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Impacts of the land use transition on ecosystem services in the Dongting Lake area

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Urbanization-induced land use transitions (LUTs) result in a decline in ecosystem services, which has implications for regional ecological security. In order to explore the relationship between ecosystem services and land use transition, this paper utilizes the InVEST model, a geographically weighted regression (GWR) model, to examine the impact of land use transition on ecosystem services in the Dongting Lake area (DLA). The results showed that 1) with the change in urbanization development, the average values of land use transition intensity (LUI) in 2000, 2010, and 2020 are 237.99, 235.82, and 238.92, respectively. Land use dynamics (LUD) show a tendency to increase and then decrease, with average values of 5.58 and 5.62 for the periods 2000–2010 and 2010–2020, respectively, and the transformation of land use shows obvious spatio-temporal heterogeneity. 2) Habitat quality and carbon sequestration showed a downward trend. In contrast, food supply followed an upward trend; soil conservation (SC) and water yield (WY) services initially increased and decreased later. The overall spatial changes in habitat quality and carbon sequestration appear to be insignificant. Food supply shows significant differences in the plains compared to other areas, while soil conservation and water yield service show significant changes in places other than the DLA. 3) From 2000 to 2020, land use transition dynamics, population density, GDP density, night lighting, and transition intensity had mainly negative effects on ecosystem services. Only the Normalized Vegetation Index (NDVI) showed a positive effect on ecosystem services. The results of the research will provide valuable references for the development and implementation of spatial ecological restoration planning and land use policies in the national territory.

KEYWORDS

ecosystem service, Dongting Lake area, land use transitions, InVEST model, geographically weighted regression

1 Introduction

Since the 21st century, with growing urbanization and industrialization (Wang et al., 2023a), the large-scale growth of building land has led to noticeable shifts in land use, in which natural and semi-natural habitat classes have shifted toward artificial habitat classes (Griggs et al., 2013). In addition, current research has identified habitat fragmentation, soil quality deterioration, and increasing environmental contamination as direct effects of human overexploitation (Banks-Leite et al., 2020). These repercussions are predominantly driven by land use transition (LUT), which considerably alters the balance between the supply and demand of ecosystem services (ESs) (Xiang et al., 2022), leading to changes in their providing ecosystem functions (Keyes et al., 2021). Therefore, disclosing the impacts on ESs in the process of LUT is vital for the creation and implementation of ecological restoration planning and land use regulations in the territorial area (Feng et al., 2023).

LUT is the result of the interaction between social and natural factors (Zhou et al., 2020) and plays an important role in regulating socioeconomic development and ecological restoration (Cao et al., 2021a). The meaning of change, its effects, and other facets have been the subject of several academic studies. Explicit and implicit LUT modes are distinguishable among them based on their respective connotations (Shi et al., 2021). Implicit LUT, on the other hand, primarily refers to changes in land use functions (Zou et al., 2024), including various land attributes in terms of property rights (Wen et al., 2020), inputs, outputs, production, etc. Among them, explicit LUT refers to changes in land use structure (i.e., quantitative and spatial structure) (de Groot, 2006; Burton et al., 2009). In terms of effect, LUT has caused changes in the land use structure, which has led to the reduction in ecological land, thus causing ecological environment damage (Yang et al., 2018). Among them are ESs, which people rely on for direct or indirect environmental benefits. Research has demonstrated that ESs are key components of ecological security (Liu et al., 2023). Natural variables like temperature and rainfall and socioeconomic factors like population growth, construction site expansion, and economic development all have an impact on ESs (Ouyang et al., 2022). Of these, land use change has a major impact on ESs (Xu et al., 2019). Prior research has mostly examined how changes in land use structure affect ESs without taking into account how these changes affect ESs themselves during the LUT process (Bai et al., 2020). Furthermore, research on the effects of changing land use on ESs (Hasan et al., 2020) is primarily conducted at the administrative division level (Liu, 1996; Chen et al., 2019; Song et al., 2022). This limits the ability to suggest relevant planning for the area and makes it challenging to characterize the phenomenon's local changes.

The Dongting Lake Ecological Reserve is an important part of the Yangtze River basin (Liu et al., 2023) and an important area for ecological restoration and food supply in China. The process of urbanization has precipitated a significant shift in land utilization within the locality, exerting a profound impact on the ESs of the area. Hence, this study focuses on the Dongting Lake area (DLA) as the subject of investigation, elucidating the transition in land use and ESs at the grid scale from 2000 to 2020 through a multi-dimensional assessment. It aims to delve into the mechanism by which land use transition impacts ESs, employing a geographically weighted regression (GWR) model. This endeavor seeks to address the following scientific inquiries: 1) What patterns characterize the changes in ESs during the process of land use transition? 2) What is the relationship between land use transition (LUT) and ESs? The ultimate objective is to furnish theoretical underpinnings for the high-quality development of land space in the DLA (Li et al., 2023).

