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Supplementary Materials: Quantification of Ecosystem Services

1. Grass Production

Grass production is the most important provisioning service in the study area's grassland ecosystem because it provides the material basis for grassland-based animal husbandry [1]. Grass yield is a basic index for assessing grassland productivity. Here, we used a remote sensing model of typical grasslands based on Modis NDVI data to estimate dry weight grass yields in the study area [2].

$$GP = 1/3 \times AGB = 1/3 \times 3.546 \times NDVI^{1.682} \quad (1)$$

where, GP is grass production (kg·ha^{-1}); AGB is above ground biomass-fresh grass production (kg·ha^{-1}); $NDVI$ is the normalized vegetation index (dimensionless); and 1/3 is the hay to fresh grass conversion factor typical of temperate grasslands.

2. Livestock Density

Livestock density was used to characterize the provisioning capacity of major livestock products in the study area. Since livestock density is traditionally expressed as the average number of livestock per unit area within a region, the data provided by administrative governments did not reflect the spatial heterogeneity of livestock within the study area [3]. Therefore, in this paper, the density data for sheep and cattle (the main livestock and meat sources in Xilinhot) was superimposed onto data obtained from the 2010 Gridded Livestock of the World database to determine livestock densities across the study area. Calculations of livestock density were performed using the following formula:

$$L_t = L_s + L_c \quad (2)$$

where, L_t is total livestock density (Tlu·km^{-2}); L_s is sheep density (Tlu·km^{-2}); and L_c is cattle density (Tlu·km^{-2}).

3. Water Yield

Water yield is an important ES in arid and semi-arid regions. Changes in land use and vegetation cover can impact the hydrological cycle by altering patterns of evaporation and water infiltration into the soil [4]. In this study, Water yield was assessed using the annual water yield module in the InVEST model. This module calculated regional water yield as the difference between actual precipitation and actual evaporation [5]. Water yield was calculated using the following formula:

$$WY_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x \quad (3)$$

where, WY_x is the total annual water yield (mm) of grid x; AET_x is the average annual actual evapotranspiration (mm) of grid x, which is calculated using the monthly data for rainfall and temperature [6]; P_x refers to the average annual precipitation (mm) of grid x; AET_x/P_x is based on an expression of the Budyko curve [7,8];

$$\frac{AET_x}{P_x} = 1 + \frac{PET_x}{P_x} - [1 + \left(\frac{PET_x}{P_x}\right)^{\omega}]^{\frac{1}{\omega}} \quad (4)$$

where, PET_x is the potential evapotranspiration and w is a non-physical parameter that characterizes natural, climatic soil properties, both detailed below.

$$PET_x = K_C \times ET_0 \quad (5)$$

where, ET_0 is the reference evapotranspiration at pixel x, which is based on the evapotranspiration of reference vegetation; K_c is the plant evapotranspiration coefficient associated with the Land Use and

Land Cover (LULC) data for pixel x and is largely determined by the vegetative characteristics of the land cover found at that pixel [9].

$$w = Z\frac{AWC_x}{P_x} + 1.25 \tag{6}$$

where, AWC_x is the volumetric (mm) plant available water content at pixel x, which is estimated using soil texture, soil depth, and root depth of vegetation; Z is an empirical constant, sometimes referred to as the "seasonality factor" [1], which captures the local precipitation pattern and additional hydrogeological characteristics [8].

4. Soil Conservation

Lack of vegetation coverage can lead to surface erosion, especially on sloped soils, thus increasing sediment discharge into rivers and reservoirs [10]. In this study, the soil conservation ES was quantitatively assessed using a Revised Universal Soil Loss Equation (RUSLE). The soil conservation services of the ecosystems in the study area were based on potential soil conservation [11]. The formula is as follows:

$$SC = A_p - A_r \tag{7}$$

where, SC is the annual potential soil conservation ($t \cdot ha^{-1}$); A_p is the amount of potential soil erosion ($t \cdot ha^{-1}$); A_r is the amount of actual soil erosion ($t \cdot ha^{-1}$).

