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Methods

S1 Ecosystem Services (ESs) Assessment

S1.1 Equivalent Value Factors (EVF) Method

Although land use/land cover (LULC) and ecosystem types do not correspond to each other, according to previous studies [1] and the specific situation of the Yellow River Delta (YRD), each LULC was associated with the closest ecosystem type, so rivers, lakes, ponds, and reservoirs corresponded to water bodies. Mudflats and reed swamps corresponded to wetlands. The barren was close to desert due to the sparse surface vegetation, so the equivalent factor of desert was used.

The surface of the construction land was relatively dense and the vegetation was relatively sparse, and its functions of food production (FP), raw material (RM), waste treatment (WT), habitat quality (HQ), water yield (WY), and soil conservation (SC) were all zero, while gas regulation (GR) and climate regulation (CR) referred to the desert, and its relaxation (Re.) referred to the recreational functions of the forest [2]. In this paper, according to the corrected grain price and the equivalent value factors of ESs applicable to China [3] (Table S1), we compiled the ES value factor equivalents per unit area for each LULC in the YRD, which were used to estimate the value of Re., WT, FP, CR, GR, and RW.

Table S1. Equivalent value factors of ecosystem services per unit area in China [3].

Ecosystem Service	Forest	Grasslands	Croplands	Wetlands	Water Bodies	Barren
Climate regulation	4.07	1.56	0.97	13.55	2.06	0.13
Waste treatment	1.72	1.32	1.39	14.4	14.85	0.26
Food production	0.33	0.43	1	0.36	0.53	0.02
Raw material	2.98	0.36	0.39	0.24	0.35	0.04
Relaxation	2.08	0.87	0.17	4.69	4.44	0.24
Gas regulation	4.32	1.5	0.72	2.41	0.51	0.06
Water yield	4.09	1.52	0.77	13.44	18.77	0.07
Soil conservation	4.02	2.24	1.47	1.99	0.41	0.17
Habitat quality	4.51	1.87	1.02	3.69	3.43	0.4

S1.2 Water Yield (WY)

The reference evapotranspiration (ET_0) in the InVEST WY model is same as the traditional concept of potential evapotranspiration. Potential evapotranspiration refers to the evapotranspiration under the assumption that the ground is completely covered by specific short-stalked green plants, there is sufficient moisture in the soil, and the soil environment is moist [4]. It can be calculated by many methods, such as the P–M algorithm [5], Hargreaves algorithm [6], and so on. However, these calculation methods require a large amount of data. Based on the data collected in the study area and the applicability of the calculation methods, and after calculation and comparison, a modified Hargreaves method (Equation (S5)) was selected to estimate the potential evapotranspiration in the study area.

$$ET_0 = 0.0013 \times 0.408 \times RA \times (T_{avg} + 17) \times (TD - 0.0123P)^{0.76} \quad \text{(S1)}$$

where ET_0 is the potential evapotranspiration (mm/d); and RA is the solar radiation in the thermosphere (MJ/(m²·d)). It is obtained by dividing the average total solar radiation of the weather station by 50%. The total solar radiation data are the average value of the multi-year monitoring data at the Fushan Meteorological Station in Yantai; T_{avg} is the average of the daily highest and lowest temperatures (℃); TD is the difference between the average daily highest temperature and the average daily lowest temperature (℃); and P is the average monthly rainfall. The spatial distribution map of average annual rainfall was obtained by the AunSPLINE interpolation method.

Table S2. The root depth and evapotranspiration coefficient of each land use/land cover.

Land Use/ Land Cover	Evapotranspiration Coefficient	Root Depth (mm)	Whether Vegetated (1=Yes; 0=No)
Croplands	0.65	300	1
Forest	1.00	3000	1
Grasslands	0.65	2000	1
Water Bodies	1.00	1	0
Wetlands	0.60	1000	0
Urban and rural build-up lands	0.30	1	0
Barren	0.20	200	0

S1.3 Carbon Storage (Ca.)

Alam et al. indicated that precipitation was significantly and positively correlated with biomass carbon density and soil carbon density (Alam et al., 2013). Therefore, combining the weights of the factors influencing carbon density and the needs of this study, the correction equation was selected as follows.

$$C_{BP} = 6.789 \times e^{0.0054 \times MAP}$$

$$C_{SP} = 3.3968 \times MAP + 3996.1$$

$$K_{BP} = \frac{C_{BP1}}{C_{BP2}} \quad \text{(S2)}$$

$$K_{SP} = \frac{C_{SP1}}{C_{SP2}}$$

where C_{BP} is the biomass density corrected according to the annual precipitation (unit: t · hm^{-2}); C_{SP} is the soil carbon density corrected according to the annual precipitation (unit: t · hm^{-2}); MAP is the annual average precipitation (mm); K_{BP} is the correction coefficient of biomass carbon density precipitation factor; K_{SP} is the correction coefficient of soil carbon density precipitation factor; C_{BP1}, C_{SP1} are the carbon density parameters in the lower reaches of the Yellow River, and C_{BP2}, C_{SP2} are the national carbon density parameters. The carbon density parameters of the study area were obtained by multiplying the national carbon density parameters and the correction coefficient, as shown in Table S3.

