

Postprint of Intra-annual Dynamic Characteristics of Soil Conservation Value in Huanghua City

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Abstract

Understanding the intra-annual dynamics of soil erosion and soil conservation capacity across different ecosystem types provides positive guidance for prioritizing and scheduling regional soil and water conservation efforts. This study, supported by GIS, employs the Universal Soil Loss Equation (USLE) to calculate intra-annual soil erosion and conservation amounts for different ecosystems in Huanghua City, Hebei Province, and utilizes the market value method and opportunity cost method to estimate the monthly soil conservation value of each ecosystem type throughout the year, thereby investigating the intra-annual dynamic characteristics of soil conservation value in Huanghua City. The research indicates that the monthly distribution of soil conservation value in Huanghua City is uneven throughout the year, with intra-annual dynamic characteristics consistent with the seasonal variation patterns of soil conservation capacity. The value reaches its maximum peak in August, while being zero in January–March, October, and December. An increasing trend is observed from May to August, with the soil conservation value from May to September accounting for 82.47% of the annual total. From the perspective of different ecosystem types, grassland exhibits the maximum per unit area soil conservation value in August at 128.87 yuan · hm², while water bodies show the minimum value in September at 11.23 yuan · hm². In terms of the composition of soil conservation value, the ranking of per unit area contribution values from various soil conservation functions throughout the year is: value of reducing soil nutrient loss > value of reducing sedimentation > value of reducing land abandonment. The soil conservation value of various ecosystem types in the study area demonstrates distinct seasonal variation patterns. During the rainy season, influenced by short-term heavy precipitation events such as rainstorms, the potential soil erosion amount increases, while the soil conservation function and value of ecosystems are realized through this process.

Full Text

Intra-annual Dynamics of Soil Conservation Value in Huanghua City

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Abstract

Understanding the intra-annual dynamics of soil erosion and conservation across different ecosystem types provides critical guidance for prioritizing regional soil and water conservation efforts. This study employs the Universal Soil Loss Equation (USLE) within a GIS framework to calculate monthly soil erosion and conservation amounts for various ecosystems in Huanghua City, Hebei Province. Market value and opportunity cost methods were then applied to estimate the monthly soil conservation value, revealing distinct seasonal patterns. Results show uneven monthly distribution of soil conservation value, peaking in August with zero values recorded for January-March, October, and December. The period from May to September accounts for 82.47% of annual soil conservation value. Among ecosystems, grassland exhibited the highest per-unit-area value in August (128.87 Yuan · hm²), while water bodies showed the lowest in September (11.23 Yuan · hm²). In terms of value composition, the contribution ranking per unit area across all months was: value of reducing soil fertility loss > value of reducing silt deposition > value of reducing abandoned land. The study demonstrates that soil conservation values in coastal ecosystems follow clear seasonal trajectories, with ecosystem functions becoming particularly vital during rainy seasons when intense precipitation events increase potential erosion.

Keywords: Soil erosion; Soil conservation function; Soil conservation value; Ecosystem type; Intra-annual dynamics

Introduction

Ecosystem service flows exhibit dynamic temporal variations, yet research on these flow processes remains limited. To date, most ecosystem service valuations have employed static annual assessments that ignore intra-annual variations, hindering systematic ecosystem service planning. Understanding intra-annual dynamics is essential for deepening our knowledge of ecosystem service formation mechanisms and optimizing their benefits to society.

Soil erosion represents a critical global challenge, with China being among the most severely affected countries. However, existing soil conservation value studies typically use annual time scales, overlooking intra-annual dynamics in rainfall erosivity and vegetation coverage. This limitation reduces valuation accuracy and obscures seasonal patterns in ecosystem soil conservation functions. While a few studies have examined intra-annual dynamics in forest or grassland ecosystems, comparative analyses across multiple ecosystem types within the same region remain scarce.

Coastal terrestrial ecosystems, situated at the land-sea interface, feature complex and diverse ecosystem types that play crucial roles in maintaining stability of both marine and terrestrial systems while supporting sustainable socioeconomic development along coastlines. With China's coastline exceeding 3.2×10^4 km and approximately 1.4×10^6 hm² of shallow sea, tidal flats, and coastal saline soils within the 15 m isobath, understanding intra-annual soil conservation value dynamics in these ecosystems is vital for ecological security and sustainable management.

This study addresses these gaps by examining Huanghua City in Hebei's coastal region as a case study. Using land use data, monthly NDVI data, soil properties from laboratory analysis, and DEM data, we applied USLE to estimate monthly soil erosion and developed a specialized assessment model to evaluate intra-annual dynamics of soil conservation value in coastal saline soil regions. The research compares seasonal patterns across different ecosystem types, providing methodological insights for regional-scale assessments.