$$A_p = R \times K \times LS \tag{8}$$

where, R is rainfall-runoff erosivity ($MJ \cdot mm \cdot ha^{-2} \cdot h^{-1}$), which is calculated using the empirical equations for arid and semiarid lands proposed by Wischmeier and Smith [12]; K is the soil erodibility factor ($t \cdot h \cdot MJ^{-1} \cdot mm^{-1}$), which is determined using the erosion-productivity impact calculator (EPIC) model [13,14]; LS is the slope length and steepness factor calculated using the Digital Elevation Model (DEM) in ArcGIS [15,16].

$$A_r = R \times K \times LS \times \mathrm{C} \times \mathrm{P} \tag{9}$$

where, C is a dimensionless factor for vegetation cover calculated by vegetation coverage fraction [17]; and P is also a dimensionless factor referring to the support practice of soil conservation using Wener's slope-based method [18]. The ranges of the above two factors are both between 0 and 1.

5. Sand Fixation

Wind erosion is a main contributor to deteriorating farmland soil quality and grassland desertification in arid and semi-arid regions of northern China [19]. When wind speeds are extremely high, dust storms can develop, causing atmospheric pollution and threatening human lives and property [20]. In this study, the ES of sand fixation was assessed quantitatively using a Revised Wind Erosion Equation (RWEQ) [21]. The formula is as follows:

$$\Delta Q = Q_0 - Q_v \tag{9}$$

where, ΔQ is the amount of sand fixation ($t \cdot km^{-2}$); Q_0 is the amount of potential sand erosion without vegetation cover ($t \cdot km^{-2}$); Q_v is the amount of actual sand erosion with vegetation cover and management ($t \cdot km^{-2}$).

$$Q_x = \frac{2 \times \mathrm{Z}}{S^2} \times Q_{max} \times e^{-(x/S)^2} \tag{10}$$

where, Q_x is the amount of sand transported by the wind at a point x downwind; Q_{max} is the maximum amount of sand that can be transported downwind; and S is the critical field length.

$$Q_{max} = 109.8 \times (WF \times EF \times SCF \times K' \times C) \tag{11}$$

Where, WF is the weather factor; EF is the soil erodibility factor; SCF is the soil crust factor; K' is the soil roughness factor; and C is the vegetation cover factor [22].

$$S = 105.71 \times (WF \times EF \times SCF \times K' \times C)^{-0.3711} \tag{12}$$

In particular, the instruction manual for the RWEQ model specifies that the wind speed input parameter should be an average of wind speed data collected every 1 to 2 min [23], which is difficult to achieve. In this study, we converted daily mean wind speed data into minute wind speed data using a formula based on the study by Guo [24].

6. Carbon Storage

Grasslands act as carbon sinks and therefore play an important role in the carbon cycle of terrestrial ecosystems. About 80% of the organic carbon contained in grassland ecosystems is stored underground [25]. Previous studies have used Net Primary Productivity (NPP) to indicate the ability of ecosystems to fix carbon and release oxygen [22,24,26,27]. This method is inadequate because NPP only represents the above-ground portion of stored carbon, but ignores carbon stored in plant litter, roots and soil. Thus, NPP does not reflect the carbon storage capacity of the entire ecosystem. In this study, carbon storage was quantitatively assessed using the carbon storage module of the InVEST model, which simplifies ecosystem carbon cycles and considers carbon storage in four major pools (above-ground biomass, underground biomass, soil, and dead organic matter) to estimate the total carbon storage of the landscape [5]. The formula is as follows:

$$C_t = \sum_{n=1}^{n} A_j \left(C_{aj} + C_{bj} + C_{sj} + C_{dj} \right) \tag{13}$$

