Supplementary material

Analyzing the interrelationships among various ecosystem services from the perspective of ecosystem service bundles in Shenyang, China

The calculation of ES

(1) Food supply

In this study, we used the farmland NPP value as the weight to obtain the spatial distribution pattern of the food supply in Shenyang. The formula is as follow:

$$FS = TP_i \times \frac{NPP_i}{\sum_{i=1}^{n} NPP_{ti}}$$

In the formula, *FS* is food supply (g/m^2), TP_i is the annual grain output (t) of the district where grid unit *i* is located, NPP_i is the NPP value of grid unit *i* (gC), and NPP_{ti} is the total NPP (gC) of the farmland in the district where the grid unit *i* is located.

(2) Grass supply

In this study, we used grassland productivity represent the ability of grass supply. The formula is as following:

$$GS = \sum_{i=1}^{n} \frac{NPP}{0.44} \times \frac{1}{1+k_i} \times H_i \times R$$

In the formula, GS is grass supply (g·m^{-2}); NPP is the net primary productivity of vegetation (gC·m^{-2}); 0.44 is the conversion coefficient of vegetation in the form of carbon NPP converted to biomass; k_i is the ratio of below-ground biomass to above-ground biomass of *i*-th grass type pasture. H_i is the standard hay conversion coefficient of the *i*-th grass type pasture, and the value is based on the agricultural industry standard of China (NY/T 635-2015). R is the grazing utilization.

Table 1. Calculation parameters of stock carrying capacity of different grassland types in Shenyang.

Type	Grassy Marshland	Grassland
Belowground to aboveground biomass ratio /k	7.91	8.95
Standard hay conversion coefficient /H	1	1
Grazing utilization R/%	52.5	47.5

(3) Water conservation

The water balance equation is used to calculate water conservation, which is closely related to precipitation, evapotranspiration, surface runoff, and vegetation coverage types. The formulas are as following:

$$WC = \sum_{i=1}^{j} \left(P_i - R_i - ET_i\right) A_i$$

$$R = P \times \alpha$$

$$ET = \frac{P\left(1+\omega \times ET_0 / P\right)}{\left(1+\omega \times ET_0 / P + P / ET_0\right)}$$

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$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \frac{900}{T+273} U_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1+0.34U_2\right)}$$

In the formula, WC is water conservation (m^3/a); P_i is the rainfall (mm); R_i is the surface runoff (mm); ET_i is the evapotranspiration (mm); A_i is the area of the type i ecosystem; i is the i-th ecosystem type in the study area; j is the number of ecosystem types in the study area, α is the average surface runoff coefficient (Table S2), ET_0 is the annual average potential evapotranspiration (mm); ω is the influence coefficient of the underlying surface (Table S3), R_n is crop surface net radiation (MJ m^{-2} d^{-1}); G is soil heat flux density (MJ m^{-2} d^{-1}); T is monthly average temperature (°C); U_2 is 2m Wind speed (m s^{-1}); es is saturated water vapor pressure (kPa); ea is actual water vapor pressure (kPa); Δ is the slope of the saturated water vapor pressure temperature curve (kPa $°C^{-1}$); γ is the psychrometric constant (kPa $°C^{-1}$).

Table S2. Mean values of surface runoff coefficients of various ecosystems types.

	Type	Average Runoff Coefficient (%)		Type	Average Runoff Coefficient (%)
Forest	Evergreen coniferous forest	4.52	Farmland	Paddy field	25
	Evergreen broad-leaf forest	4.65		Irrigable land	18.45
	Deciduous coniferous forest	0.88		Dry land	18.45
	Broadleaved deciduous forest	2.7	Settlement	Urban construction land	45
	Theropencedrymion	3.52		Rural Settlement	30
	Bush fallow	4.17	Wetland	Marsh	0
Grassland	Meadow grassland	9.13		Coastal wetland	0
	Typical grassland	3.94		Inland water	0
	Desert grassland	18.27		Hongze lake shoal	0
	Alpine meadow	8.2		Ice and snow	0
	Alpine grassland	6.54	Desert	Bare rock	70
	Shrubland	5.56		Bare land	19.72
				Desert	23

Table 3. Reference value of parameter ω for evaluating the importance of water conservation function.

Type	Farmland	Forest	Bush Fallow	Grassland	Artificial Land	Others
ω	0.5	1.5	1	0.5	0.1	0.1

(4) Carbon sequestration

In this study, the carbon sequestration is calculated according to the photosynthesis equation: $CO_2+H_2O \rightarrow CHO+O_2$. The formulas are as following:

$$CS = NPP \times 1.63$$

where CS is carbon sequestration (t) and NPP is net primary productivity (t).