1. Materials and Methods

1.1 Study Area

Huanghua City is a county-level city in southeastern Hebei Province, administered by Cangzhou Municipality. Located along the Bohai Sea coast (38°09' - 38°39' N, 117°05' - 117°49' E), the city covers 2,177.83 km² with a 65.8 km coastline [Figure 1: see original paper]. The region experiences a warm temperate semi-humid continental monsoon climate with slight maritime influences, featuring an average annual temperature of 12.0–12.9°C and annual evaporation of 1,909.6 mm. Dominant vegetation includes summer maize (*Zea mays*), alfalfa (*Medicago sativa*), reed (*Phragmites australis*), and jujube (*Zizyphus jujuba*), with phenological periods detailed in . Administratively, Huanghua comprises 4 towns, 6 townships, 327 villages, and three industrial zones (Zhongjie Industrial Park, Nandagang Industrial Park, and Huanghua Port Area).

1.2 Data Sources and Processing

Remote Sensing Data. LandSat-7 TM imagery from June 25, 2011 (Path/Row: 122/33, cloud cover <1.5%) was obtained from the Geospatial

Data Cloud. ENVI 4.7 was used for band combination, geometric correction (error <0.5 pixels), and subsetting. Supervised classification combined with visual interpretation in ArcGIS 9.3 produced a 2011 land use database, validated against land change survey data to achieve overall accuracy and Kappa index >0.8.

Monthly NDVI data were derived from MOD13Q1 MODIS products (16-day composite, 250 m resolution) for January–December 2011. Maximum Value Composition (MVC) was applied to generate monthly NDVI datasets [Figure 2: see original paper] consistent with meteorological data temporal resolution.

Field Survey Data. Field investigations conducted in July–August 2014 collected 300 soil samples from 310 sites [Figure 3: see original paper]. Laboratory analysis determined soil bulk density (averaged to $1.17 \text{ t} \cdot \text{m}^{-3}$) and nutrient contents (total N, P, K) for each ecosystem type. Soil type distribution was mapped by overlaying administrative boundaries with the Hebei Soil Map, with characteristic parameters obtained from *Hebei Soils* (2nd Edition) and the China Soil Database [Figure 4: see original paper], .

Meteorological Data. Daily precipitation data for January–December 2011 were obtained from the China Meteorological Data Sharing Service System for Huanghua, Botou, and Cangzhou stations, supplemented by data from 20 surrounding county meteorological stations.

Topographic Data. A 30 m resolution GDEM digital elevation model was downloaded from the Geospatial Data Cloud.

2. Assessment Framework

2.1 Ecosystem Classification

Based on existing studies and considering coastal land cover characteristics, we established a specialized classification system linking land use types to analogous ecosystems. Nine land cover types were identified: cultivated land, garden plot, grassland, construction land, water area, saline land, wetland, salt field, and other land. These were aggregated into eight ecosystem types: farmland, garden plot, grassland, urban, water area, saline land, wetland, salt field, and other land .

2.2 Dynamic Estimation Model for Soil Erosion and Conservation

The Universal Soil Loss Equation (USLE) was applied to assess monthly soil erosion:

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

where A is monthly soil erosion ($t \cdot hm^2 \cdot month^{-1}$), R is rainfall erosivity ($MJ \cdot mm \cdot hm^2 \cdot h^{-1}$), K is soil erodibility ($t \cdot h \cdot MJ^{-1} \cdot mm^{-1}$), L is slope length factor, S is slope factor, C is monthly vegetation cover factor, and P is conservation practice factor.

Soil conservation amount (Ac) represents the difference between potential and actual erosion:

$$Ac = Ap - A \quad (2)$$

$$Ap = R \times K \times L \times S \quad (3)$$

where Ap is potential erosion (without vegetation cover or conservation measures) and A is actual erosion.

Parameter Calculation:

1. **Rainfall Erosivity Factor (R).** Zhang et al.'s semi-monthly model based on daily rainfall data was used, where Ri represents monthly erosivity, Dj is daily rainfall 12 mm, k is time period, $Pd12$ is average daily rainfall 12 mm, and $Py12$ is annual average rainfall 12 mm.
2. **Soil Erodibility Factor (K).** Williams et al.'s EPIC model was applied:

$$K = 0.2 + 0.3 \exp \left[-0.0256 \times Sd \times \left(1 - \frac{Si}{100} \right) \right] \times \left(\frac{Si}{Se + Si} \right)^{0.3} \times \left[1 - \frac{0.25 \times Sc}{Sc + \exp(3.72 - 2.95 \times Sc)} \right] \times \left[1 - \frac{1}{(1 - \dots)} \right]$$

where Sd , Si , Se are sand, silt, and clay percentages, and Sc is organic carbon content.

