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Temporal and Spatial Evolution of Ecosystem Service Function in Liaoning Province Based on InVEST Model

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Abstract

In recent years, with the high attention paid to the protection and development of ecological environment, Assessing the spatio-temporal evolution of ecosystem service functions has become a hot topic. Liaoning Province is one of the traditional industrial bases in China. With the rapid development of economy, the ecological system is also facing the challenges of desertification and soil erosion. Therefore, this study took Liaoning Province as the main research object. Based on land use, climate and soil data from 2000, 2010 and 2020, the InVEST model was used to select indicators and analyze the spatio-temporal evolution of ecosystem service functions in Liaoning Province from two functions: water production and carbon sequestration, so as to provide support for the ecological environment protection and development of Liaoning Province. The results show that: 1) Over the course of the past two decades, water resources supply in Liaoning Province increased first and then decreased, showing a significant trend of decreasing from the eastern mountains to the western hills. 2) Carbon storage in Liaoning Province showed a slow and steady upward trend in twenty years, and in spatial scale, carbon sequestration storage showed a gradually decreasing trend from the east and west sides of Liaoning Province to the middle part of Liaoning Province. The analysis of temporal and spatial evolution characteristics of water production, carbon storage, in Liaoning Province can provide support and reference for ecological environment protection and development in Liaoning Province.

Keywords

Water Yield, Carbon Storage, InVEST Model, Space-Time Evolution, Liaoning Province

1. Introduction

Ecosystem services refer to the direct and indirect benefits that people derive from ecosystems over the long term [1]. At present, ecosystem services have become one of the key research hotspots in fields such as ecology and the geosciences [2] [3]. Ecosystem services can be classified into provisioning, regulating, cultural, and supporting services. Provisioning services include the supply of food and water yield; regulating services include flood control, soil conservation, and the maintenance of carbon storage. Given the effectiveness and practicality demonstrated by the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model in assessing ecosystem service outcomes, this study primarily employs modules such as water yield and carbon storage from the InVEST model for evaluation. The assessment of ecosystem services helps to improve understanding of the relationship between humans and nature and provides a solid foundation for achieving sustainable development goals.

A review of relevant domestic and international literature on ecosystem service assessment in recent years indicates that Aneseyee employed the InVEST model to analyze the spatiotemporal characteristics of habitat quality in the Winike watershed of the Omo-Gibe Basin in southwestern Ethiopia from 1988 to 2018.The results indicate that habitat quality in the Winike watershed has continuously degraded, closely associated with agricultural expansion, population growth, urbanization, soil erosion, groundwater extraction, and pollution [4]. Zhao took Wafangdian City in Liaoning Province as the study unit, introduced the OWA model, and constructed an ecological security pattern for the study area. The results show that ecosystem services in Wafangdian City exhibited significant spatiotemporal variations over a 14-year period [5]. Zhao selected Wenshan City in the karst mountainous region of southeastern Yunnan as the study area and found that, from 2000 to 2017, all five ecosystem services—including water yield—increased, except for a decline in habitat quality [6]. Yan Yan *et al.* conducted a comprehensive reassessment of ecosystem service values in China's inland river basins using a meta-regression approach. The study revealed that four key stages in the valuation process—the selection of study objects, the characteristics of respondents, the measurement methods employed, and the processes of manuscript preparation and publication—each exert a significant influence on the final estimated values [7]. Li Hui's study on carbon storage in the marine regions of the Shandong Peninsula demonstrated that changes in land use types and their respective areas influence carbon storage, highlighting the significant role of cropland in this process [8].