2 Methods

2.1 Overview of the study area

DLA (28°30′N-29°40′N, 113°10′E–114°40′E) is the second largest freshwater lake in China (Song et al., 2022). It is located in the northern part of Hunan Province and the southern part of Hubei Province, serving as an essential storage lake and ecological security function area in the Yangtze River basin (Liu et al., 2022). The region is predominantly characterized by plains, which can be categorized into four main types: lake water bodies and shoals, plains surrounding the lake, hills and low mountains adjacent to the lake, and valley plains and hills (Zhao et al., 2023). The current investigation centered on a subset comprising 19 counties (cities and districts) from the three prefecture-level cities, namely, Yueyang, Yiyang, and Changde, within the DLA (Jiang and Zeng, 2024). These areas encompassed Yueyang city, Linxiang city, Yueyang County, Huarong County, Miluo City, Xiangyin County, Yiyang city, Yuanjiang city, Nan County (including the Datong Lake area), Changde city, Hanshou County, Anxiang County, Li County, Jin city, and Linli County (Jie et al., 2023). As shown in Figure 1, the total area spans approximately 25,800 km^2, constituting 12.18% of Hunan Province. As of the end of 2020, the resident population numbered approximately 10,705,800, accounting for approximately 16.11% of the province. The GDP amounted to 710.44 billion yuan, representing roughly 17% of the province.

In terms of land use, we reclassified land cover into six categories. Of these, forest land accounted for the largest share of 46% of the total area in 2020, followed by cropland at 37%, grassland and unused land both at 2%, watershed at 11%, and built-up land at 3%. There was a shift in land use between 2000 and 2020, mainly for cropland—from 38% of the total area to 37%—and built-up land—from 2% to 3%. The 46% coverage of forested land around Dongting Lake underscores the substantial forest resources in the area, reflecting not only its biodiversity but also its contribution to water yield (WY) and soil conservation (SC), which are pivotal for maintaining the ecological balance of the lake region. The 37% allocation to cultivated areas highlights the significance of agriculture in the Dongting Lake vicinity, particularly in the production of staple crops such as rice, which is vital for local and neighboring food supplies. Moreover, the 11% designated as watershed areas signifies the abundant water resources surrounding Dongting Lake, crucial for sustaining crop growth and ecological equilibrium. Prudent conservation and management of these land resources, including preserving forest cover and wetland ecosystems, as well as enhancing agricultural productivity and sustainability, are essential for maintaining the ecological balance and food security in the Dongting Lake region, ensuring a healthy and stable environmental landscape within the area.

2.2 Materials

2.2.1 Data sources

The data mainly include land use data, food supply, carbon density, night light data, and others, as shown in Table 1.

2.3 Methods

2.3.1 Land use transition intensity

Land use transition intensity (LUI) is a significant metric of the land use function (Yang et al., 2020). From a socio-economic

