the upper reaches in recent decades. For example, there was once serious forest shrinkage, degradation of natural vegetation and loss of biodiversity in the past, which seriously threatened the water conservation capacity in the upper reach of Heihe River Basin [28]. In particular, the continuous droughts and overgrazing of grassland led to serious grassland degradation and decline of water conservation capacity of grassland, which further threatened the sustainable development of animal husbandry and caused significant eco-environmental deterioration. What's worse, the ecological degradation (from 1990 to 2000) in the upper reaches seriously affected the provision of water supply service as well as other ecosystem services, decreased the runoff into the middle and lower reaches of the Heihe River Basin and consequently increased the potential risk of land degradation in the downstream area [30]. The middle and lower reaches of the Heihe River Basin are extremely dry, with very low annual precipitation. These regions are also characterized by large evapotranspiration and very scarce water resources, which cannot meet the needs of the local economic development and maintenance of the ecological balance. Actually, there has been very serious contradiction between the water supply and demand in the middle and lower reaches of the Heihe River Basin throughout history. There has also been over-exploitation of the water resource due to the population growth and economic development in the Heihe River Basin [31]. The amount of water into the downstream has gradually reduced since the 1960s, leading to the intensification of a series of ecological problems, such as drying up of rivers and lakes, death of trees, degradation of grassland and occurrence of sandstorms [32]. The inter-provincial water disputes have been also more prominent, therefore it is of great importance to protect the ecological environment and guarantee the provision of water conservation services in the upper reach of Heihe River Basin.

3. Data and Methodology

This study first simulated the annual water yield, which represents the water supply service in the upper reaches in 1990, 1995, 2000 and 2005, and then analyzed the influence of LUCC and precipitation change on the water yield. The data from these four years were accordingly prepared, including the LUCC data, precipitation data and other data. It was assumed that all factors except LUCC and precipitation remain unchanged in this study in order to better understand the impacts of LUCC and precipitation change on the water supply service. Two scenarios were established for analyzing the influencing mechanism of the water yield. Under Scenario 1, LUCC data in 1990 were used as the input data, which is assumed to remain unchanged, while the precipitation will change, and the change in the water yield reflects the impacts of precipitation change. Similarly under Scenario 2, precipitation data in 1990 were used as the input data, which is assumed to remain unchanged, while LUCC will change, and the change in the water yield reflects the impacts of LUCC. Comparison between the results under Scenario 1 and 2 can reflect the influence of LUCC on the water supply service in the upper reach of the Heihe River Basin.

3.1. Data Collection and Processing

The data used in this study mainly include the LUCC, biophysical table, annual precipitation, average annual reference evapotranspiration, soil depth, plant available water fraction (PAWF), watersheds and sub-watersheds, and seasonality factor (Z). The LUCC data used in this study include the LUCC data in 1990, 1995, 2000 and 2005, which were extracted from the land use database developed by the Chinese Academy of Sciences (CAS) [33,34]. The land use data was interpreted by CAS according to the Landsat Thematic Mapper (TM) and/or Enhanced Thematic Mapper (ETM) images, and the interpretation accuracy is as high as 92.7% [31,35]. The biophysical table is used to represent the attributes of each land use and land cover type, including the LUCC code, descriptive name of LUCC, maximum root depth for vegetated land use classes in millimeters, and plant evapotranspiration coefficient for each LUCC class. The root depth of main vegetation types was obtained following FAO. We estimated the evapotranspiration coefficient of each LUCC type based on the research of Allen *et al.* [36] and the InVEST user guide.

The meteorological data, including the annual precipitation, were obtained from the daily meteorological observation data of meteorological station maintained by the China Meteorological Administration. The original meteorological observation data were saved in the form of text, and were then interpolated into 1 km × 1 km grid data with the Kriging interpolation method. Besides, the annual potential evapotranspiration data were calculated with the data evapotranspiration data provided by Heihe Plan Science Data Center due to the limitation of data availability. The evapotranspiration data with the resolution of 1 km × 1 km were estimated with the ETWatch model [37–40]. In addition, the soil depth data were extracted from the second national soil survey data, which were interpolated into 1 km × 1 km grid data with the Kriging interpolation method.

PAWF is defined as the difference between the fraction of volumetric field capacity and permanent wilting point, which is an important influencing factor of crop production, agro-ecological zoning, irrigation planning, and land cover changes [41]. PAWF can be estimated on the basis of physical and chemical properties of soil. There is a mathematical equation of the relationship between PAWF and proportion of sand, silt, clay and organic matter in soil [41], and this method is used to estimate PAWF as follows:

$$\begin{aligned} \text{PAWF} = {} & 54.509 - 0.132 \times \text{sand\%} - 0.003 \times (\text{sand\%})^2 - 0.055 \times \text{silt\%} - 0.006 \times (\text{silt\%})^2 - \\ & 0.738 \times \text{clay\%} + 0.007 \times (\text{clay\%})^2 - 2.688 \times \text{OM\%} + 0.501 \times (\text{OM\%})^2 \end{aligned}$$

where PAWF is the plant available water fraction (%); sand %, silt %, clay %, OM % represent the measured contents of sand, clay, silt and organic matter (%), respectively [41].

