Supporting Information

Analyzing the Spatiotemporal Evolution and Driving Forces of Gross Ecosystem Product in the Upper Reaches of the Chaobai River Basin

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S1 Data Sources

This paper calculated the Gross Ecosystem Product (GEP) of the study area for 2005, 2010, 2015, and 2020 and studied the driving factors. We used multi-source data, including geographic spatial data, statistical department data, price parameters, and other data.

Geographic spatial data include land use, soil, digital elevation model, precipitation, potential evapotranspiration, net primary productivity, Chinese lake dataset, fractional vegetation cover, integrated eco-environmental quality data, temperature, slope, gross domestic product, population density, night-time light index, land use degree density, and other basic data. These data are mainly used to calculate the functional amounts of various ecosystem services in the regulating services of GEP, as well as analyzing the driving factors behind the spatial differentiation of GEP. A detailed description of the data, along with their respective sources, can be found in **Table S1**.

Table S1 Data Description and Sources

Data name	Data description	Data source
Land use/cover data	Raster，30m×30m	the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences （www.resdc.cn）
GLC_FCS30-1985-2020	Raster，30m×30m	Earth Big Data Shared Service System （http://data.casearth.cn/）
Soil thickness	Raster，90m×90m	National Earth System Science Data Center（www.geodata.cn）
available soil water capacity	Raster，250m×250m	ISRIC Soil Data Center （www.isric.org）
Soil erodibility factor	Raster，30m×30m	National Earth System Science Data Center（www.geodata.cn）
Digital Elevation Model	Raster，30m×30m	National Earth System Science Data Center（www.geodata.cn）
Precipitation	Raster，1000m×1000m	National Earth System Science Data Center（www.geodata.cn）
Potential vapor dispersion	Raster，1000m×1000m	National Earth System Science Data Center（www.geodata.cn）
Temperature	Raster，1000m×1000m	National Earth System Science Data Center（www.geodata.cn）
Net Primary Productivity	Raster，500m×500m	U S. Geological Survey （www.usgs.gov）
China Lakes Dataset	Vector	National Qinghai-Tibet Plateau Scientific Data Center （data.tpdc.ac.cn）
Fractional Vegetation Cover	Raster，250m×250m	National Qinghai-Tibet Plateau Scientific Data Center （data.tpdc.ac.cn）
Integrated Eco-environmental Quality Data	Raster，100m×100m	National Earth System Science Data Center（www.geodata.cn）
Slope	Raster，30m×30m	Fine Resolution Mapping of Mountain environment
Multi-year average rainfall data for Beijing, Tianjin and Hebei	Raster，30m×30m	Fine Resolution Mapping of Mountain environment
Gross Domestic Product	Raster，1000m×1000m	the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences（www.resdc.cn）
Population density	Raster，1000m×1000m	the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences（www.resdc.cn）
EANTLI/nighttime light data	Raster，1000m×1000m	Global Change Science Research Data Publishing System （geodoi.ac.cn）
Land use degree Density	Raster，1000m×1000m	Scientific Data Bank（www.scidb.cn）

The statistical data used in this study included the added value of agriculture, forestry, animal husbandry, and fishery in each county and district, and were obtained from sources such as the "Hebei Statistical Yearbook", "Zhangjiakou Economic Yearbook", "Chengde Statistical Yearbook", "Beijing Regional Statistical Yearbook" and "China County Statistical Yearbook". These data are used to calculate the value of material supply products in the study area. Tourism income data for each county and district are derived from the "Beijing Tourism Statistics Brief" official website of Beijing Municipal Bureau of Culture and Tourism, Hebei Database of Xiaokang Project, and statistical bulletins of Zhangjiakou and Chengde. 70% of the study area's tourism income is used to calculate the value of cultural services in ecological tourism. Seeding area, yield per unit area, and unit price of food crops (rice, wheat, corn) are obtained from the "National Agricultural Product Cost and Benefit Data Summary", "Beijing Statistical Yearbook" and "Hebei Statistical Yearbook" and are used to calculate the value generated by unit area farmland. The total amount of water resources and precipitation in the Haihe North system is derived from the Haihe River Basin Water Resources Bulletin and is used to correct the results of the InVEST model for calculating water production.

The price parameters used in this study included the unit cost of storage reservoir construction, unit price of excavation and transportation of earthwork, trading price of carbon emission rights, cost of afforestation, average market-traded price of oxygen, fees for water pollutant treatment, fees for atmospheric pollutant treatment, electricity prices, and other relevant parameters. These price parameters are obtained through consultations with relevant departments, market research, and literature references. In cases where data is missing, the current year's Producer Price Index (PPI) is used for calculation. The price coefficient is sourced from the "Beijing Statistical Yearbook" and

"Hebei Statistical Yearbook".