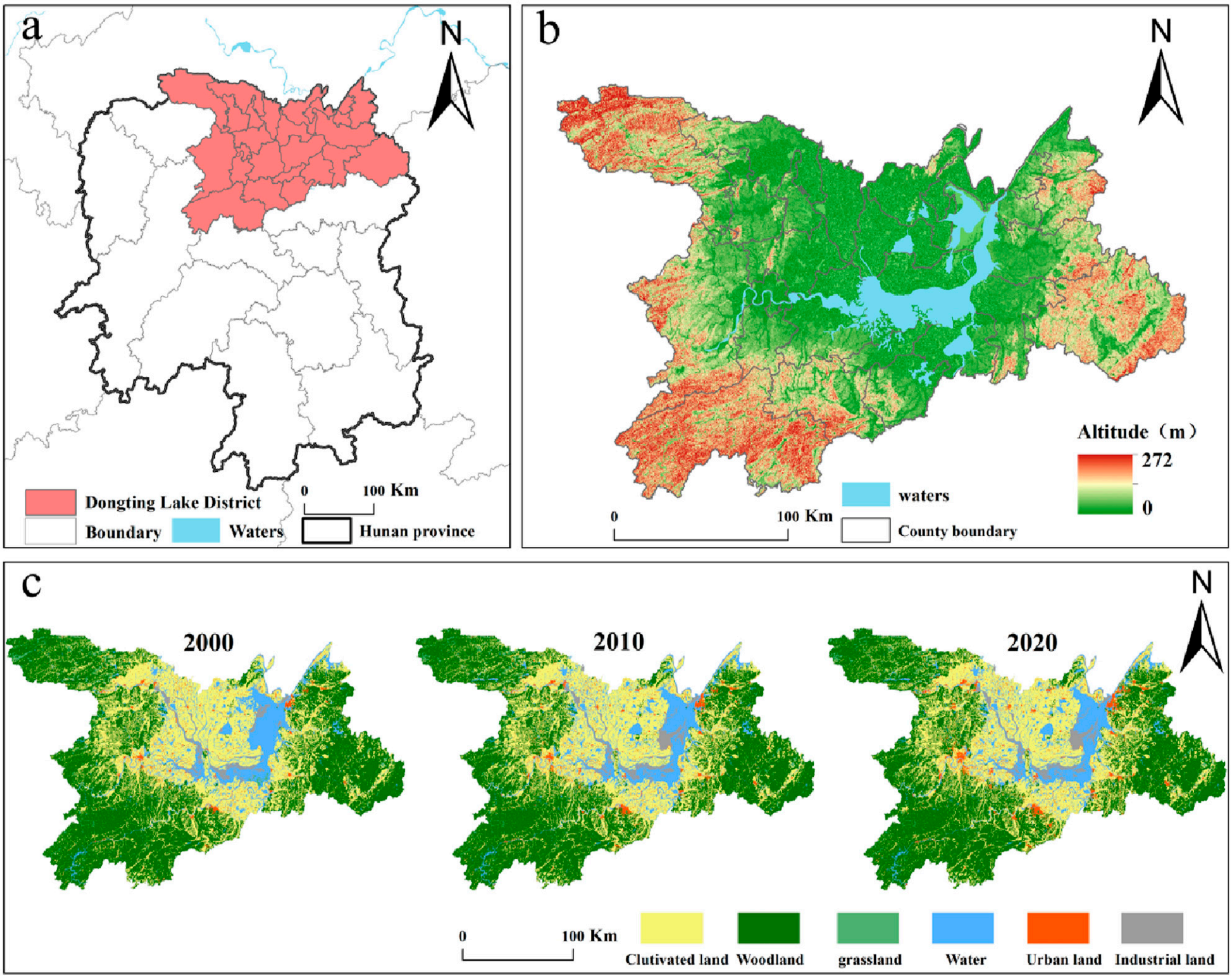

FIGURE 1
Geographic location and land use classification of the Dongting Lake ecological and economic zone. Location of the region **(A)**, digital elevation model **(B)**, and class of land use **(C)**.

standpoint, LUI can indicate varied degrees of land transitions, development, and exploitation. The study will treat each land raster as a sampling point, generating a 1 km × 1 km grid and calculating the LUI of each grid independently, as depicted in Figure 3. Each land use type can be defined as the ability of different land use types to provide products and services for human beings (Kleijn et al., 2009). Their contribution to LUI is consistent with their weights. Therefore, using the grid, LUI can be calculated using the following formula:

$$LUI = \sum_{i=1}^{n} (B_i / B) \times C_i \tag{1}$$

In this formula, B represents the total land area, n is the number of land use types (n = 6 in this study), B_i is the area of each land use type, and C_i is the value of the degree of exploitation of the land use type (Yang et al., 2020). LUI can be classified into four categories, with each land use type within each category having the same value. Specifically, the value of industrial, urban, and rural–urban land, collectively known as build-up land, is defined as "4." Farmland is assigned a value of "3" due to its socio-economic and natural attributes. The Chinese government reinforces the protection of farmland, grassland, and woodland resources, owing to their ecological functions (Yang et al., 2018), which are assigned a value of 2. Bare land is valued at "1" as it has yet to be developed for socio-economic activities.

2.3.2 Land use dynamics model

Land use dynamics (LUD) serves to depict the rate and trajectory of land transition and reflects its overall characteristics within a region over time (El-Naggar et al., 2022). Similarly, this study utilizes the grid as the fundamental unit for LUD calculation. The specific equations are provided below (Li et al., 2021):

$$LUD = \frac{\sum_{i=1}^{n} B_{i \to j}}{B} \times \frac{1}{\mathrm{t_b} - t_a} \times 100\% \tag{2}$$

Here, B is the total land area, n is the number of land use types (n = 6 in this study), and $\Delta B_{i \to j}$ is the area where land use type i is

TABLE 1 Data sources.