The watersheds and sub-watersheds data were obtained from the digital elevation model (DEM). The watershed and sub-watersheds were generated using Hydrology Analyst Tools based on 90 m DEM data [42]. The watershed was delineated into 179 sub-watersheds, and each sub-watershed was given only one identification number (Figure 2).

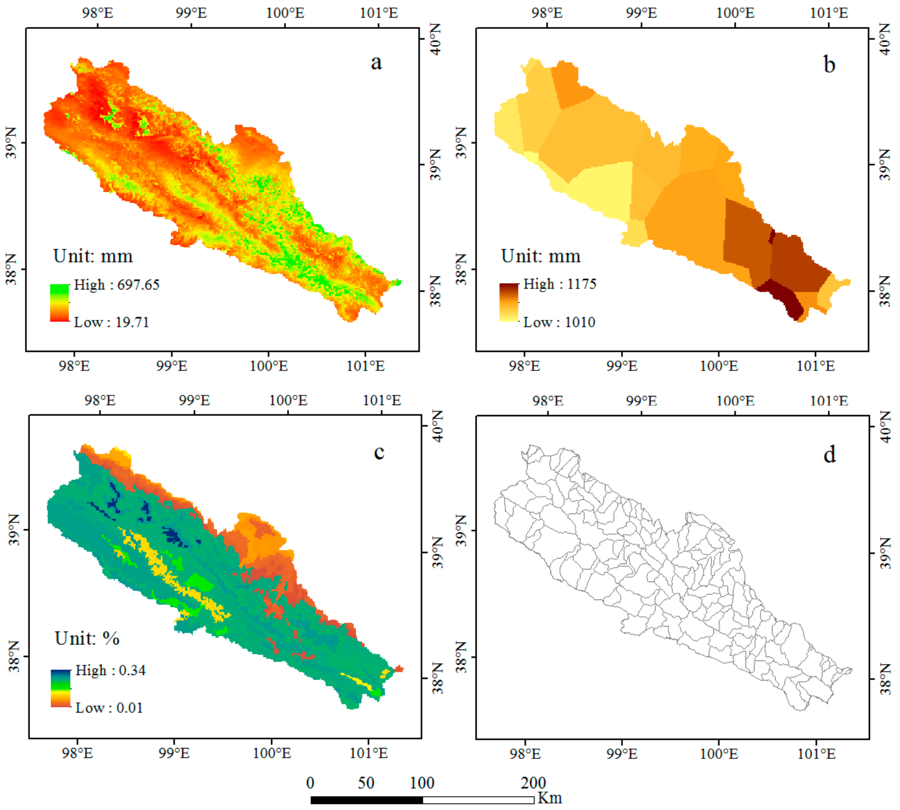

Figure 2. Spatial heterogeneity of the levels of ETo (**a**); Soil depth (**b**); plant available water fraction (PAWF) (**c**); Boundaries of small watersheds (**d**) in the Upper Reaches of Heihe River Basin.

The Z constant characterizes the seasonality of precipitation, with the possible floating point value ranging from 1 to 10, which is corresponding to the seasonal distribution of precipitation. The Z constant was estimated and validated with the water balance method based on the observation data of average annual evapotranspiration and runoff. As shown in Figure 3, the difference between the observed and simulated runoff is 0, when the Z constant is 6, which represents the best simulation results. In this study, Z constant is accordingly set to be 6, which is thereafter used to validate the simulation results obtained with the water yield model in the InVEST model.

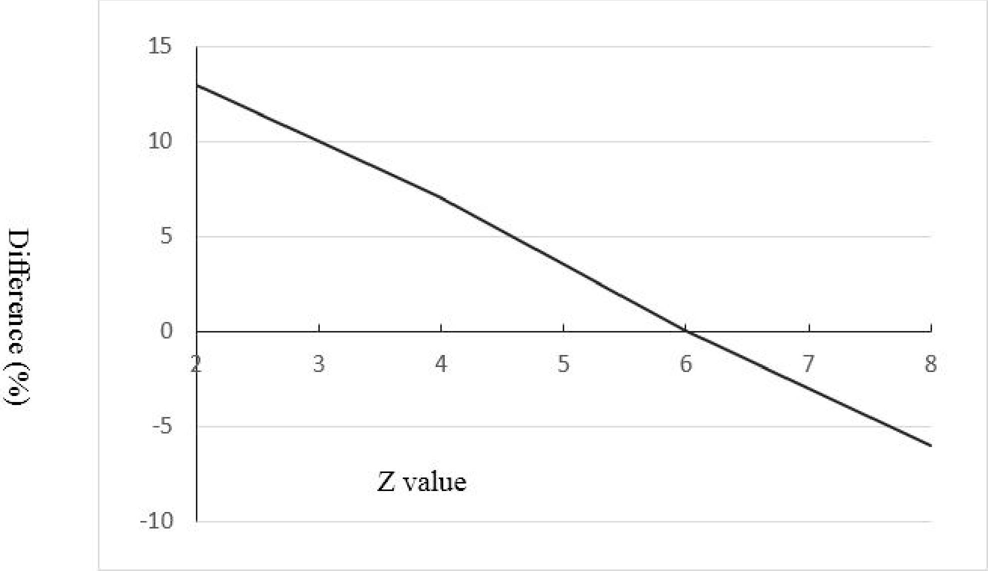

Figure 3. Difference between the observed and simulated annual natural runoff.