Table S3. The carbon density of each land use/land cover (Mg·ha^{-1}).

Land Use/Land Cover	C_above	C_below	C_soil	C_dead
Croplands	9.0	4.0	25.0	0.3
Forest	5.0	3.0	20.0	0.0
Grasslands	2.0	1.0	5.0	0.0
Water bodies	1.5	0.5	16.0	0.0
Wetlands	17	8.0	15.0	0.6
Urban and rural build-up lands	0.0	0.0	12.0	0.0
Barren	0.1	0.0	0.0	0.0

S1.4 Soil Conservation (SC)

The management factor refers to the factor that reduces the potential soil erosion due to some physical and chemical measures, and is expressed by P. The value of P is [0,1], and the P value is 0 when very good soil and water conservation measures are taken, and 1 when no soil and water conservation measures are taken. According to the above research and related literature in the similar study area [7–11], we determined the selection of the P value. By looking up Appendix 3 of "the list of counties and cities in China's farming system", we found the category to which Dongying City belonged. According to the name of the national rotation area in Appendix 5 of "Technical regulations on dynamic monitoring of regional soil and water loss", we found that the P value of cropland was 0.391 and other LULCs were set to 1, as shown in Table S4.

Table S4. The management factor expressed by P of different LULCs.

LULC	Management Factor (P)
Forest	1.000
Grasslands	1.000
Croplands	0.391
Urban and rural build-up lands	1.000
Barren	1.000
Wetlands	1.000
Water bodies	1.000

S1.5.1 Rainfall Erosivity

According to relevant literature, we decided to use the rainfall erosivity mapping over mainland China based on high-density hourly rainfall records published by Yue et al. [12], including annual rainfall erosivity (R-factor) in the Chinese Mainland from 1951 to 2018. Hourly and daily data for more than 2000 stations were collected, together with the 1 min data for 62 of them to develop high-quality maps of the R-factor. They not only provided high spatial–temporal resolution rainfall erosivity over the mainland China, but also greatly improved the accuracy of the existing rainfall erosivity dataset.

The R-factor was calculated using Equations (S3)–(S5) [13]:

$$R = \frac{1}{N}\sum_{i=1}^{N}\sum_{j=1}^{m}(EI_{30})_{ij} \tag{S3}$$

$$E = \sum_{r=1}^{l}(e_r \cdot P_r) \tag{S4}$$

$$e_r = 0.29[1 - 0.72exp(-0.082i_r)] \tag{S5}$$

where EI_{30} (event rainfall erosivity, MJ mm ha^{-1} h^{-1}) is the product of the total storm energy *E* (MJ ha^{-1}) and the maximum 30 min intensity I_{30} (mm h^{-1}); i = 1,2, . . ., *N*, where *N* is the number of effective years, and *j* = 1,2, . . ., m means there are m erosive storm events in the *i*th year. For each storm event, rainfall was divided into *l* time intervals depending on the temporal resolution of rainfall data. The total storm energy *E* was the sum of the energy for each time interval *r*, which was the unit energy e_r (energy per mm of rainfall, MJ ha^{-1} mm^{-1}) multiplied by the rainfall amount P_r (mm) for each time interval. In addition, i_r was the intensity (mm h^{-1}) of the *r*th interval, and I_{30} (mm h^{-1}) was the maximum intensity over 30 consecutive minutes for each storm event. For hourly data, the I_{30} was assumed to be the same as the maximum 1 h intensity.

S1.5.2 Soil Erodibility Factor

The soil erodibility factor (*K*) reflects the sensitivities of different soil types to erosion. The soil data were adopted from the Chinese Soil Database (vdb3.soil.csdb.cn). The sand grains, powder particles, clay particle, and organic carbon were calculated using the EPIC model equations [14] as follows:

$$K = \left\{0.2 + 0.3exp\left[-0.0256 \times SAN\left(1 - \frac{SIL}{100}\right)\right]\right\} \times \left(\frac{SIL}{CLA + SIL}\right)^{0.3} \times \left[1 - 0.025 \times \frac{C}{C + exp(3.72 - 2.95\, C)}\right] \times \left(1 - 0.7 \times \frac{SN_1}{22.9\, SN_1 - 5.51}\right) \tag{S6}$$

$$SN_1 = 1 - \frac{SAN}{100}$$

where *SAN*, *SIL* and *CLA* are the mass fractions (%) of sand, powder, and clay, respectively; and *C* is the mass fraction of organic carbon (%).