Data name	Description of the data	Source of data
Nighttime lighting data	The nighttime light data (NTL) is sourced from the Defense Meteorological Satellite Program Operational Line Scan System (DMSP/OLS), offering a spatial resolution of 1 km × 1 km. Population density datasets for the years 2000, 2010, and 2020 are accessible under the Creative Commons Attribution 4.0 International License, also with a spatial resolution of 1 km × 1 km (Wang et al., 2023b)	Data are provided by the Institute of Geographic Sciences and Natural Resources (IGSNRR), the Centre for Environmental Sciences and Data, Chinese Academy of Sciences (CAS), accessible at https://www.resdc.cn
Population density	The population density datasets for 2000, 2010, and 2020 are accessible under the Creative Commons Attribution 4.0 International License at a spatial resolution of 1 km × 1 km (Wang et al., 2023a)	Taken from ORNL LandScan Viewer—Oak Ridge National Laboratory (landscan.ornl.gov)
GDP intensity	Gross domestic product (GDP), as an essential and comprehensive statistical indicator in the accounting system, shows the rate of economic development in China. It is an indicator that measures the results of productive activities in resident units. The spatial resolution of GDP data for 2000, 2010, and 2020 is 1 km × 1 km	Retrieved from the Center for Resource and Environmental Sciences and Data, Institute of Geographic Sciences and Natural Resources, Chinese Academy of Sciences, available at https://www.resdc.cn
Food supply	The study focused on major food types, including cereals, sugar crops, oil crops, meat, milk, and fruits	Data was sourced from the China Statistical Yearbook (2001–2021) and China Rural Statistical Yearbook (2001–2021), and information on the caloric composition of various foods was obtained from the U.S. agricultural databases and related studies (Cao et al., 2021b)
Habitat quality	Land use data were primarily used for the habitat quality calculations derived from the inVEST Habitat Quality Module	Habitat quality-related parameter settings are taken from the existing literature (Wentland et al., 2020)
Carbon density data	Primarily utilized as references for carbon density data across different carbon pools	Data were mainly obtained from the literature (Wang et al., 2018; Zhou et al., 2020; Buckley Biggs, 2022))
Water yield services data	Derivation of the inVEST water production module	Precipitation data are sourced from the annual spatial precipitation interpolation dataset of China since 2000, available at http://www.resdc.cn/data.aspx?DATAID=229. Potential evapotranspiration data are obtained from World Climate, accessible at https://www.worldclim.org/data/worldclim21.html. Watershed and sub-basin boundary data are derived from the Chinese watershed and river network extraction dataset based on DEM, retrievable from http://www.resdc.cn/DOI/doi.aspx?DOIid=44
Soil data	The soil data resolution is 1000 m, and the terrain ASTER GDEM data resolution is 30 m	National Cryosphere Desert Data Centre can be accessed at https://www.ncdc.ac.cn, while the Geospatial Data Cloud is available at http://www.gscloud.cn
LULC	Spatial resolution of 30 m (2000–2020)	The dataset was provided by the ESA CCI Land Cover Project (https://www.esa-landcover-cci.org/)

transformed into land use type j (Buckley Biggs, 2022). The difference between t_b and t_a represents the time of the study. Broadly speaking, the larger the LUD, the faster and larger the land use transition. The trend will also be more pronounced, and *vice versa*.

2.3.3 Methods for quantifying ecosystem services

Ecosystem services can be classified into four main types: provisioning services (providing food and water), regulating services (controlling floods and diseases), cultural services (offering spiritual, entertainment, and cultural benefits), and supporting services (maintaining nutrient cycling that sustains life on earth) (MA et al., 2017; Ning and Ouyang, 2023).

In this study, we selected carbon sequestration, water yield services, food production, habitat quality, and soil conservation. Carbon sequestration and soil conservation fall under regulating services; water yield services and food production belong to provisioning services; and habitat quality is classified as a supporting service (Yu et al., 2024). Specific quantification was done using the InVEST model (Wei et al., 2021), and the corresponding equations are shown in Table 2.

Since the five ESs of carbon sequestration, water yield services, food production, habitat quality, and soil conservation have different units, a standardized method was used to standardize the ESs to [0,1]. Then all the values were added to obtain the total ESs (TES).

2.3.4 Geographically weighted regression

The GWR model is a classic approach for analyzing spatial heterogeneity. It effectively captures the influence of geographical location on the relationship between dependent and independent variables. Compared to other models, GWR offers higher accuracy. Additionally, the ecosystem service observation data in this paper exhibit spatial correlation. Therefore, incorporating temporal attributes into the GWR model allows for the exploration of the spatio-temporal driving mechanisms underlying the explanatory power of the independent variable on the dependent variable. The specific formula of the GWR model is presented below:

$$Y_{ij} = \beta_0(\mu_i, v_i, t_i) + \sum_{k=1}^{p} \beta_k(\mu_i, v_i, t_i) X_{ik} + \varepsilon_i \tag{3}$$

where Y_{ij} represents the ecosystem services in grid ij, a normalized means of five categories of ecosystem services; (μ_i, v_i, t_i) represents the spatial and temporal coordinates of sampling point i; $\beta_0(\mu_i, v_i, t_i)$ is the regression constant for