3. **Slope Length Factor (L).** Based on McCool et al.:

$$L = \left(\frac{l}{22.13} \right)^m$$

where l is slope length and m is the slope coefficient (0.5 for 9% ; 0.4 for $3\% < 9\%$; 0.3 for $1\% < 3\%$; 0.2 for $< 1\%$).

4. **Slope Factor (S).**

$$S = \begin{cases} 10.8 \sin \theta + 0.03 & \text{if slope} < 5^\circ \\ 16.8 \sin \theta - 0.05 & \text{if } 5^\circ \leq \text{slope} < 14^\circ \\ 21.91 \sin \theta - 0.96 & \text{if slope} \geq 14^\circ \end{cases}$$

5. **Vegetation Cover Factor (C).**

$$C = \begin{cases} 0.6508 - 0.3436 \log_{10}(\sigma_v) & \text{if } \sigma_v > 78.3\% \\ 0 & \text{if } \sigma_v \leq 78.3\% \end{cases}$$

where v is monthly vegetation cover fraction derived from NDVI.

6. **Conservation Practice Factor (P)**. Values range 0-1, where 0 indicates no conservation and 1 indicates optimal practices. Ecosystem-specific values are listed in .

2.3 Soil Conservation Value Assessment

Total soil conservation value (Vac) comprises three components:

$$Vac = Vef + Ven + Ves \quad (4)$$

where Vef is value of reducing soil fertility loss, Ven is value of reducing silt deposition, and Ves is value of reducing abandoned land.

2.3.1 Value of Reducing Soil Fertility Loss (Vef). This includes nutrient (N, P, K) retention valued at fertilizer prices, and organic matter retention valued by firewood substitution:

$$Vef = Ac \times D_{soil} \times \left(\sum_{i=1}^3 C_i \times P_i + oC \right) \quad (5)$$

where C_i are N, P, K contents, P_i is unit price (2,549 Yuan \cdot t⁻¹ for 2011 fertilizer prices), D_{soil} is bulk density (1.17 t \cdot m⁻³), and oC is organic carbon value.

2.3.2 Value of Reducing Silt Deposition (Ven). Calculated using replacement cost method based on reservoir construction:

$$Ven = Ac \times 24\% \times \frac{P_w}{D_{soil}} \quad (6)$$

where 24% of eroded soil deposits in water bodies, P_w is reservoir construction cost (7.53 Yuan \cdot m³ in 2011), and D_{soil} is bulk density.

2.3.3 Value of Reducing Abandoned Land (Ves). Estimated via opportunity cost of prevented land loss:

$$Ves = Ac \times \frac{P_f}{D_{soil} \times T_{soil} \times 10^4} \quad (7)$$

where P_f is average economic benefit (26,208 Yuan \cdot hm² \cdot a⁻¹ based on 2011 agricultural output), and T_{soil} is soil thickness (0.5 m).

3. Results

3.1 Intra-annual Dynamics of Soil Erosion and Conservation

3.1.1 Soil Erosion Dynamics. Total annual soil erosion in Huanghua was $5.59 \text{ t} \cdot \text{hm}^{-2}$ in 2011, with 93.38% occurring during April–September. August showed the highest erosion ($1.90 \text{ t} \cdot \text{hm}^{-2}$, 33.99% of annual total), while November had the lowest non-zero value ($0.42 \text{ t} \cdot \text{hm}^{-2}$, 6.62%) [Figure 4: see original paper]. Per-unit-area erosion ranked: grassland ($1.06 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$) > garden plot (0.96) > farmland (0.83) > saline land (0.28). All values were below the national tolerance threshold of $2 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, indicating stable soil fertility and effective conservation functions.

3.1.2 Soil Conservation Dynamics. Total annual soil conservation reached $1,944.19 \text{ t} \cdot \text{hm}^{-2}$, with 93.40% occurring in April–September. August peak conservation was $558.31 \text{ t} \cdot \text{hm}^{-2}$ (28.72% of annual total), while the minimum occurred in November ($128.36 \text{ t} \cdot \text{hm}^{-2}$, 6.60%). All ecosystem types showed similar seasonal patterns, increasing from May to August and peaking in September [Figure 5: see original paper]. Grassland reached maximum conservation in August ($87.77 \text{ t} \cdot \text{hm}^{-2}$, 25.65% of its annual total), while water bodies showed minimum conservation in November ($7.51 \text{ t} \cdot \text{hm}^{-2}$, 6.94% of their annual total).