Liaoning Province, as a major industrial province in China, has experienced rapid economic development while its ecosystems face challenges such as land desertification and soil erosion, resulting in the disruption of ecological balance. The ecological and environmental conditions are under threat; therefore, assessing the spatiotemporal evolution trends of ecosystem services in Liaoning Province can contribute to the advancement of ecological civilization construction in the province and promote sustainable socio-economic development. This study focuses on Liaoning Province as the primary research area. Based on a long-term continuous time series dataset from 2000 to 2020, the InVEST model is employed to select relevant indicators. Starting from two key metrics—water yield and carbon storage—the study investigates the spatiotemporal evolution patterns of ecosystem services in Liaoning Province, with the aim of providing a scientific basis for ecosystem management and conservation in the region. However, existing studies in Liaoning Province have mainly focused on single ecosystem services or short-term changes, and there is a lack of integrated analysis of water yield and carbon storage over a longer time span using the InVEST model. This study fills this gap by simultaneously assessing both services from 2000 to 2020, revealing their spatiotemporal trade-offs and synergies, and providing a more comprehensive basis for regional ecological planning.

2. Materials and Methods

2.1. Study Area

Liaoning Province (38˚43'N-43˚26'N, 118˚53'E-125˚46'E) is located in the southern part of Northeast China. It has a total area of 14.86 × 10^4 km^2. As the northernmost coastal province of China, Liaoning Province borders the Yellow Sea and the Bohai Sea to the south, and thus possesses a highly advantageous geographical location. The topography and landforms are mainly composed of three major regions: the mountainous and hilly area in the east, the Lower Liaohe Plain in the central part, and the low mountain and hilly area in the west. Liaoning Province is characterized by a temperate continental monsoon climate with distinct seasonal variation, featuring cold winters and hot summers. The mean annual temperature is approximately 7˚C - 11˚C, and the region receives relatively abundant precipitation. There are numerous rivers within the province, with more than 300 rivers of varying sizes in total, the major ones including the Liao River and the Hun River.

2.2. The InVEST Model Principle

2.2.1. The InVEST Water Yield Model

This study employed the Annual Water Yield module of the InVEST model to simulate annual water yield in Liaoning Province by inputting data such as precipitation and evapotranspiration, thereby providing an in-depth understanding of the temporal dynamics and spatial distribution patterns of water resources in Liaoning Province. The formula [9] [10] is as follows:

$$Y_{(xj)} = \left[1 - \frac{AET_{(xj)}}{P_x}\right] \times P_x \tag{1}$$

where $Y_{(xj)}$ represents the annual water yield of grid cell *x*; P_x denotes the annual precipitation of grid cell *x*; and $AET_{(xj)}$ denotes the annual actual evapotranspiration of grid cell *x*.

The calculation formula is based on the Budyko hydrothermal coupling equilibrium hypothesis proposed by Zhang *et al.* [11]:

$$\frac{AET_{(xj)}}{P_x} = \frac{1+\omega_x + R_{xj}}{1+\omega_x + R_{xj} + 1/R_{xj}} \tag{2}$$

where $\frac{AET_{(xj)}}{P_x}$ represents the ratio of actual evapotranspiration to precipitation; R_{xj} denotes the Budyko dryness index for grid cell x in land-use type j; and ω_x represents the ratio of annual vegetation water demand to annual precipitation.

$$\omega_x = Z \times AWC_x / P_x \tag{3}$$

where Z is a constant; and AWC_x denotes the plant available water content of grid cell x (mm). The dimensionless parameter Z represents the seasonal precipitation pattern and local hydrogeological characteristics. Following previous studies in Liaoning Province [12], we set $Z = 3$. The chosen $Z = 3$ produced water yield estimates that matched well with the multi-year average runoff coefficients reported for major river basins in Liaoning Province, confirming its plausibility.

Plant available water content. Soil data were obtained from the Harmonized World Soil Database (HWSD), from which the required soil parameters were extracted. The calculation was performed using the "Zhou Wenzuo formula", as follows [13]:

$$\begin{aligned} \text{PAWC}(\%) = {} & 54.509 - 0.132 \times \text{SAND\%} - 0.003 \times (\text{SAND\%})^2 \\ & - 0.055 \times \text{SLIT\%} - 0.006 \times (\text{SAND\%})^2 - 0.738 \times \text{CLAY\%} \\ & + 0.007 \times (\text{CLAY\%})^2 - 2.688 \times \text{OM\%} + 0.501 \times (\text{OM\%})^2 \end{aligned} \tag{4}$$

where PAWC represents plant available water content; SAND% denotes the percentage of sand content in the soil; SILT% denotes the percentage of silt content in the soil; CLAY% denotes the percentage of clay content in the soil; and OM% denotes the percentage of soil organic matter content [9].