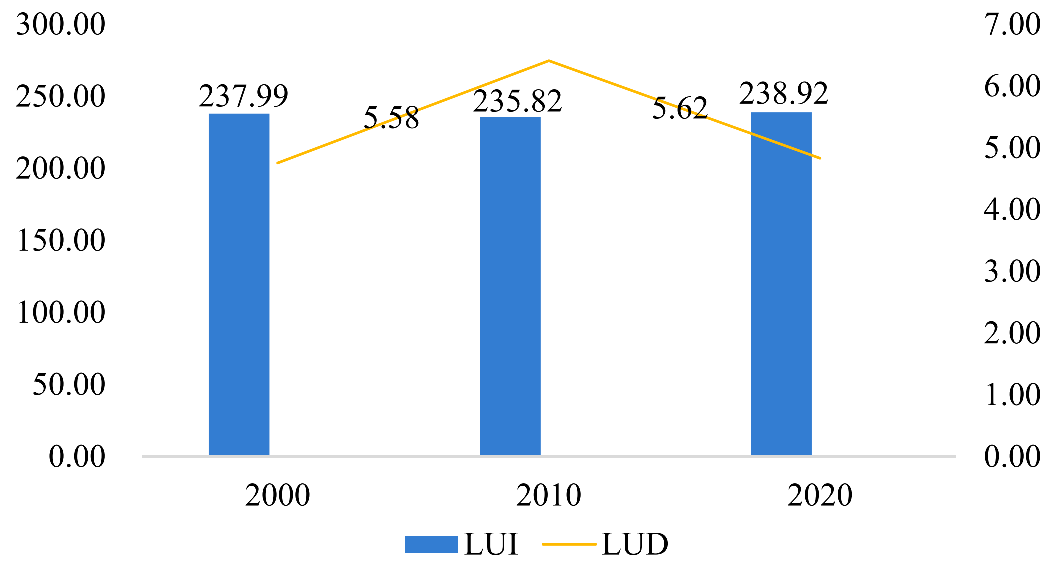

FIGURE 2
Intensity of land use transition and motivation, 2000–2020.

sampling point i; $\beta_k(\mu_i, v_i, t_i)$ represents the kth regression parameter for sample point i; X_{ik} is the driving factor k for sampling point i; and ε_i is the residual term of the model.

3 Results

3.1 Characteristics of spatial and temporal changes in LUT

Overall, the LUI exhibited slight fluctuations, with average values of 237.99, 235.82, and 238.92 in 2000, 2010, and 2020, respectively. The average annual growth rate of the LUI from 2000 to 2010 was −0.22, and from 2010 to 2020, it was 0.31. In contrast, LUD demonstrated a trend of initially increasing and then decreasing, with average values of 5.58 and 5.62 for the periods 2000–2010 and 2010–2020, respectively. Spatially, high-value areas in 2000–2010 were predominantly situated around the lake area and in urban expansion zones, while those in 2010–2020 were dispersed across urban, rural, and urban expansion areas (see Figure 2). The concentration of high-value areas of land use transition intensity in 2000, 2010, and 2020 was observed in the DLA, indicating favorable topography and optimal utilization of land resources in the region (see Figures 3D–F).

From 2000 to 2010, the high-value area of LUD for land use transition motivation was primarily concentrated in the eastern coastal area at the northern end of DLA and in urban construction areas around the region. Conversely, from 2010 to 2020, the high-value area of LUD for land use transition motivation was mainly concentrated in the suburbs of cities and urban and rural areas, particularly in the townships around cities, with a significant range of land use changes. The motivation for change slowed down around the lake area during this period (see Figures 3A–C).