3.2. InVEST Model

The InVEST model is a tool for ecosystem service assessment to support environmental decision-making, which is developed in 2007 by Stanford University, the World Wide Fund for Nature and the Nature Conservancy. It comprises many sub-models, and the water yield model is a vital component for assessing water-related ecosystem service, and the water yield model generates and outputs the total and average water yield at the sub-basin level. The water yield model in the InVEST model is based on the Budyko curve [43] and annual average precipitation. Annual water yield (Y_{xj}) for each pixel (indexed by $x = 1, 2, \ldots, X$) on the landscape with LUCC ***j*** is calculated as follows:

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x \tag{1}$$

where Y_{xj} is the water yield of pixel x, $\boldsymbol{l}_x$ is the land cover type for pixel x, AET_{xj} is the annual actual evapotranspiration for pixel x with LUCC ***j***, and $\boldsymbol{P}_x$ is the annual precipitation on pixel x.

The evapotranspiration partition of the water balance, $\frac{AET_{xj}}{P_x}$ can be estimated as follows [44]:

$$\frac{AET_{xj}}{P_x} = \frac{1+\omega_x R_{xj}}{1+\omega_x R_{xj} + \frac{1}{R_{xj}}} \tag{2}$$

where R_{xj} is defined as the ratio of potential evapotranspiration to precipitation [43] as follows:

$$R_{xj} = \frac{k_{xj} ET0_x}{P_x} \tag{3}$$

k_{xj} is the plant (vegetation) evapotranspiration coefficient associated with the LUCC $\boldsymbol{j}$ on pixel x, which is largely determined by the vegetation characteristics of the LUCC found on that pixel.

ω_x is a modified dimensionless ratio of plant accessible water storage to expected precipitation during the year. As defined by Zhang *et al.* [44], ω_x is a non-physical parameter to characterize the natural climatic-soil properties, which is calculated as follows:

$$\omega_x = Z \frac{AWC_x}{P_x} \tag{4}$$

where AWC_x is the plant-available water content (in mm) that can be held and released in the soil for use by plants, it can be estimated as the product of the difference between field capacity and wilting point and the minimum of soil depth and root depth, Z is a seasonality factor that represents the seasonal distribution and depth of precipitation.

4. Results and Discussions

4.1. Analysis of Historical LUCC

As shown Figure 4 and Table 1, the sharp decline of the water body area during 1990–1995 is mainly due to the precipitation decrease, and the gradual increase of the water body area during 1995–2005 is caused by the gradual increase in precipitation. The cultivated land in the upper reach of the Heihe River Basin showed a decreasing trend as time goes by, declining from 174 km^2 in 1990 to 99 km^2 in 2005. By comparison, the forestland showed a slightly expanding trend, increasing from 4392 km^2 in 1990 to 4460 km^2 in 2005. This is mainly due to the influence of policies of returning cultivated land to forest land [45]. Besides, grassland first decreased during 1990–1995, but then recovered during 1995–2005, and it showed an overall increasing trend throughout the whole study period, with an increment of 205 km^2. In addition, Built-up area increased during 1990–2005, with an increment of 8 km^2. Bare land decreased by 197 km^2 during 1990–2005. Overall, LUCC in the upper reaches is characterized by the decrease of cultivated land, which is mainly converted into forestland and grassland.

Table 1. Temporal changes of land use and land cover in the upper reach of Heihe River Basin (Unit: km^2).

Year	1990	$\Delta_{1995-1990}$	1995	$\Delta_{2000-1995}$	2000	$\Delta_{2005-1990}$	2005
Cultivated land	174	−18	156	−13	143	−44	99
Forest land	4392	42	4434	17	4451	9	4460
Grassland	14,007	−16	13,991	156	14,147	65	14,212
Water area	385	−48	337	35	372	4	376
Built-up area	15	4	19	1	20	3	23
Bare land	8294	36	8330	−196	8134	−37	8097

Note: $\Delta_{1995-1990}$ represent the difference between 1995 and 1990.