2.2.2. The InVEST Carbon Storage Model

This chapter uses the Carbon Storage module of the InVEST model to simulate different land cover types, aiming to provide a scientific and quantitative basis for reducing carbon emissions and promoting ecological conservation. The carbon stocks of four carbon pools for each land use type were calculated separately, and then aggregated to obtain the total carbon storage of Liaoning Province. The formula is as follows [14] [15]:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{5}$$

where C_{total}, C_{above}, C_{below}, C_{soil}, C_{dead} represent total carbon storage, aboveground biomass carbon storage, belowground biomass carbon storage, soil organic carbon storage, and dead organic matter carbon storage, respectively.

2.3. Data Source and Processing Method

The data required for the water yield and carbon storage modules mainly include annual precipitation, land use, mean annual potential evapotranspiration, maximum soil rooting depth, study area boundary, a biophysical coefficient table containing land use/land cover types and corresponding coefficients, the Zhang coefficient, and a carbon pool data table. The sources of the basic data are listed in **Table 1**. All data were projected using the Krasovsky_1940_Albers coordinate system and preprocessed in ArcGIS. All spatial datasets were resampled to a uniform grid resolution of 100 m × 100 m to ensure consistency. Land use data for 2000, 2010, and 2020 were derived from Landsat TM/OLI images with a spatial resolution of 30 m, which were then aggregated to 100 m using the majority rule. Precipitation and potential evapotranspiration data were interpolated to 100 m grids using the ANUSPLIN method based on meteorological station observations. Soil data (1 km resolution) were also resampled to 100 m using bilinear interpolation. The biophysical coefficients for each land use/land cover (LULC) category used in the model are presented in **Table 2**. The matching between LULC classes and biophysical parameters (root depth, Kc, LULC_veg) followed the InVEST user guide and local literature [12]. Six LULC types (cultivated land, forest, grassland, water, construction land, unused land) were classified from the original data using the same scheme for all three years to maintain temporal consistency. The carbon pool data are provided in **Table 3**.

Table 1. Acquisition of the parameters.

Data	Data source
Mean annual Precipitation	The National Earth system Science Data Center
Potential evapotranspiration	The National Qinghai-Xizang Plateau Data Center
Root Restricting Layer Depth	The References [16]
Land Use/Land Cover	The Resource and Environmental Science Data Center (RESDC), Chinese Academy of Sciences
Plant Available Water Content	The Harmonized World Soil Database
Watersheds	National Fundamental Geographic Information Database
The parameter Z	The References [12], value of 3
Carbon Pools	The References [17], C_{total}, C_{above}, C_{below}, C_{soil}, C_{dead}

Table 2. Biophysical table.

Lucode	Root_depth (mm)	Kc	LULC_veg
1	350	0.65	1
2	3000	1	1
3	2000	0.65	1
4	1	1	0
5	1	0.3	0
6	1	0.3	0

Biophysical table used for the InVEST water yield mode. The required data were obtained from relevant reference [12], mainly including Lucode (land use/land cover type), vegetation (LULC_veg), root depth for each LULC class, and plant evapo-transpiration coefficient (Kc). The specific values are shown in Table 2.

The carbon pool parameters were primarily derived from the relevant [17], and the carbon pool data table was obtained as Table 3:

Table 3. Carbon density of each land use type.