3.2 Characteristics of spatial and temporal changes in ESs

The temporal and spatial variations over the period 2000–2020 for different ESs are discussed in this section. As shown in Table 3 and Figure 4, the mean value of WY increased from 490.18 mm in 2000 to 902.01 mm in 2010. High-value areas are distributed in the southeastern and southern hilly areas; low-value areas are spread in the waters of the Dongting Lake basin. The mean value of WY increased from 902.01 mm in 2010 to 690.10 mm in 2020. High-value areas are sporadically scattered; low-value areas are still distributed in the waters of the Dongting Lake Basin. The average value of CS decreased from 2289.35 t/hm^2 in 2000 to 2255.01 t/hm^2 in 2010, and the high-value areas are distributed in the hilly areas and the Dongting Lake Basin, while the low-value areas are distributed in the plains. The average value of CS in 2010 decreased from 2255.01 t/hm^2 to 2247.46 t/hm^2 in 2020. High values are still distributed in the hilly mountainous areas and the Dongting Lake basin; low values are distributed in the built-up areas and part of the waters of the Dongting Lake. The average value of SC in 2000 increased from 1088.32 t/ha^2/ha^2 to 1822.64 t/ha^2/ha^2 in 2010. High values are distributed in the mountainous areas at the edges of the study area; low values are distributed in the Dongting Lake basin. The mean value of SC increased from 1088.32 t/ha^2 in 2000 to 1822.64 t/ha^2/in 2010. High-value areas were distributed in the marginal mountains of the study area; low-value areas were distributed in the watershed of Dongting Lake. The mean value of SC decreased from 1822.64 t/ha^2 in 2010 to 626.29 t/ha^2 in 2020. High-value areas were distributed in the marginal mountains; low-value areas were distributed in the watershed of Dongting Lake. The mean value of HQ decreased from 0.71 in 2000 to 0.697 in 2010. High-value areas are distributed in the marginal mountains of the study area and in the Dongting Lake Basin; low-value areas are

TABLE 2 Formulas and descriptions of ecosystem service calculations.

ES	Calculation formula	Description
Carbon sequestration (CS)	$CS = C_{\text{above}} + C_{\text{below}} + C_{\text{soil}} + C_{\text{dead}}$	CS represents the total sequestered carbon supply (t/ha), C_{above} denotes the above-ground biochar, C_{below} signifies the below-ground biochar, C_{soil} stands for the organic carbon in the soil, and C_{dead} represents the dead organic carbon. These four carbon pools were obtained from the results of a literature review (Terrado et al., 2016; Wang et al., 2018; Qi et al., 2023)
Water yield services (WY)	$Y_{x,j} = (1 - \frac{AET_{x,j}}{P_x}) \times P_x$	$Y_{x,j}$ represents the annual water yield in pixel x in land use type j; $AET_{x,j}$ denotes the actual annual evapotranspiration in pixel x in land use type j, which was estimated based on the reference evapotranspiration data, land use data, and related parameter data. P_x signifies the annual precipitation in pixel x, compiled using precipitation data from the study area. Parameter data for estimating water yield, such as biophysical tables and tensor constants, were obtained through a literature review (Cong et al., 2020; Sancho Santos et al., 2021)
Food supply (FS)	$P_i = \sum_{k=1}^{k}\sum_{c=1}^{c} A_{cki} \times P_{cki}$. Food availability in a given area c can be calculated using the following formula: $P_{cki} = \frac{P_i}{\sum_{k=1}^{k}\sum_{c=1}^{c} A_{cki}} = \frac{\sum_{c=1}^{c} Y_c \times E_c}{\sum_{k=1}^{k}\sum_{c=1}^{c} A_{cki}}$	P_i is the total food energy produced in the area (kJ), A_{cki} is the area occupied by food C in the area I in the land use type K (HM^2), and P_{cki} represents the supply per unit area of the corresponding food c. Y_c here for a given area is the yield of the different food types c (kg), and E_c is the calorie content of the different foods (kJ/kg)
Habitat quality (HQ)	$Q_{xj} = H_j[1 - (\frac{D_{xj}^z}{D_{xj}^z + k^z})]$. Here, the Q_{XJ} series is the habitat quality of the grid x in the habitat type j, k is a semi-saturation constant, H_j the suitability of the habitat for the habitat type j, and the Q_{XJ} series is the degree of disturbance of the habitat type j on the grid x such that the Q_{XJ}'s series $= \sum_{r=1}^{R}\sum_{y=1}^{Y_r} (w_r / \sum_{r=1}^{R} w_r) r_y i_{rxy} \beta_x S_{jr}$ $i_{rxy} = 1 - (\frac{d_{xy}}{d_{r\max}})$	R is the threat factor, y is the number of image elements of the grid layer cells of the threat factor r, Y_r is the total number of cells occupied by the threat factor, and w_r is the weight of the threat factor r taking values in the range of [0,1]. r_y is the value of the threat factor of the grid Y (0 or 1), i_{rxy} is the degree of disturbance of the grid threat factor r on the habitat grid, S_{jr} is the sensitivity of the habitat type j to the threat factor r, and β_x is the availability of the grid x taking values in the range [0,1]. Degree of disturbance i_{rxy} d_{xy} is the linear distance between grids x and y, and $d_{r\max}$ is the maximum working distance r of the threat factor (Sancho Santos et al., 2021)
Soil conservation (SC)	$R = \sum_i^{12} 1.735 \times 10^{[(1.5 \times \log_{10}\frac{p_i^2}{p}) - 0.8188]}$ $K = \{0.2 + 0.3\exp[0.256SAN(1 - \frac{SIL}{100})]\} \times (\frac{SIL}{CLA+SIL})^{0.3} \times (1 - \frac{0.25C}{C + \exp(3.72 - 2.95C)}) \times (1 - \frac{0.7(1-SAN)}{(1-SAN) + \exp[2.29(1-SAN)] - 5.51})$	R is the rainfall erosion rate, MJ•mm/(ha•hr•yr); p_i is the monthly precipitation (mm/month); and p is the annual precipitation (mm/year). K is the erodibility of the soil using the Erosion Productivity Impact Calculator (EPIC) model (Williams et al., 1984), where SAN, SIL, CLA, and C stand for the proportions of organic matter, sand, silt, and clay in the soil, respectively