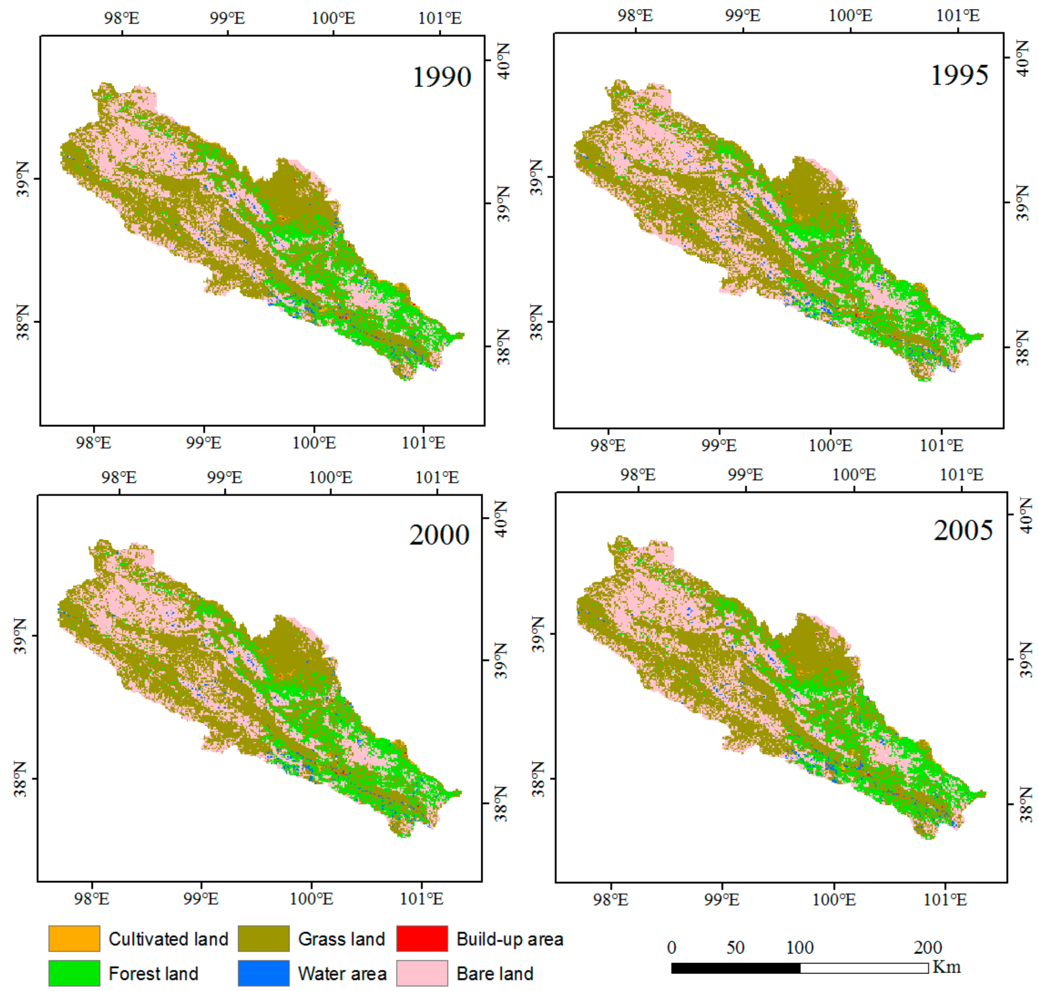

Figure 4. Land use and land cover change (LUCC) patterns in the upper reach of Heihe River Basin in the year of 1990, 1995, 2000, and 2005.

4.2. Analysis of Historical Precipitation

We have calculated the annual average precipitation during 1990–2005 using the annual precipitation data of sixteen years from 1990 to 2005, which is used as the baseline precipitation for further analysis.

The spatial patterns of precipitation suggest that the annual precipitation in the upper reach of the Heihe River Basin showed a declining trend from southeast to northwest (Figure 5), The spatial pattern of precipitation in 1990 differ obviously from that in 1995, 2000 and 2005. Most of the regions with annual precipitation below 200 mm were located in the northwest part, while the regions with annual precipitation above 400 mm all concentrated in the southeast part. Besides, regions with annual precipitation below 200 mm showed an expanding trend during the study period, while regions with annual precipitation above 400 mm showed a shrinking trend.

The results in Figure 6 showed that the precipitation in the study area first declined during 1990–1995 and then increased during 1995–2005 generally. The precipitation in 1990 increased by about 0–60 mm compared to the baseline precipitation. While in 1995, the precipitation decreased by about 0–60 mm compared to the baseline precipitation. In 2000, only the southeastern part of the study area showed a decreasing trend, and the precipitation in northwestern part increased by about 0–40 mm compared to the baseline precipitation. In 2005, the total study area showed an increasing trend, with increment about 0–40 mm compared to the baseline precipitation.