Where, Ct denotes total carbon storage (MgC); j denotes a specific type of land use; n denotes the number of land use types; A_j denotes the area of land use type j (ha); C_{aj} denotes the above-ground carbon density of land use type j ($MgC \cdot ha^{-1}$); C_{bj} is the underground carbon density of land use type j ($MgC \cdot ha^{-1}$); C_{sj} is the soil carbon density of land use type j ($MgC \cdot ha^{-1}$); and C_{dj} is the organic carbon density of dead organic matter for land use type j ($MgC \cdot ha^{-1}$). To calculate the carbon density of grasslands, we calculated the biomass of grasslands with high, medium, and low vegetation coverage directly from field sampling measurements, and converted these measurements to carbon content using the common conversion rate of 0.45. In addition, underground carbon pools were converted to above-ground carbon pools using the root-crown conversion ratio coefficient of 5.3 for typical grasslands [28]. Soil carbon density was derived from direct measurements of the organic carbon content of soils. Since forest coverage in the study area was extremely low, we used a table for forest carbon density included in a relevant study [29]. Because carbon storage in crops is relatively low and highly variable, we ignored the above-ground carbon content of annual crops and only calculated stored carbon in farmland soils. Although carbon storage by open water, developed land, and unused land is not zero, it is difficult to measure. Therefore, following previous studies [29,30], we assumed that carbon storage by these three land types is negligible and set the carbon density as zero.

7. Habitat Quality

Habitat quality can serve as a proxy for biodiversity because it reflects the capacity of the ecosystem to provide suitable living conditions for individual animal, plant and human as well as their populations [31]. Here, habitat quality was quantitatively assessed using the habitat quality module of the InVEST model. The formulas for these calculations are as follows:

$$Q_{xj} = H_j \left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \right] \tag{14}$$

where, Q_{xj} is the habitat quality (dimensionless) of grid x in land use type j; H_j is the habitat suitability (dimensionless) of land use type j; D_{xj} is the level of stress by all threats (dimensionless) in grid x of land use type j; k is the half-saturation constant, which usually equals half the maximum value of D_{xj};

and z is a normalized constant (dimensionless) and is usually 2.5.

$$D_j = \sum_{r=1}^{R} \sum_{y=1}^{Yr} \left(W_r / \sum_{r=1}^{R} W_r \right) r_y i_{ry} \beta S_{jr} \tag{15}$$

where, R is the the number of threat; Y_r is the number of grids occupied by the threat r; W_r is the weight of the threat and its value is 0-1; r_y is the value of the threat in grid y (with a value of 0 or 1); i_{ry} is the stress level of the habitat induced by the value ry of the threat in grid y; β is the level of accessibility and its value is 0–1, with 1 indicating extremely accessible; S_{jr} is the sensitivity of habitat type j to the threat r and its value is 0–1, with a value closer to 1 indicating higher sensitivity.

In general, natural environments are most sensitive to external threat, followed by semi-artificial environments, whereas artificial environments are largely unaffected by external threat. Therefore, this study regarded construction land as a source of habitat threat [5,32].

8. Landscape Aesthetics

The aesthetic appeal of scenic areas in natural grasslands directly affects tourism development. We adapted a visual quality index (VQI) to include five parameters: terrain, water source, green space, human influence, and accessibility [33]. The original VQI included a historical parameter instead of accessibility. Here, we used accessibility due to data availability and to the fact that landscape aesthetics have a largely touristic appeal. We also simplified the method used to quantify the five parameters in the VQI. We used a terrain roughness index, distance to a water source, vegetation coverage, percentage of developed land, and distance from the main road, respectively, to quantify the five parameters. Specifically, we quantified distances to a water source and to a main road using the multi-ring buffer zone function in ArcGIS. The scores for the five parameters were added to obtain a total VQI score, which represented the relative aesthetic value of a grid unit. The formula is as follows:

$$VQI_{xt} = \left(VQI_p + VQI_b + VQI_g + VQI_h + VQI_a \right) \tag{16}$$

where, VQI_{xt} is the total VQI score (dimensionless) of grid x and its range is [0,1]; VQI_p is the terrain parameter score for grid x; VQI_b is the water source parameter score for grid x; VQI_g is the green space parameter score for grid x; VQI_h is the human influence parameter score for grid x; and VQI_a is the landscape accessibility parameter score for grid x.

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