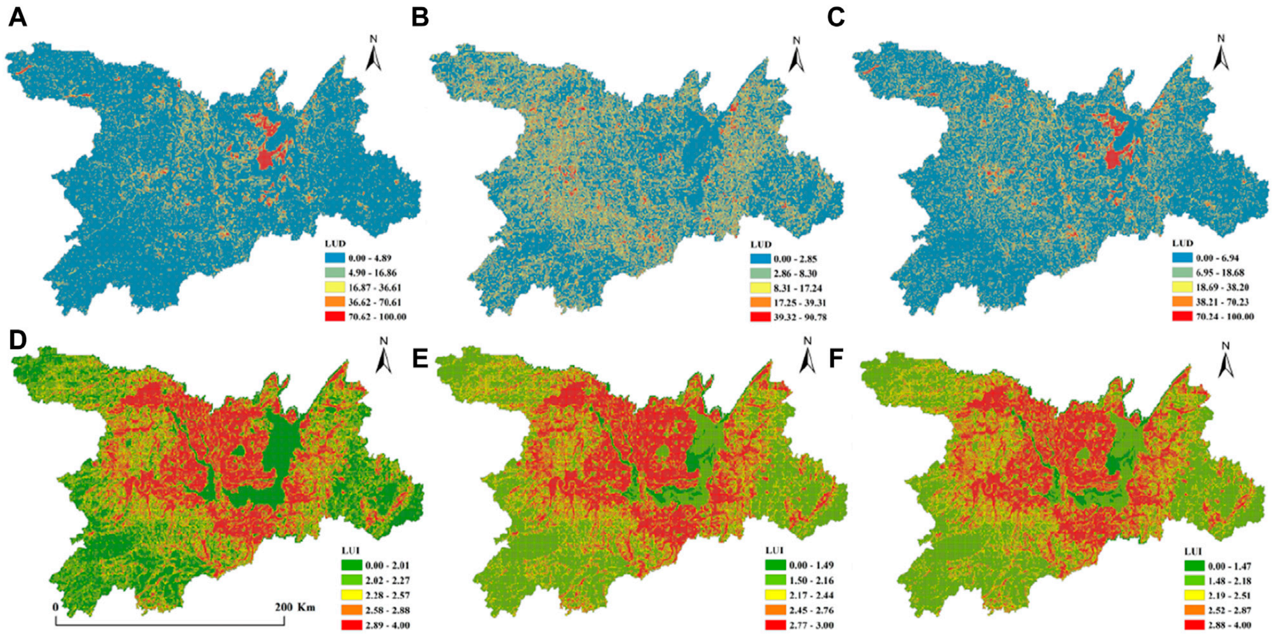

FIGURE 3
Intensity of land use transition and dynamics of motivation. **(A)** LUD during 2000-2010; **(B)** LUD during 2010-2020; **(C)** LUD during 2000-2020; **(D)** LUI 2000; **(E)** LUI 2010; **(F)** LUI 2020.

distributed in the urban areas. The mean value of HQ decreased from 0.697 in 2010 to 0.695 in 2020. High-value areas are still distributed in the marginal mountains and the Dongting Lake basin; low-value areas are still distributed in the urban areas. The average value of FS increased from 4740855.49 KJ in 2000 to 6024647.79 KJ in 2010. High-value areas were distributed in the plains and hills of the Dongting Lake basin; low-value areas were distributed in the marginal mountains of the study area and the Dongting Lake Basin. The average value of FS in 2010 increased from 60246447.79 KJ to 7036502.47 KJ in 2020. High-value areas are still distributed in the Dongting Lake Basin. The high-value areas are still distributed in the plains and hills of the Dongting Lake Basin; the low-value areas are still distributed in the mountains at the edge of the study area and in the Dongting Lake Basin.