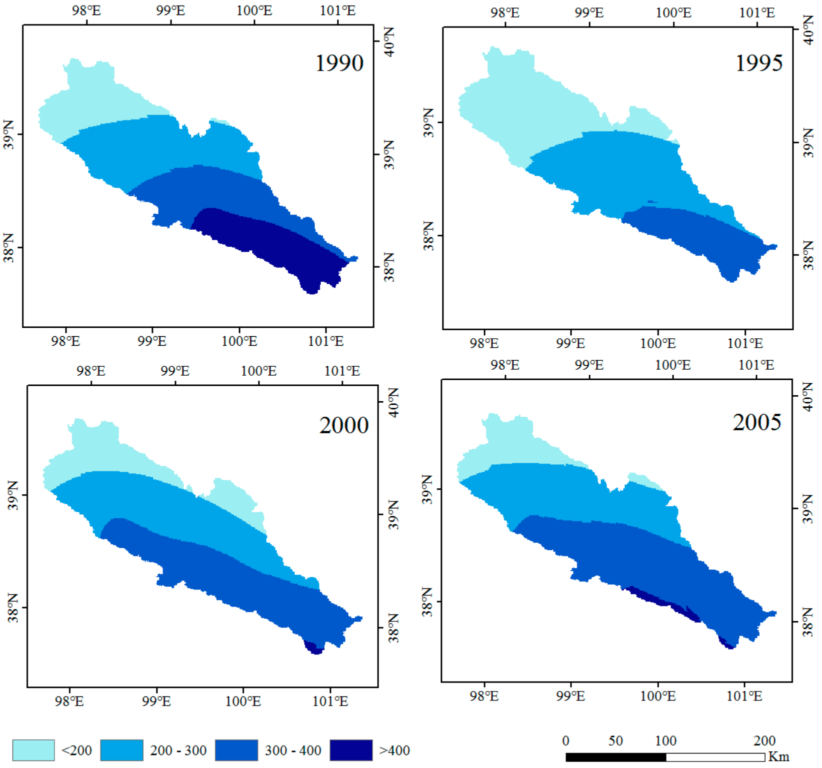

Figure 5. Spatial patterns of the annual precipitation in the upper reach of Heihe River Basin in the year of 1990, 1995, 2000, and 2005 (Unit: mm).

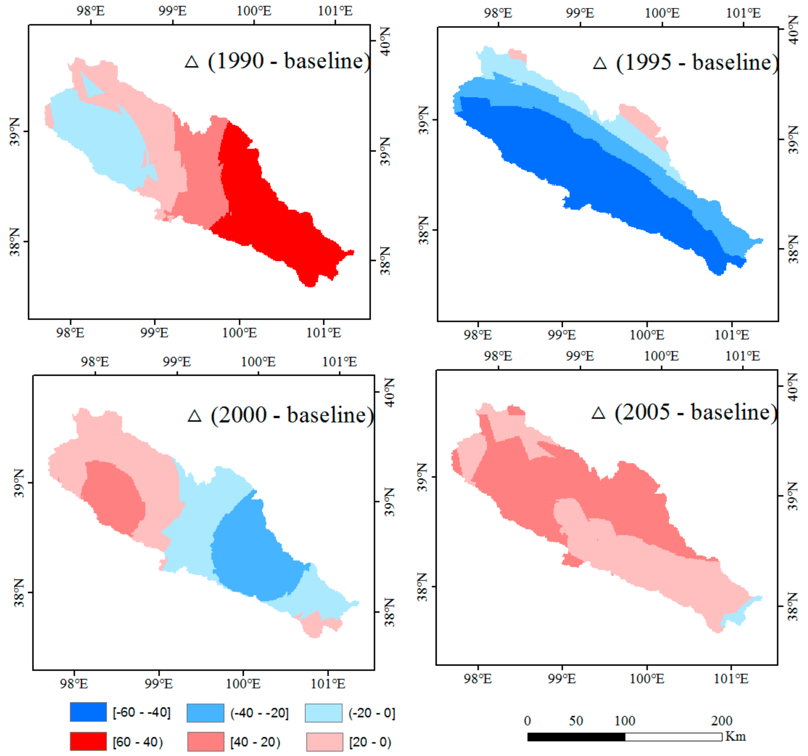

Figure 6. Difference between the annual precipitation in 1990, 1995, 2000, 2005 and the baseline precipitation (Unit: mm). Δ (1990-baseline); Δ (1995-baseline); Δ (2000-baseline);

Δ (2005-baseline) refer to the difference between the precipitation in 1990, 1995, 2000, 2005 and the baseline precipitation.

4.3. Impacts of LUCC and Precipitation Changes on Water Yield in Upper Reach of Heihe River Basin

Three scenarios were designed in this study, which were used to analyze the impacts of LUCC on the water yield (Table 2). The annual water yield in 1990, 1995, 2000 and 2005 under the three scenarios was estimated using the InVEST, with different precipitation data and LUCC data as the input data. Under the baseline scenario, the annual water yield in each year was jointly influenced by the annual precipitation and LUCC in the same year. Under Scenario 1, there is no change in the input precipitation data in the InVEST, which is always the precipitation data from 1990. But the LUCC data in 1990, 1995, 2000 and 2005 were used as the input data for the corresponding years in order to check whether LUCC influences the water yield. Similarly under Scenario 2, there is no change in the input LUCC data in the InVEST, which is always the LUCC data from 1990. The precipitation data in 1990, 1995, 2000 and 2005 were used as the input data for the corresponding years in order to check whether the precipitation change influences the water yield.

Table 2. Scenario design for analyzing impacts of land use and land cover change (LUCC) on the annual water yield.