The other data used in this study encompassed surface runoff coefficients for different ecosystem types, coefficients for converting reservoir capacity into flood control capacity, unit area purification capacity for various atmospheric pollutants by different ecosystems, unit area purification capacity for various water pollutants by wetlands, water surface evaporation conversion coefficients, landscape aesthetic service equivalent factors, and heat consumption per unit area of different ecosystem types, among others. These empirical data are primarily sourced from the "Technical Guide for Gross Ecosystem Product (GEP) Accounting", " Gross Ecosystem Product Accounting Standard (Trial)", Beijing local standard " Gross Ecosystem Product Accounting Technical Specification" and other relevant norms and literatures.

S2 GEP Accounting Methods

According to the relevant researches (Costanza et al., 1997, 2014, 2017; Jiang et al., 2021; Ouyang et al., 2016, 2020; Zheng et al., 2019), we constructed a GEP accounting system consisting of 11 functional indicators in three major categories of products: material products, regulation services, and cultural services. Among them, material products include one indicator of agricultural, forestry, animal husbandry, and fishery products, regulation services products include eight indicators of water conservation, soil conservation, carbon sequestration, oxygen release, water purification, air purification, climate regulation, and flood regulation and storage, and cultural services include two indicators of ecological tourism and landscape aesthetics.

S2.1 Material products value

The value of material products is measured by the agriculture, forestry, animal husbandry, and fishery contribution in each district and county, sourced from the "Hebei Statistical Yearbook", "Zhangjiakou Economic Yearbook", "Chengde Statistical Yearbook", "Beijing Regional Statistical Yearbook" and "China County Statistical Yearbook".

S2.2 Regulating services value

S2.2.1 Water conservation

Water conservation service intercepts stagnant precipitation, enhances soil infiltration and accumulation, maintains soil moisture, regulates storm runoff, replenishes groundwater, and increases available water resources. Water conservation was calculated by using the water balance equation and InVEST model, which were shown in equations (1)-(7).

$$C_{WY} = \left(1 - \frac{AET}{P}\right) \times P \tag{1}$$

$$\frac{AET}{P} = \frac{1 + \omega R}{1 + \omega \times R + \frac{1}{R}} \tag{2}$$

$$\omega = Z \times \frac{AWC}{P} \tag{3}$$

$$R = \frac{k \times ETo}{P} \tag{4}$$

$$H_{JL} = \lambda \times P_A \tag{5}$$

$$C_{wr} = \left(H_{WY} - H_{JL}\right) \times P \times A \times 1000 \tag{6}$$

$$V_{wr} = C_{wr} \times C_{we} \tag{7}$$

Where, C_{WY} is the water yield (mm/a); AET is the annual actual evapotranspiration (mm/a); P is the annual precipitation (mm/a); R is the Budyko aridity index; ω is the ratio of vegetation available water content to the annual expected precipitation; AWC is the available water content for plants (%); Z is the Zhang coefficient; Et_o is the potential evapotranspiration (mm/a); k is the evapotranspiration coefficient of vegetation; H_{JL} is the depth of surface runoff (mm); λ is the surface runoff coefficient; P_A is the multi-year average precipitation (mm); H_{WY} is the water yield depth (mm); A is the area of a certain ecosystem(km^2); C_{wr} is the water conservation function(m^3/a); C_{we} is the unit storage cost of reservoir construction(m^3/yuan); V_{wr} is the value of water conservation (yuan/a).

S2.2.2 Soil conservation

Soil retention service is the ecosystem's function in protecting soil and reducing the erosion capacity of rainfall, thus decreasing soil loss. Soil retention amount can be obtained by the difference between the amount of potential soil erosion and the actual amount of soil erosion, which was calculated using the Universal Soil Loss Equation (USLE) and InVEST model, which were shown in equations (8)-(9).

$$Q_{sdr} = R \times K \times L \times S \times (1 - C \times P) \tag{8}$$

$$V_{sdr} = \left(Q_{sdr} / n\right) \times P_{tf} \tag{9}$$

Where Q_{sdr} is the soil conservation function (t/a); R is the rainfall erosivity factor

MJ • mm/(h·ha·a); K is the soil erodibility factor t·h·ha/(ha·MJ·mm); L is the slope length factor; S is the slope gradient factor; C is the vegetation management factor; P is the soil conservation measure factor; n is the conventional earthwork density, taken as 1.5; P_{tf} is the price for excavation and transportation of unit volume earthwork (m^3/yuan); V_{sdr} is the value of soil conservation (yuan/a).