3.2 Intra-annual Dynamics of Soil Conservation Value

3.2.1 Annual Soil Conservation Value. Total annual soil conservation value was 7.305×10^4 Yuan. The value of reducing soil fertility loss dominated (6.434×10^4 Yuan, 88.07%), while reducing abandoned land contributed minimally (0.61×10^4 Yuan, 0.84%). Farmland contributed most to total value (3.227×10^4 Yuan, 43.9%) due to its large area, while garden plots contributed least (2.85×10^4 Yuan, 3.9%) despite high per-unit values, reflecting their small area (2.95% of total). Per-unit-area annual value ranked: grassland ($495.24 \text{ Yuan} \cdot \text{hm}^{-2}$) > garden plot > farmland > wetland > salt field > other land > urban > saline land > water area ($207.75 \text{ Yuan} \cdot \text{hm}^{-2}$).

3.2.2 Monthly Value Dynamics by Ecosystem. The value of reducing soil fertility loss dominated all months, peaking in August for grassland ($110.17 \text{ Yuan} \cdot \text{hm}^{-2}$) and reaching minimum in September for water bodies ($10.97 \text{ Yuan} \cdot \text{hm}^{-2}$) [Figure 6a: see original paper]. The value of reducing silt deposition followed the same ranking, with grassland peaking at $17.08 \text{ Yuan} \cdot \text{hm}^{-2}$ in August and water bodies showing minimum of $0.12 \text{ Yuan} \cdot \text{hm}^{-2}$ in May [Figure 6b: see original paper]. The value of reducing abandoned land was consistently smallest (<1% of total), peaking at $1.62 \text{ Yuan} \cdot \text{hm}^{-2}$ for grassland in August [Figure 6c: see original paper]. Total soil conservation value showed greatest monthly variation in wetland (33.89 – $105.77 \text{ Yuan} \cdot \text{hm}^{-2}$ from April to August) and smallest variation in other land (16.94 – $76.86 \text{ Yuan} \cdot \text{hm}^{-2}$) [Figure 6d: see original paper].

3.2.3 Value Composition Dynamics. Across all ecosystem types, the con-

tribution ranking remained constant: reducing soil fertility loss ($2,722.01 \text{ Yuan} \cdot \text{hm}^2 \cdot \text{a}^{-1}$) > reducing silt deposition > reducing abandoned land ($26.20 \text{ Yuan} \cdot \text{hm}^2 \cdot \text{a}^{-1}$) [Figure 7: see original paper]. All three components showed identical seasonal patterns—zero values in January–March, October, and December; increasing values from May to August; and peaks in August that aligned with soil conservation dynamics. The May–September period generated 82.47% of annual value, with accumulation rates accelerating through August then stabilizing after September.

4. Discussion and Conclusions

This study quantified intra-annual dynamics of soil conservation value across typical coastal ecosystems at 30 m resolution. Results demonstrate that vegetation cover and climatic conditions create pronounced seasonal variations, with a bimodal pattern emerging from the interaction of rainfall erosivity and ecosystem protection. Different land use patterns among ecosystems generate distinct value profiles, with grassland showing highest per-unit values ($128.87 \text{ Yuan} \cdot \text{hm}^2$ in August) and water bodies the lowest ($11.23 \text{ Yuan} \cdot \text{hm}^2$ in September). The dominance of fertility loss reduction value (88% of total) reflects the critical role of nutrient retention, while the minimal contribution of abandoned land reduction (<1%) indicates limited land abandonment pressure in this intensively managed coastal region.

The clear seasonality reveals that ecosystem soil conservation functions become most critical during rainy seasons when intense rainfall events increase potential erosion. This underscores the importance of timing conservation interventions to protect vegetation and other soil-retaining factors before high-risk periods. The concentration of 82% of annual value in May–September highlights the need for focused management during these months.

Limitations include the exclusion of wave and tidal erosion processes due to data constraints, and the use of moderate-resolution MODIS and GDEM data which may introduce uncertainties. Future research should incorporate high-resolution remote sensing and expand to include marine erosion processes. The methodological framework developed for this coastal saline soil region can be adapted for other coastal areas, contributing to improved ecosystem service assessment and management strategies for China's coastal zones.

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