<table>
<tr><th>Scenarios</th><th>1990</th><th>1995</th><th>2000</th><th>200</th></tr>
<tr><td>Baseline</td><td rowspan="5">Precipitation 1990
LUCC 1990</td><td>Precipitation 1995
LUCC 1995</td><td>Precipitation 2000
LUCC 2000</td><td>Precipitation 2005
LUCC 2005</td></tr>
<tr><td rowspan="2">Scenario 1</td><td colspan="3">Precipitation 1990</td></tr>
<tr><td>LUCC 1995</td><td>LUCC 2000</td><td>LUCC 2005</td></tr>
<tr><td rowspan="2">Scenario 2</td><td>Precipitation 1995</td><td>Precipitation 2000</td><td>Precipitation 2005</td></tr>
<tr><td colspan="3">LUCC 1990</td></tr>
</table>

4.3.1. Simulated Water Yield under Baseline Scenario: LUCC Change and Precipitation Change Combined

The result in Figure 7 showed that simulation results under the baseline scenario show that the water yield in the upper reach of the Heihe River Basin ranges from below 800 m^3/ha to above 4000 m^3/ha during 1990–2005. The water yield ranges between 1600–3200 m^3/ha in most part of the study area, while it only exceeds 4000 m^3/ha in a few areas in 1990. The water yield shows an increasing trend from northwest to southeast, and the overall spatial pattern kept consistent during 1990–2005. The water yield in the upper reaches mainly concentrates in the southeast part, where it is the Qilian Mountains, while the regions with the water yield above 4000 m^3/ha also generally concentrated in the southeast part. By comparison, the water yield is generally below 800 m^3/ha in the northwest part of the study area. In addition, the results show that the annual total water yield in the upper reach of the Heihe River Basin first declined dramatically, then rebounded and thereafter increased slightly during 1990–2005, however, the total water yield in 2005 still decreased in comparison to that in 1990, with a decrement of approximately 13 million m^3 (Table 4).

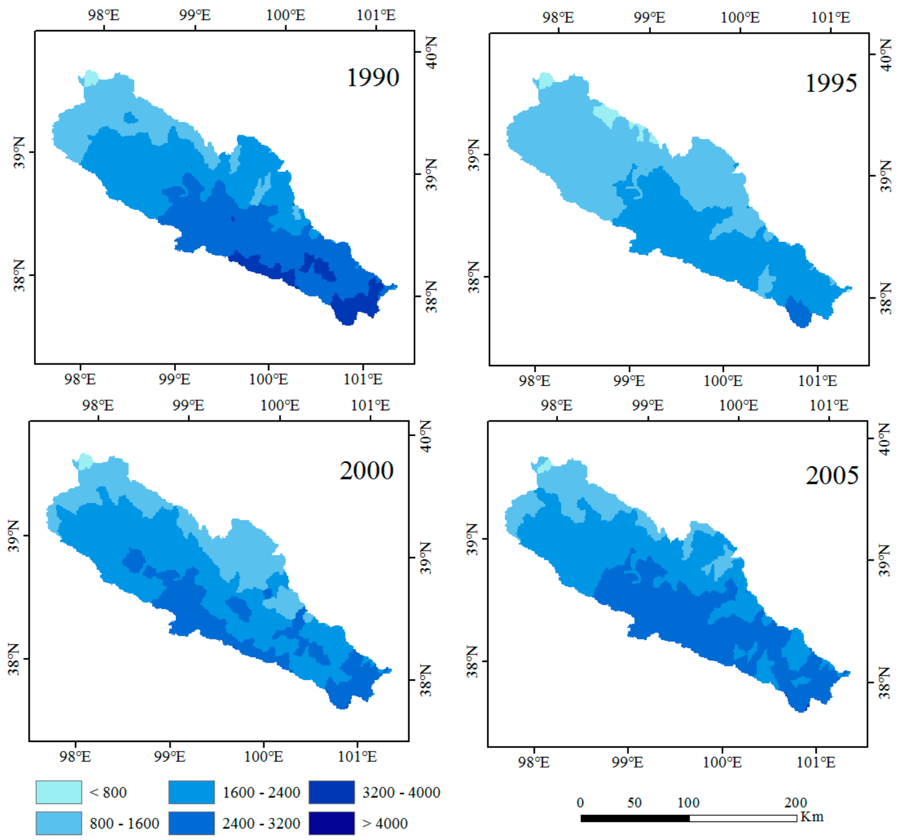

Figure 7. Spatial patterns of simulated annual water yield of the upper reach of the Heihe River Basin under Baseline in the year of 1990, 1995, 2000, and 2005 (Unit: m^3/ha).

4.3.2. Simulated Water Yield under Scenario 2: Only Impact of LUCC Change

The Pearson correlation was carried out to further study the influence of LUCC on the water yield. The Pearson correlation coefficients between changes in the water yield and area changes of cultivated land, forestland, grassland, water area, built-up land and bare land were calculated. Results show that change in the water yield is highly correlated to the change of LUCC: The change in the cultivated land, grassland and water area made major contribution to the change in the water yield; Whereas there is no result of Pearson correlation between changes in the built-up land and the water yield since there is very little change in the built-up land (Table 3).