S2.2.3 Carbon sequestration

Carbon sequestration service is the ecosystem's function in absorbing carbon dioxide to synthesize organic matter, fixing carbon in plants and soil, and reducing carbon dioxide concentration in the atmosphere. According to the principle of material balance, the net ecosystem productivity method is used to calculate the amount of CO_2 fixed in the terrestrial ecosystem, as shown in equations (10)-(13), which is then used to determine the carbon sequestration value.

$$RS = 0.22 \times (e^{0.0913 \times T} + \ln(0.03415 \times P + 1)) \times 30 \times 46.5\% \quad (10)$$

$$NEP = NPP - RS \quad (11)$$

$$Q_{CO_2} = \frac{M_{CO_2}}{M_c} \times NEP \quad (12)$$

$$V_{cf} = Q_{CO_2} \times C_{CO_2} \quad (13)$$

Where, RS is the annual soil microbial respiration (t·C/a); T is the annual average temperature (℃); P is the annual average precipitation (mm); NPP is the net primary productivity (t·C/a); NEP is the net ecosystem productivity (t·C/a); M_{CO2}/M_C is the conversion factor of C to CO_2, 44/12; Q_{CO2} is the total amount of CO_2 sequestration

($t \cdot CO_2/a$); C_{CO2} is the price of CO_2 in the carbon market (yuan/ton); V_{cf} is the value of carbon sequestration (yuan/a).

S2.2.4 Oxygen release

Oxygen release service is the ecosystem's function in releasing oxygen through photosynthesis and maintaining a stable atmospheric oxygen concentration. The amount of oxygen is calculated according to the chemical equation of photosynthesis. The value of the oxygen release function is calculated by the following equations (14)-(15).

$$Q_{O_2} = \frac{M_{O_2}}{M_{CO_2}} \times Q_{CO_2} \tag{14}$$

$$V_{of} = Q_{O_2} \times C_{O_2} \tag{15}$$

Where, Q_{O2} is the oxygen release function ($t \cdot O_2/a$); M_{O2}/M_{CO2} is the conversion factor of CO_2 to O_2, 32/44; C_{O2} is the price of oxygen (yuan/ton); V_{of} is the value of oxygen release (yuan/a).

S2.2.5 Water purification

Water purification service is the ecosystem's function in adsorbing, degrading, and biologically absorbing water pollutants through physical and biochemical processes, reducing pollutant concentrations and purifying the water environment. Each ecosystem type has a capacity to absorb or filter each water pollutant type given. The value of the water purification function is calculated by the following equations (16)-(17).

$$Q_{wp} = \sum_{i=1}^{m} \sum_{j=1}^{n} P_{ij} \times A_i \tag{16}$$

$$V_w = \sum_{i=1}^{n} Q_{wpi} \times C_w / 1000 \quad (17)$$

Where, Q_{wp} is the total amount of water pollutant purification (kg/a); P_{ij} is the purification amount of water pollutants per unit area of a certain ecosystem (kg/km^2); A_i is the area of a certain ecosystem (km^2); C_i is the treatment price for water pollutants (yuan/ton); V_w is the value of water purification (yuan/a).

S2.2.6 Air purification

Air purification service is the ecosystem's function in absorbing and filtering atmospheric pollutants such as SO_2, NO_X, and dust, reducing air pollution concentration and improving air quality. Each vegetation type has a capacity to absorb or filter each air pollutant type given. The value of the air purification function is calculated by the following equations (18)-(19).

$$Q_{ap} = \sum_{i=1}^{m} \sum_{j=1}^{n} Q_{ij} \times A_i \quad (18)$$

$$V_a = \sum_{i=1}^{n} Q_{api} \times C_a / 1000 \quad (19)$$

Where, Q_{ap} is the total amount of atmospheric pollutant purification (kg/a); Q_{ij} is the purification amount of atmospheric pollutants per unit area of a certain ecosystem (kg/km^2); A_i is the area of a certain ecosystem (km^2); C_a is the treatment price for atmospheric pollutants (yuan/ton); V_a is the value of air purification (yuan/a).