S1.5.3 The Slope and Slope Length

The InVEST Sediment Delivery Ratio (SDR) Model automatically generates the slope and slope length at the backend based on the digital elevation model (DEM). The slope and slope length were calculated using a two-dimensional surface calculation method as follows:

$$L_x \times S_x = S_x \times \frac{(A + D^2)^{m+1} - A^{m+1}}{D^{m+2} \times x_x^m \times 22.13^m} \tag{S7}$$

where S_x is the slope factor of the grid cell, and it is the function of slope, and $S_x = 10.8 \cdot \sin(\theta) + 0.03$ if slope <9%, and $S_x = 16.8 \cdot \sin(\theta) - 0.50$ if ≥9%; *A* is the area of the sand-producing area above the grid runoff inlet (m[2]); *D* is the grid cell size (m); $x_n = |\sin\alpha_n| + |\cos\alpha_n|$, where α_n represents the sediment transport direction of grid cell *x*; and *m* is the RUSLE length exponential factor (Equation (S13)).

$$\begin{cases} \theta \le 1\%, & m = 0.2 \\ 1\% < \theta \le 3.5\%, & m = 0.3 \\ 3.5\% < \theta \le 5\%, & m = 0.4 \\ 5\% < \theta \le 9\%, & m = 0.5 \\ \theta > 9\%, & m = \beta/(1+\beta) \end{cases} \tag{S8}$$

where $\beta = \sin\theta / [0.0986 \cdot (3\sin\theta \cdot 0.8 + 0.56)]$.

2. Social–Ecological Drivers of ESs

2.1. Landscape Disturbance

The landscape disturbance index (Gi) indicates the ability of the landscape to resist external disturbance and self-recovery. The greater the intensity of human and natural disturbance to the landscape pattern, the greater the sensitivity of the entire ecosystem and the greater the ecological risk of the landscape. The formula was as follows.

$$G_i = W_1 \times PO_i + W_2 \times D_i + W_3 \times F_i \tag{S9}$$

where *W1*, *W2*, and *W3* are the weights of landscape fragmentation (PO_i), landscape separation (D_i), and landscape sub-dimensionality (F_i), respectively, which are assigned 0.5, 0.3, and 0.2, respectively, based on related research results [15,16]; and *i* is the specific LULC type. The above indices were calculated using ArcGIS 10.2 and Fragstats 4.2.

S2.2 Shoreline Use Intensity

Based on the development and utilization statuses of island coastline, shoreline developments can be classified into different types. The reference values for evaluating the impacts of different shoreline development types on the island ecosystem can be set, usually based on common knowledge of technicians in the field.

The impact of the development of *N* shoreline segments on any grid of ecosystem on the island land can be calculated with the equation below [17]:

$$I(x,y) = \frac{1}{N}\sum_{i=1}^{N}\frac{P_i}{1 + D_i(x,y)/w} \tag{S10}$$

where $I(x,y)$ represents the impact of the development of *N* shoreline segments on any grid of the island ecosystem; P_i is the reference value for the assessment of the impact of the shoreline type on the island ecosystem; $D_i(x,y)$ is the attenuation distance from the central point of any grid to the midpoint of the *i*th shoreline segment; *N* is the number of shoreline segments'; and w is the half attenuation coefficient, which was 0, 0.4, 0.6, 0.8, and 1.0, respectively, [17] for different types of shoreline developments including the undeveloped shoreline, embankment dam, protective dam, industrial and town, and port and dock on the YRD, respectively

We extracted shoreline types using remote sensing images downloaded from the Geospatial Data Cloud (https://www.gscloud.cn). Radiation calibration, band blending, and island contour extraction were conducted on the satellite remote sensing images of 1980 (LANDSAT 4), 1990 (LANDSAT 5), 2000 (LANDSAT 5), 2010 (LANDSAT 5), and 2020 (LANDSAT 8).

S2.3 Salinization

Seawater intrusion is a serious threat to natural ecosystems [18]. Soil salinization is a common ecological problem in coastal wetlands, caused mainly by seawater intrusion, and considerably threatens soil quality, biological community, and agricultural production [19–21].