Table 3. Pearson correlation between the water yield and land use and land cover change (LUCC).

	p	*r*
Cultivated land	0.049	−0.578
Forest land	0.990	0.004
Grassland	0.061	0.555
Water area	0.064	−0.550
Built-up area	N/A	N/A
Bare land	0.994	0.003

Note: p shows whether the two variables are correlated or not, there is significant correlation between two variables if p is <0.1. Besides, r is the Pearson correlation coefficient, which ranges between −1 and 1. The larger the absolute value of r is, the more closely correlated the two variables are. N/A: Not Applicable

The simulation results under Scenario 1 show that when there is no change in the precipitation; the water yield in the upper reach of the Heihe River still shows obvious spatial heterogeneity; and there is only slight change in the spatial pattern of the water yield. Besides, there is some inter-annual variation of the total water yield, which first increased and then decreased during 1995–2005, but it showed an increasing trend throughout the whole study period; increasing from 202.81 million m^3 in 1995 to 204.40 million m^3 in 2005 (Table 4). By integrating the information on LUCC and water yield in the four years, it can be found that the water yield change is highly correlated to the change of cultivated land, water area, and grassland. The water yield increase is mainly correlated to the decrease of cultivated land and water area and increase of grassland, while the water yield decrease is mainly related to the land degradation caused by human activities, e.g., decrease of forest land and grassland and water area. The increasing human activities have damaged the ecosystems in the upper reach of the Heihe River Basin, decreasing the water supply service and leading to the decline of the total water yield [46].

Table 4. Simulated patterns of per sub-watershed annual water yield of upper reach of Heihe River Basin under the three Scenarios (Unit: million m^3).

Year	1990	1995	2000	2005
Baseline	202.81	139.10	180.62	199.63
Scenario 2	202.81	204.38	205.32	204.40
Scenario 3	202.81	142.71	180.49	200.53

4.3.3. Simulated Water Yield under Scenario 2: Only Impact of Precipitation Change

The simulation results under Scenario 2 show that when there is no LUCC, the change of precipitation also has some influence on the water yield, which is even more significant than that of LUCC. In particular, when there is no change in the precipitation, the water yield remains above 4000 m^3/ha in most part of the southeast part of the study area over the time period (Figure 8). By comparison, when there is precipitation change over the time period, there will be significant change in the water yield, and the regions with the water yield above 4000 m^3/ha will shrink from most of the southeast area to only a few parts (Figure 9). Overall, the annual water yield in the study area decreased from 202.81 million m^3 in 1990 to 200.53 million m^3 in 2005), to which the precipitation change made the dominant contribution, while the influence of LUCC was only secondary.

The precipitation changed significantly in the Heihe River Basin during 1990–2005, which decreased during 1990–1995 and increased during 1995–2005 (Figure 6). The precipitation also showed an increasing trend on the whole in the past decades, but at a lower increase rate. The precipitation led to an overall increasing trend of the water yield and the surface runoff in the upper reaches in past decades. The water yield in the upper reach of the Heihe River Basin changed significantly during 1990–1995 under the influence of precipitation changes and human activities. The water yield subsequently increased to some extent as the "Grain for Green" policy was carried out, but it still showed an overall decreasing trend during 1990–2005. Besides, the water demand in the middle and lower reaches of the Heihe Basin has continuously increased, so it is a key problem to be solved for the water resource management of the Heihe River Basin to protect the ecological environment and increase the water supply service in the upper reaches.

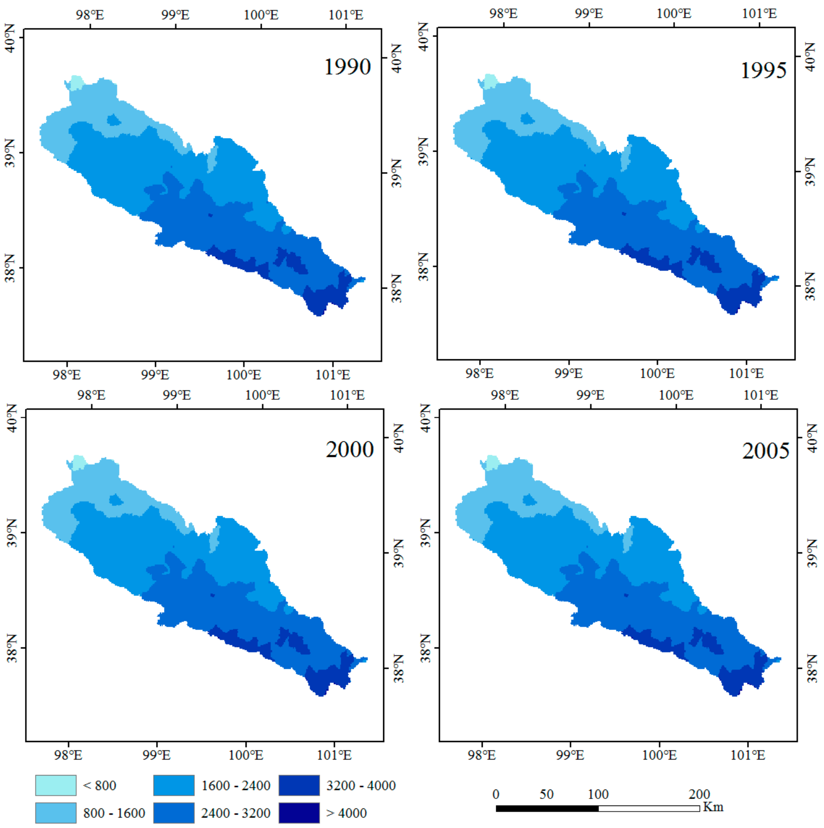

Figure 8. Spatial patterns of simulated annual water yield of the upper reach of the Heihe River Basin under Scenario 1 in the year of 1990, 1995, 2000, and 2005 (Unit: m^3/ha).