S2.2.7 Climate regulation

Climate regulation service is the ecosystem's function in absorbing energy, lowering temperature, and increasing humidity through vegetation transpiration and surface evaporation processes. The energy consumed by transpiration and evaporation is used as the accounting index, which are shown in equations (20)-(23).

$$E_{tt} = E_{pt} + E_{we} \tag{20}$$

$$E_{pt} = \sum_{i=1}^{n} EPP_i \times S_i \times D \times 10^6 / (3600 * r) \tag{21}$$

$$E_{we} = E_w \times q \times 10^3 / (3600) + E_w \times y \tag{22}$$

$$V_{tt} = E_{tt} \times P_e \tag{23}$$

Where, E_{tt} is the total energy consumption of evapotranspiration in the ecosystem (kW·h/a); E_{pt} is the energy consumption of plant transpiration in the ecosystem (kW·h/a); E_{we} is the energy consumption of water surface evaporation (kW·h/a); EPP_i is the heat consumption of evapotranspiration per unit area for the i-th type of ecosystem ($kJm^{-2}d^{-1}$); E_W is the water surface evaporation volume (m^3); S_i is the area of a certain ecosystem (km^2); D is the number of days with daily maximum temperature above 26℃; r is the air conditioning energy efficiency ratio, taken as 3.0; i is the ecosystem type; q is the latent heat of vaporization, the heat required to evaporate 1 gram of water, taken as 2453.2 (J/g); y is the power consumption of a humidifier to convert $1m^3$ of water into steam, taken as 120 (kw·h); P_e is the local electricity price (yuan/kw·h); V_{tt} is the value of climate regulation (yuan/a).

S2.2.8 Flood regulation and storage

Flood regulation and storage is the ecosystem's function in regulating stormwater runoff, reducing flood peaks, and mitigating flood damage. The water storage capacity of vegetation and the amount of stagnant water during flood periods (ponds, lakes) are selected to represent the flood storage capacity of the ecosystem. The value of flood regulation and storage is calculated according to equations (24)-(28).

$$C_{fm} = C_{vc} + C_{rc} + C_{lc} \tag{24}$$

$$C_{vc} = C_{WY} \tag{25}$$

$$C_{lc} = 134.83 \times \exp\left(0.927 \times \ln\left(A\right)\right) \tag{26}$$

$$C_{rc} = 0.35 \times C_t \tag{27}$$

$$V_{fm} = C_{fm} \times C_{we} \tag{28}$$

Where, C_{fm} is the flood regulation and storage capacity (m^3/a); C_{vc} is the flood storage capacity of vegetation (m^3/a); C_{WY} is the water yield calculated by the InVEST model during the water conservation calculation process; C_{rc} is the flood storage capacity of reservoirs (m^3/a); C_{lc} is the flood storage capacity of lakes (m^3/a); A is the lake surface area(m^2); C_t is the total storage capacity of the reservoir(m^3); C_{we} is the construction cost per unit storage capacity of the reservoir (m^3/yuan); V_{fm} is the value of flood regulation and storage (yuan/a).

S2.3 Cultural services value

S2.3.1 Ecological tourism

Ecological tourism refers to the intangible benefits humans obtain from the ecosystem through spiritual experiences, knowledge acquisition, leisure and entertainment, health and wellness, and other recreational activities. The tourism income data for each district and county are sourced from the "Beijing Tourism Statistics Handbook" the official website of the Beijing Municipal Bureau of Culture and Tourism, the Record Xiaokang Project Hebei database, as well as the statistical bulletins of Zhangjiakou and Chengde cities. On this basis, the cultural service value is calculated using the approximation substitution method, which involves estimating it as 70% of the annual tourism revenue (Ni et al., 2022).

S2.3.2 Landscape aesthetics

Landscape aesthetics is the landscapes with potential recreational purposes, cultural and artistic value. Due to the availability of data, we referred to previous study (Xie et al., 2017) and used the equivalent factor method to calculate the landscape aesthetics value, as shown in equation (29)- (30).

$$D = \frac{1}{7}\sum \frac{A_i U_i V_i}{A} \tag{29}$$

$$V_d = \rho \times D \tag{30}$$

Where, D is the value of farmland ecosystem services per unit equivalent factor (yuan/hm^2); i is the type of grain crops (rice, wheat, corn); A_i is the sown area of the i-th type of grain crop (hm^2); U_i is the yield per unit area of the i-th type of grain crop (kg/hm^2); V_i is the price of the i-th type of grain crop (yuan/kg); A is the total area of major grain crops (hm^2); ρ is the value of landscape aesthetics provided by the ecosystem relative to the equivalent factor of the farmland ecosystem; V_d is the value of landscape aesthetics (yuan/a).