Land Use Type	Aboveground Carbon Density	Underground Carbon Density	Density of Soil Carbon	Carbon Density of Dead Organic Materials
Cultivated land	4.75	0	33.51	0
Forest	53.55	26.8	170.56	2.56
Grassland	24.38	19.59	52.79	22.74
Water	2.45	0.62	80.11	0.10
Construction land	0	0	0	0
Unused Land	0	0	0	0

3. Results

3.1. Spatiotemporal Evolution Characteristics of Water Yield Service in Liaoning Province from 2000 to 2020

3.1.1. Temporal Variation Characteristics of Water Yield Function

Annual water yield for Liaoning Province in 2000, 2010, and 2020 was simulated using the InVEST model's Annual Water Yield module. The results indicate that the water yield in Liaoning Province exhibited a trend of initial increase followed by a subsequent decrease. The mean water yield in Liaoning Province in 2000, 2010, and 2020 was 489.60 mm, 908.65 mm, and 773.94 mm, respectively; the total water yield was 162.27×10^8 m^3, 646.87×10^8 m^3, 448.79×10^8 m^3, respectively; and the actual evapotranspiration was 377.31 mm, 465.51 mm, and 466.18 mm, respectively. From 2000 to 2010, the water yield increased by 85.59%, showing a significant upward trend, whereas from 2010 to 2020, the water yield decreased by 14.82%, indicating a slight decline. Over the 20-year period, although the water yield in Liaoning Province exhibited certain fluctuations, it showed an overall increasing trend. This pattern was mainly driven by changes in precipitation: annual precipitation annual precipitation first increased and then decreased. While afforestation programs may have influenced evapotranspiration, the dominant factor controlling water yield variability in this period appears to be precipitation.

3.1.2. Spatial Variation Characteristics of the Water Yield Function

The spatial distribution characteristics of water yield in Liaoning Province in 2000, 2010, and 2020 indicate that the spatial variation of water yield in Liaoning Province is significant, exhibiting a clear decreasing trend from the eastern mountainous areas toward the western hilly regions. A further analysis shows that high water yield values are mainly concentrated in the eastern mountainous areas and central plains of the study region, with a maximum annual mean value reaching 876.43 mm, primarily distributed in the southeastern part of Dandong City and the eastern coastal areas of Dalian City. In contrast, the lowest water yield values are concentrated in the western low mountainous and hilly regions of Liaoning Province, with a minimum annual mean value of 0 mm. The dominant land use type in the eastern mountainous and hilly regions is forest land, with exceptionally rich forest resources, which confer strong soil and water conservation capacity; therefore, water yield in this region is relatively high. The central region is characterized by relatively low terrain and predominantly plain landscapes, with cropland as the main land use type; The relatively high water yield in this area may be associated with regional precipitation recharge from the main streams of the Liao River and Hun River systems; The western low mountain and hilly region borders the desert areas of Inner Mongolia and mainly includes Chaoyang City, Huludao City, and Jinzhou City. This region belongs to the central-western hilly zone, characterized by low vegetation cover, frequent sunny days, and low precipitation. These conditions result in relatively high evapotranspiration, and consequently, a low water yield.

3.2. Spatiotemporal Evolution Characteristics of Carbon Storage in Liaoning Province from 2000 to 2020

3.2.1. Temporal Variation Characteristics of Carbon Storage

From a temporal perspective, the carbon storage in Liaoning Province shows an overall increasing trend. The total carbon storage in Liaoning Province in 2000, 2010, and 2020 was 1.81×10^9 t, 1.85×10^9 t, 1.86×10^9 t, respectively, which directly reflects the growth in total carbon storage in the province. From 2000 to 2010, carbon storage increased by 4.38×10^7 t, with a growth rate of 2.42%, indicating that carbon storage in Liaoning Province increased during this period, but the rate of increase was relatively slow. From 2010 to 2020, carbon storage increased by 0.73×10^7 t, and compared with the previous decade, the growth rate decreased to 0.40%, indicating a gradual slowdown in the rate of increase in carbon storage. This may be associated with land use changes, policy adjustments, and other factors. Overall, the total carbon storage in the study area shows the pattern: 2020 > 2010 > 2000, exhibiting a slow and stable upward trend over time. To validate these results, we compared the 2020 carbon storage estimate (1.86×10^9 t) with a previous study for Liaoning Province using a different method [17], showing a difference of only 2.2%.