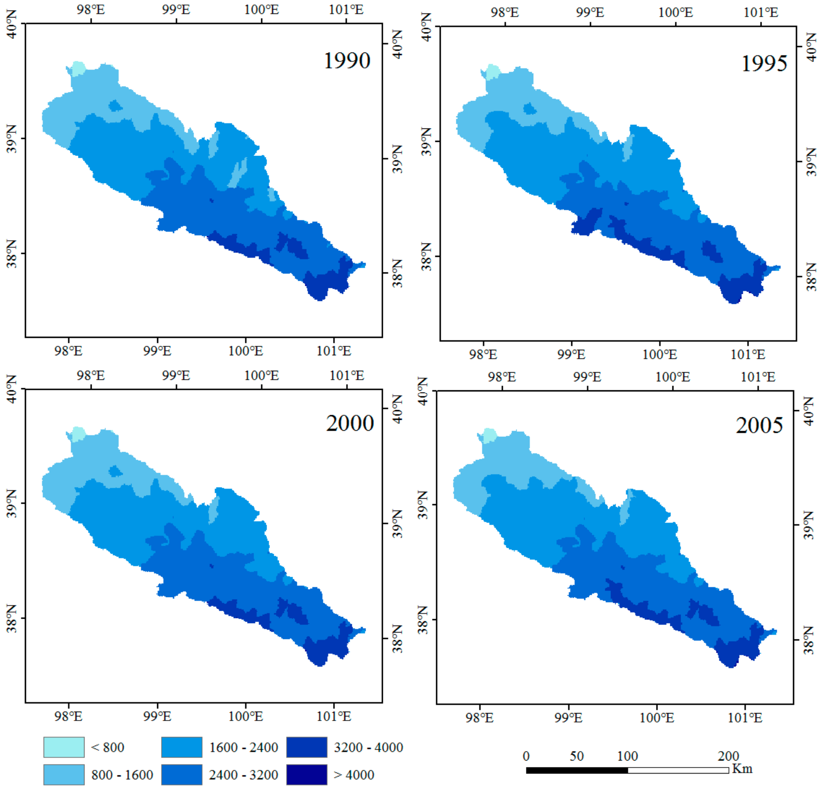

Figure 9. Spatial patterns of simulated annual water yield of the upper reach of the Heihe River Basin under Scenario 2 in the year of 1990, 1995, 2000, and 2005 (Unit: m^3/ha).

There are still some uncertainties in the results of this study. For example, the reference evapotranspiration is an important indicator in the model input data, and it is assumed to remain unchanged in this study, which may have some negative influence on the simulation accuracy, so it is necessary to make some further improvement in future research. Besides, this study has simulated only the water yield in the upper reaches in the past decade and focused on the model validation, and more research on the future water yield may be carried out with the expectation of providing scientific support decision making of local ecological managers. Although with these uncertainties, the results of this study can still provide some reference information for conserving the ecological environment and improving the water supply service in the upper reach of the Heihe River Basin.

5. Conclusions

It is of great management value to analyze water supply service in the upper reach of the Heihe River Basin, which serves as the water source of the whole basin in this region. This study simulated the water yield in the upper reach of the Heihe River Basin in 1990, 1995, 2000, and 2005, and also analyzed the influence of LUCC and precipitation change on the water supply service. The results show that water yield in those four years reached 202.81, 139.1, 180.6, and 199.63 million m^3, respectively. Two scenarios with LUCC and precipitation change were established to further explore the driving mechanism of the water yield. The results show that LUCC and precipitation change both have important influence on water yield during 1990–2005, and the influence of precipitation change is more significant, indicating that any long-term variations in precipitation can have greater influence on water supply service in the upper reach of the Heihe River Basin. This study is the first to analyze the impacts of LUCC and climate change with the InVEST model as a tool. There are still some uncertainties in the simulation, but the simulation results still can provide some valuable reference information for water resource management and ecological conservation in the upper reach of the Heihe River Basin.

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Author Contributions

Xiaoli Geng and Xinsheng Wang designed research; Xiaoli Geng, Xinsheng Wang, Haiming Yan, and Qian Zhang performed research; Xiaoli Geng, Haiming Yan, Qian Zhang, and Gui Jin analyzed data; and Xiaoli Geng, Xinsheng Wang, Haiming Yan, Qian Zhang, and Gui Jin wrote the paper. Xiaoli Geng and Haiming Yan revised the paper. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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