(5) SO_2 absorption

$$SA = \sum_k \sum_i \frac{NPP_{ij}}{NPP_i} \times P_{SO_2}$$

where SA is SO_2 absorption (kg/(hm^2)), NPP_{ij} is the net primary productivity of the jth grid of the i-th vegetation (gC/(m^2·a)); NPP_i is the average net primary productivity of the i-th vegetation (gC/(m^2·a)); P_{SO_2} is the ability to absorb SO_2 (kg/(hm^2·a)) (Table S4).

(6) NO_x absorption

$$NA = \sum_k \sum_i \frac{NPP_{ij}}{NPP_i} \times P_{NO_2}$$

where NA is NO_x absorption (kg/(hm^2)), NPP_{ij} is the net primary productivity of the jth grid of the i-th vegetation (gC/(m^2·a)); NPP_i is the average net primary productivity of the i-th vegetation (gC/(m^2·a)); P_{NO_x} is the ability to absorb NO_x (kg/(hm^2·a)) (Table S4).

Table S4. The ability of vegetation to absorb air pollutants.

Type	SO_2 Absorption Capacity kg/(hm^2·a)	No_x absorption Capacity kg/(hm^2·a)
Evergreen coniferous forest, deciduous coniferous	215.6	6
forest	88.65	6
Broadleaved deciduous forest	152.13	6
Theropencedrymion Deciduous broad leaf shrub forest	15.213	0.6
Grassland/ farmland	15.213	0.6

From: Report on China's Biodiversity National Conditions, 1998.

(7) Humidification

$$HU = Q_{vw} + Q_{ww}$$

$$Q_{vw} = \sum_{ij} LAI_{ij} \times q_{wi} \times 62 \times A_{ij}$$

$$Q_{ww} = \sum_i \alpha_i \times A_i \times ET$$

Where HU is the total amount of vegetation and wetland humidification (kg/a); Q_{vw} is the vegetation evapotranspiration and humidification (kg/a); Q_{ww} is the wetland water surface evaporation (kg/a), A_{ij} is the area of the jth grid of the i-th vegetation (900 m^2); LAI_{ij} is the leaf area index of the j-th grid of the i-th vegetation (m^2/ m^2); q_{wi} is the daily transpiration capacity per unit leaf area of the type i vegetation (kg/(m^2·d)); α_i is the wetland water surface ratio (%) (Table S 5); A_i is the area of the i-th wetland (m^2); ET is the water surface evaporation in Shenyang from July to August (mm).

Table S5. The water surface ratio of different types of wetlands in Shenyang.

Type	Water Surface Ratio (%)
Herb wetland	77
Lake	85
Reservoir	85
River	83
Canal	83

(8) Soil conservation

Use the Revised Universal Soil Loss Equation (RUSLE) to calculate the soil conservation. The formulas are as following:

$$SC = A_p - A_r$$

$$A_p = R \cdot K \cdot LS$$

$$A_r = R \cdot K \cdot LS \cdot C \cdot P$$

SC is the soil conservation amount per unit area (t/(hm²·a)); A_p is the potential soil erosion amount per unit area (t/(hm²·a)), A_r is the actual soil erosion amount per unit area (t/(hm²·a)); R is the rainfall erosive force (MJ·mm/(hm²·h·a)); K is the soil erosion erodibility (t·h/(MJ·mm)); LS is the slope-slope length factor; C is the vegetation cover factor; P is the management factor (soil and water conservation measure factor). L, S, C, P are dimensionless.

(9) Flood regulation

Wetlands are huge reservoirs and natural water resources, which can store excess precipitation during the flood season, and equalize flood runoff. Wetland vegetation can slow down the flood flow rate, reduce the downstream flood peak water level, and make it discharge smoothly, eventually delaying the flood peak time. Thereby reducing flood disasters. At the same time, the floodwater stored in the wetland can be released slowly, which can provide a balanced water supply to the downstream industrial, agricultural, urban and rural residents, and increase the groundwater storage through infiltration to meet the needs of drinking water, industrial water and agricultural irrigation water in dry seasons. Therefore, the flood regulation and storage function of wetlands refers to the flood containment, regulation and storage effect of wetland resources through their own water cycle process.

Rivers, reservoirs, lakes swamps, artificial canals and ponds can provide flood regulation services for Shenyang. The flood regulation is calculated according to their area and average water depth, and the formula is:

$$FR = \sum_i h_i \times A_i$$

In this formula, FR is the flood regulation capacity of the wetland (m³/a); h_i is the average water depth of the wetland (m); A_i is the area of the i-th wetland (hm²).