In this paper, the salinity index (SI) [22] was used as a soil salinity inversion model to extract information on soil salinity in the YRD. According to the relevant research results [23], the correlation coefficient R^2 between the salinity index and the measured total salt content of soil reached more than 0.6, which meets the requirements of soil salinization inversion. Moreover, the calculation is simpler and more convenient for the analysis of spatial and temporal variation of multiphase soil salinity.

$$SI = \sqrt{B \times R} \tag{S11}$$

where B is the blue wave band of the image and R is the red wave band. We extracted salinization information using remote sensing images downloaded from the Geospatial Data Cloud (https://www.gscloud.cn). Radiation calibration, band blending, and island contour extraction were conducted on the satellite remote sensing images of 1980 (LANDSAT 4), 1990 (LANDSAT 5), 2000 (LANDSAT 5), 2010 (LANDSAT 5), and 2020 (LANDSAT 8).

S2.4 Runoff

The Yellow River is the most unique and important external factor affecting the YRD, whose water and sand input is an important driver for the formation and extension of the YRD [24,25]. In addition, the Yellow River, as an important water source, has important ecological functions for vegetation growth and soil quality improvement, which decrease with increasing distance from the river.

The annual runoff from the Lijin hydrological station, which is the last hydrological station where the Yellow River enters the sea, was used to represent the Yellow River input. The average runoff from 1980 to 2020 was considered as the evaluation criterion. The equation was as follows.

$$E_1 = \frac{Runoff_x}{Runoff_a} - 0.5 \times \frac{Runoff_x}{Runoff_a} \times \frac{DTY_y}{DTY_{max}} \tag{S12}$$

where E_1 is the evaluation value of Yellow River runoff; $Runoff_x$ and $Runoff_a$ are the runoff in year x and average runoff from 1980 to 2020, respectively (m^3); and DTY_y and DTY_{max} are the distance of position y and maximum distance to the Yellow River, respectively (km). The distance data were obtained through the Euclidean Distance tool in ArcGIS 10.2.

S2.5 Index of Connectivity

The hydrological connectivity of the basin, such as the internal relationship between the upstream sediment yield source area and the downstream river channel, is an important method to study the redistribution of runoff and sediment in the basin under topographic changes [26,27]. The application of hydrological connectivity on the basin scale is helpful to understand the potential possibility of the basin inner diameter flow and sediment transport process better, and also helps to explain the difficulty of the basin inner diameter flow and sediment transport from one location to another. Borselli et al. proposed a topographic index algorithm based on the digital elevation model (DEM) and LULC to calculate the hydrological connectivity of a watershed, which revealed the potential for the transport of eroded sediment from the slope-producing source area to the downstream sedimentation area at the watershed scale, and was simple to calculate, required fewer data for implementation, and whose results were complementary to the field runoff plot test values [28]. The index of connectivity (IC) takes into account the characteristics of the upstream part of the catchment nodes in the study basin and the path length of eroded sediment transport to the nearest sedimentation point downstream. The easier the runoff or sediment transport between different areas, the greater the connectivity between them. Therefore, IC can be used to quantitatively describe the hydrological connectivity among nodes at the watershed scale.

The IC was calculated as follows.

$$IC = \ln \left(\frac{\overline{w}\overline{s}\sqrt{A}}{\sum \frac{d_i}{w_i s_i}} \right) \tag{S13}$$

where *IC* represents the IC of the grid cell; and *W* is the average weight factor (dimensionless) of the upstream area, which represents the impedance encountered in the process of runoff or erosion sediment transport, and affects the efficiency of runoff sediment transport to the river and downstream sedimentation area, and is related to the vegetation cover and LULC changes in the study area. Therefore, the vegetation coverage factor *C* in the RUSLE model is used as the weight factor in this study. In addition, *S* is the average slope of the upstream catchment (m/m); *A* is the area of the upstream catchment (m^2); d_i is the distance of the *i*th grid cell along the runoff path to the sediment deposition point downstream (m); w_i is the weight factor of the *i*th grid cell (dimensionless); and s_i is the slope factor of the *i*th grid cell (m/m).

In order to avoid extreme or erroneous values, the above equation was used to calculate the connectivity index, with s_i=0.005 as the threshold value when the topographic slope was less than 0.005, and the upper slope was s_i=1. Borselli et al. defined the range of the connectivity index as (-∞, +∞), i.e., when the connectivity index tends to +∞ at a point in the watershed, the greater the hydrological connectivity at that point, which indicates the greater the probability that runoff sediment will be transported to the channel or downstream sedimentation zone [28].

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