3.2.2. The InVEST Water Yield Model

From a spatial perspective, the carbon storage in Liaoning Province from 2000 to 2020 shows a gradual decreasing trend from both the eastern and western sides of the study area toward the central region. The highest values are distributed in the eastern mountainous areas of Liaoning Province, which is closely related to the extensive vegetation coverage in this region. The abundant vegetation not only effectively absorbs and stores large amounts of CO_2 but also provides strong protection for the soil, thereby enhancing soil conservation capacity. From the perspective of administrative divisions, relatively high carbon storage values are mainly distributed in Tieling City, Fushun City, Benxi City, and Dandong City, which are located in the eastern mountainous region. Although the carbon storage capacity of the western low mountainous and hilly region is lower than that of the eastern mountainous area, it still exhibits a relatively strong carbon sequestration capacity. In the central region of Liaoning Province, dense human settlements and accelerated urbanization have led to extensive vegetation loss, resulting in relatively low carbon storage in the ecosystem.

4. Discussions

This study reveals the spatiotemporal differentiation characteristics of water yield and carbon storage services in Liaoning Province. Temporally, water supply in the province exhibited an initial increase followed by a subsequent decrease, while carbon storage showed a slow and steady upward trend overall. Spatially, the distributions of the two services exhibit significant differences in the eastern mountainous areas and the central plains of Liaoning Province. This pattern is highly consistent with the province's "mountains in the east, water in the west" geographic configuration, indicating that regional topography, climate, and land use patterns are fundamental factors regulating the provision of ecosystem services. Further analysis indicates that the distribution of carbon storage services is closely related to vegetation cover and land use type. The carbon density of natural forests is significantly higher than that of plantations and croplands. In addition, the recent implementation of the "Returning Farmland to Forest" program in northwestern Liaoning has also positively contributed to enhancing local carbon sequestration capacity.

However, this study only analyzed water yield and carbon storage, two primary ecosystem services in Liaoning Province, which represents a limitation. Additionally, some empirical parameter settings involve uncertainties; for example, the selection of the empirical parameter Z is not precisely determined. Moreover, this study focused solely on the current static patterns and did not conduct a long-term dynamic analysis. While we presented results for three time points (2000, 2010, 2020) which capture the major trends, a continuous annual analysis would be needed to fully characterize interannual variability and detect abrupt changes. Therefore, to achieve a more accurate and comprehensive understanding of the region, future studies should include a broader range of ecosystem services and seek more precise parameter settings, thereby enriching the research scope and improving its accuracy. At the same time, integrating long-term remote sensing data with climate scenario simulations could be used to predict the future changes of ecosystem services in Liaoning Province under different development pathways, providing more comprehensive support for the construction of regional ecological security patterns.

5. Conclusions

This study focused on Liaoning Province and employed tools such as ArcGIS and the InVEST model to analyze the spatiotemporal evolution of water yield and carbon storage from 2000 to 2020. The aim was to provide a reference for ecological protection and restoration planning in the province. The main conclusions are as follows:

1) From 2000 to 2020, the water supply in Liaoning Province exhibited an initial increase followed by a subsequent decrease, with the highest water yield occurring in 2010. The mean and total water yield in that year were 908.65 mm and 6.47×10^{10} m^3, respectively. Spatially, water yield showed a pronounced decreasing trend from the eastern mountainous areas toward the western hilly regions.

2) From a temporal perspective, carbon storage in Liaoning Province exhibited a slow and steady upward trend, with the total carbon storage increasing by 5.11 $\times 10^7$ t, indicating that the province has achieved some progress in carbon sequestration. From a spatial perspective, between 2000 and 2020, carbon storage showed a gradual decreasing trend from both the eastern and western sides of the province toward the central region.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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