(10) Sand fixation

The Revised wind erosion equation (RWEQ) was used to calculate sand fixation. The formulas are as following:

$$SF = S_{LP} - S_L$$

$$S_{LP} = \frac{2 \cdot z}{S_P^{\,2}} Q_{\max P} \cdot e^{-\left(z/S_p\right)^2}$$

$$Q_{\max P} = 109.8\left(WF \times EF \times SCF \times K'\right)$$

$$S_P = 150.71 \cdot \left(WF \times EF \times SCF \times K'\right)^{-0.3711}$$

$$S_L = \frac{2 \cdot z}{S^2} Q_{\max} \cdot e^{-\left(z/S\right)^2}$$

$$S = 150.71 \cdot \left(WF \times EF \times SCF \times K' \times C\right)^{-0.3711}$$

$$Q_{\max} = 109.8\left(WF \times EF \times SCF \times K' \times C\right)$$

where SF is the amount of sand fixation (kg/(m² a)); S_{LP} is the potential wind erosion amount (kg/(m² a)); S_L is the actual wind erosion amount (kg/(m² a)); S is the key plot length (m); S_P is the length of the potentially key plot length (m); Q_{max} is the maximum transfer amount (kg/m); Q_{maxP} is the potential maximum transfer amount (kg/m); z is the maximum wind erosion distance (m); WF is the climate erosion factor (kg/m); K' is the surface roughness factor; EF is the soil erosion factor; SCF is the soil crust factor; C is the vegetation cover factor.

(11) Outdoor recreation

Different landscape variables serve as indicators for the recreation potential. We selected hemeroby, land cover types and terrain roughness as indicators to measure outdoor recreation, and all indicators were considered to equally contribute to the recreation potential and were rescaled to 0–100. The specific calculation process is as follows:

(1) The hemeroby index measures the extent of human impacts on the natural environment on a scale from 1 (natural) to 7 (artificial) and can be attributed to land cover types. The hemeroby was calculated based on land use data. The index was inverted to assign highest recreational values to more natural environments and rescaled from 0 to 100.

(2) Diverse landscapes provide high recreational and visual attractiveness (Kienast et al., 2012; Ode et al., 2009). The landscape diversity was assessed by calculating the number of different land use types per unit. The result was rescaled from 0 to 100. Great landscape diversity indicates high recreation potential.

(3) Rough landscapes provide many recreational opportunities and are visually more appealing than flat landscapes (Weyland & Laterra, 2014). The Terrain Ruggedness Index (TRI) reveals the degree of topographic heterogeneity by measuring elevation differences between adjacent cells (Riley et al., 1999). We calculated the TRI based on the DEM, which was aggregated to 30m×30m and classified into seven classes as proposed by Riley et al. (1999). All scores were rescaled from 0 to 100. High ruggedness suggests high recreation potential.

(4) All indicators were considered to equally contribute to the outdoor recreation. All indicators, which were first rescaled to 0–100, were overlaid to obtain outdoor recreation by summing all layers and dividing them by 3. The outdoor recreation ranges from 0 (low) to 100 (high).

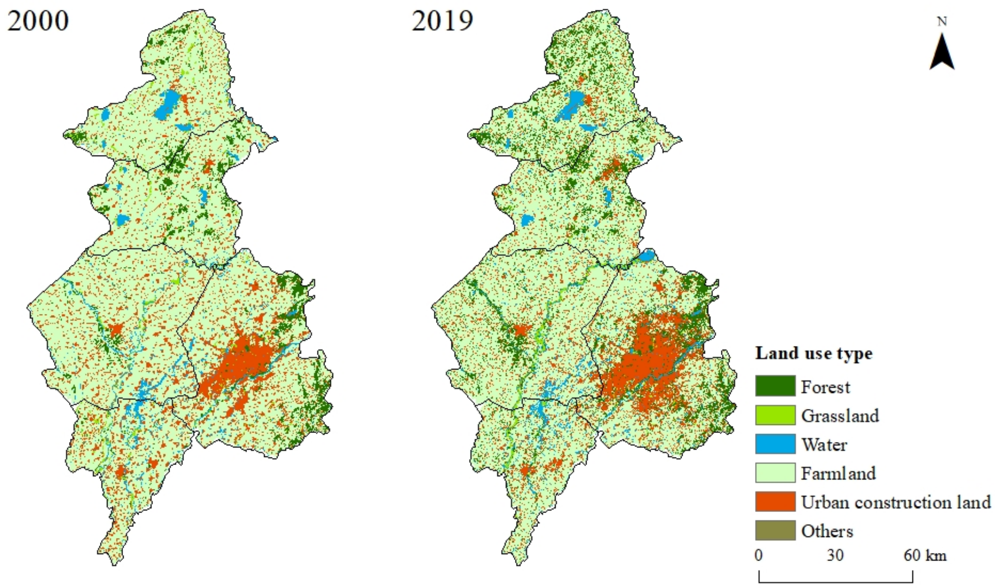

Figure S1. Types of land use in Shenyang.

Table 6. Data sources.