S3 Ecosystem Classification System

Based on the ecosystem composition characteristics of the upstream section of the Chaobai River Basin and referring to the ecosystem classification system (Ouyang et al., 2015), the ecosystems are reclassified into six categories: agriculture, forest, grassland, wetland, urban, and bare land, including 20 land use types **(Table S2)**.

Table S2 Ecosystem types in the upstream section of the Chaobai River Basin

Ecosystem types	Land use types
Agriculture	Dry land
Forest	Forested land, Shrubland, Sparse forest land, Other forest land
Grassland	High, Medium, Low coverage grassland
Water	Rivers and canals, Lakes, Reservoirs and ponds, Beaches, Marshland
Urban	Urban land, Rural residential areas, Other construction land
Bare land	Sandy land, Saline-alkali land, Bare soil land, Bare rocky land

S4 Geodetector Model

S4.1 Interaction factor detection

Interaction factor detection can determine whether the simultaneous action of factor X_1 and factor X_2 will increase or decrease the influence on the dependent variable Y to a certain extent, the relationship between the two factors can be further divided into the following categories **(Table S3)**.

Table S3 Types of two-factor interactions

Judgment basis	Interaction types
$q(X_1 \cap X_2) < \min[q(X_1), q(X_2)]$	Nonlinear strengthening weakened
$\min[q(X_1), q(X_2)] < q(X_1 \cap X_2) < \max(q(X_1), q(X_2)]$	Single factor nonlinear weakening
$q(X_1 \cap X_2) > \max(q(X_1), q(X_2))$	Two-factor enhancement
$q(X_1 \cap X_2) = q(X_1) + q(X_2)$	Independence
$q(X_1 \cap X_2) > q(X_1) + q(X_2)$	Nonlinear enhancement

S4.2 Parameters preferences

We generated square grids at different spatial scales (5 km, 3 km, 2 km, 1.75 km, 1.5 km, and 1 km) based on the 2020 GEP results, extracted the corresponding values of explanatory variables, and used the OPGD model to calculate the q value and significance p value of factor detection under the optimal discretization combination at each spatial scale, and compared the results **(Table S4)**. we found that the geographic detector performed better at a grid scale of 1.75 km × 1.75 km. Therefore, the OPGD model at a grid scale of 1.75 km × 1.75 km was chosen for subsequent factor detection, interaction detection, and ecological detection analysis.

Table S4 Factor detection results at different grid scale

Grid scale	5 km×5km		3km×3km		2km×2km		1.75km×1.75km		1.5km×1.5km		1km×1km	
	q	p	q	p	q	p	q	p	q	p	q	p
RSEI	0.010	0.090	0.002	0.696	0.000	0.833	0.002	0.025	0.001	0.261	**0.003**	**0.000***
FVC	0.007	0.500	0.003	0.233	0.002	0.197	**0.032**	**0.000***	0.001	0.100	0.000	0.534
PRE	0.013	0.069	0.003	0.665	0.002	0.207	**0.018**	**0.000***	0.002	0.012	0.000	0.303
DEM	0.008	0.442	0.002	0.596	0.001	0.084	**0.005**	**0.000***	0.001	0.349	0.000	0.620
TEM	**0.017**	**0.050***	0.005	0.036	**0.008**	**0.000***	**0.031**	**0.000***	0.001	0.486	0.000	0.112
SL	0.012	0.089	0.004	0.153	0.001	0.721	0.001	0.641	0.001	0.282	0.000	0.148
NPP	0.011	0.168	**0.008**	**0.001***	0.003	0.203	**0.044**	**0.000***	0.001	0.686	0.000	0.056
PL	**0.029**	**0.000***	**0.012**	**0.000***	**0.006**	**0.000***	**0.004**	**0.000***	**0.004**	**0.000***	**0.002**	**0.000***
POP	0.007	0.308	0.003	0.179	0.002	0.208	**0.158**	**0.000***	0.001	0.424	0.000	0.453
GDP	0.006	0.534	0.002	0.190	0.004	0.114	**0.034**	**0.000***	0.001	0.329	**0.001**	**0.000***
NL	0.011	0.236	0.003	0.354	0.002	0.396	**0.003**	**0.001***	**0.002**	**0.010***	0.000	0.283
LD	**0.045**	**0.000***	**0.018**	**0.000***	**0.012**	**0.000***	**0.004**	**0.000***	**0.009**	**0.000***	0.000	0.073

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