Data	Data Sources	Format	Spatial Resolution	Year
Shenyang administrative boundary data	Shenyang Institute of Applied Ecology, Chinese Academy of Sciences	SHP	—	—
DEM	EARTHDATA (https://search.asf.alaska.edu/#/)	TIFF	90m	—
Land use	Shenyang Institute of Applied Ecology, Chinese Academy of Sciences	TIFF	30m	2000 and 2019

NDVI	NASA (https://e4ftl01.cr.usgs.gov/MOLT/)	TIFF	250m	
NPP	NASA (https://e4ftl01.cr.usgs.gov/MOLT/)	TIFF	500m	
Soil Type	Harmonized World Soil Database (http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/ harmonized-world-soil-database-v12/en/)	TIFF	1km	—
Temperature	China Meteorological Data Network (http://data.cma.cn/)	TEXT	—	2000 and 2019
Precipitation				
Wind speed				
Relative humidity				
Sunshine duration				
Snow depth	National Tibetan Plateau/Third Pole Environment Data Center (http://data.tpdc.ac.cn/en/)		25km	

Table 7. Statistics of ES in Shenyang in 2000 and 2019.

	FS	**GS**	**WC**	**CS**	**SA**	**NA**	**HU**	**SC**	**FR**	**SF**	**OR**
2000	0.24	47.75	22.92	0.68	24.97	1.10	441.60	66.02	1.523	3.36	45.36
2019	0.47	76.39	66.28	1.03	25.61	1.13	551.88	117.80	1.516	2.03	45.86

*FS: kg/m^2, GS: g/m^2, WC: mm, CS: kg/m^2, SA: kg/hm^2, NA: kg/hm^2, HU: kg/m^2, SC: t/hm^2, FR: m^3/m^2, SF: kg/m^2, OR: Index.

Table S8. Loadings of ES onto each principal component in 2000.

	PC1 (28%)	**PC2 (19%)**	**PC3 (13%)**	**PC4 (11%)**
FS	0.667	−0.378	−0.448	0.112
GS	−0.001	0.331	0.170	0.673
SC	0.442	−0.197	0.073	−0.337
CS	0.658	−0.557	−0.050	0.308
NA	0.817	0.157	0.434	−0.162
HU	0.451	−0.532	−0.288	0.369
SF	−0.186	−0.134	0.648	0.505
SA	0.787	0.147	0.477	−0.202
FR	0.144	0.636	−0.425	0.313
WC	0.442	0.612	−0.368	−0.106
OR	0.520	0.604	0.086	0.181

Table S9. Loadings of ES onto each principal component in 2019.

	PC1 (31%)	**PC2 (18%)**	**PC3 (13%)**	**PC4 (10%)**
FS	0.725	−0.394	0.250	−0.243
GS	0.082	0.390	0.527	0.303
SC	0.500	−0.115	−0.355	−0.232
CS	0.817	−0.393	0.271	−0.103
NA	0.773	0.254	−0.440	0.238
HU	0.593	−0.554	0.360	−0.060
SF	0.135	−0.230	0.336	0.775
SA	0.762	0.243	−0.479	0.228
FR	0.105	0.657	0.442	−0.255
WC	0.400	0.555	0.238	−0.320
OR	0.528	0.606	0.067	0.153

Table S10. The number and proportion of grids per bundle.

	2000		**2019**	
	Grid	**Ratio**	**Grid**	**Ratio**
Bundle 1	35233	69.93%	34939	69.35%
Bundle 2	6822	13.54%	7778	15.44%
Bundle 3	2316	4.60%	2784	5.53%

Bundle 4	3831	7.60%	3976	7.89%
Bundle 5	2179	4.33%	904	1.79%

Table S11. Data source of social-ecological factors.

Factor	Data Sources
Annual rainfall	China Meteorological Data Network
Annual average temperature	
Average wind speed	
Elevation	NASA
Population density	WorldPop
Forest	Shenyang Institute of Applied Ecology, Chinese Academy of Sciences
Grassland	
Farmland	
Waterbody	
Urban construction land	

Table S12. Distribution of predicted membership in 2000 (Grid).

	Bundle 1	**Bundle 2**	**Bundle 3**	**Bundle 4**	**Bundle 5**
Bundle 1	10354	41	72	364	93
Bundle 2	44	1891	38	90	45
Bundle 3	29	16	537	14	2
Bundle 4	99	78	10	629	2
Bundle 5	33	24	1	6	524

Table S13. Distribution of predicted membership in 2019 (Grid).

	Bundle 1	**Bundle 2**	**Bundle 3**	**Bundle 4**	**Bundle 5**
Bundle 1	10314	9	90	483	89
Bundle 2	69	2220	20	71	19
Bundle 3	6	12	721	5	0
Bundle 4	139	31	7	659	2
Bundle 5	16	17	0	4	154

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