3.3 Spatial and temporal correlation between LUT and ESs

The regression parameters of TES between and socio-economics are less variable than those between natural ecological factors (Figures 5, 6). The regression coefficients of NDVI ranged from −0.097836 to 0.208317, with the largest changes in regression coefficients and significant spatial heterogeneity. During the period of 2000–2010, 85% of the grids consisted of negative coefficient spaces, whereas the positive coefficient spaces were distributed in the southwest of Dongting Lake; between 2010 and 2020, the proportion of negative coefficient spaces decreased significantly, while positive coefficient spaces were distributed in the east coast, the western basin, and the southern edge of the study area.

The regression coefficients of LUD ranged from −0.001908 to 0.000521. The magnitude of the change in the regression coefficients varied slightly, indicating weaker spatial heterogeneity. During 2000–2010, 60% of the grids exhibited negative coefficients, with relatively positive coefficient spaces mainly distributed in the southern part of Dongting Lake, the southwestern edge, and the northwestern part of the study area. However, from 2010 to 2020, the positive coefficient spaces varied significantly, with a substantial increase in the proportion of negative coefficient spaces. Positive coefficient spaces were primarily distributed in the southwestern and northeastern parts of the study area.

Additionally, the regression coefficients of LUI ranged from −0.000593 to 0.000370, showing small variations and weak spatial heterogeneity. Positive coefficients during the period 2000–2010 were predominantly observed in the southern and eastern parts of Dongting Lake, as well as the western and northeastern fringes of the study area. Conversely, for the period 2010–2020, high-value areas were primarily concentrated in the northeastern and southwestern parts of the study area, as well as in the southern basin of Dongting Lake.

The socio-economic data encompass population density, GDP density, and nighttime light data. The regression coefficients of the nighttime light data ranged from −0.002690 to 0.002625. Spatially, during the period from 2000 to 2010, high values were primarily concentrated in the eastern, southern, and northern regions of Dongting Lake, as well as the southern part of the western watershed and the northern edge of the study area. Conversely, in the period from 2010 to 2020, high values shifted to the northern, southeastern, and southwestern parts of Dongting Lake, along with the northwestern and western edges of the study area. For GDP density, the regression coefficients ranged from −0.000008 to 0.000024. During the period 2000–2010, high values were dispersed in the southern part of the study area, while during 2010–2020, they were primarily located toward the northwestern

TABLE 3 Changes in ecosystem services, 2000–2020.

Type of ESs	2000	2010	2020	2000–2010	2010–2020
WY	490.726	902.007	690.102	41.128	−21.191
CS	2,289.954	2,255.008	2,247.457	−3.494	−0.755
SC	1,088.317	1,822.635	929.607	73.432	−89.303
HQ	0.711	0.698	0.695	−0.001	−0.001
FS	4,740,855.284	6,024,647.791	7,036,502.467	128,379.251	101,185.468

The unit of WY is mm; the unit of C is t/hm^2; the unit of SC is t/ha^2; the unit of FS is KJ; rate of change is provided in the last two columns.

part of Dongting Lake. The regression coefficients of population density ranged from −0.000008 to 0.000011. During the period 2000–2010, high-value areas were mainly distributed in the northwestern part of the study area and the western part of the Dongting Lake basin, whereas during 2010–2020, they shifted to the western and northwestern parts of the study area, as well as the southern part.

4 Discussion

4.1 Impacts of LUT on ESs

The structure of ecosystems (e.g., cropland and woodland) and processes (e.g., habitat quality) in the process of land-use transition are influenced by human-social factors, which aim to maximize human benefits by transforming natural ecosystems (Long and CHEN, 2021). Concurrently, the process of land use transition affects socio-economic characteristics correspondingly, as evidenced by the growth of night-time lighting data, population density, and GDP density, following the expansion of urban construction land (Song, 2017). As depicted in Figure 4, habitat quality and carbon sequestration exhibit a downward trend, while food supply trends upward; soil conservation and water yield services initially increase and then decrease. During the period 2000–2010, the eastern littoral area at northern Dongting Lake experienced a significant land transition. This transformation can be attributed to the implementation of policies related to the return of farmland to the lake and forests in 2002, which reduced the human occupation of land in the lake area. Subsequently, there was an expansion of land for urban construction, aligning with China's high rate of development during this decade, characterized by rapid growth in urban, rural, and city areas. In the functional spatial layout of ESs, the high-value areas of WY, CS, SC, and HQ were mainly in the mountainous hills at the edge of the study area, and the spatial pattern of the distribution of the high-value areas of FS was mainly in the plains around the Dongting Lake watershed. In the 2000–2020 changes, the ESs showed changes in WY in Dongting Lake waters, a slow decrease in the mean value of HQ, an overall increase in SC, an overall slow decrease in CS, and a gradual increase in FS. The land use overuse pattern is mainly policy-oriented, with obvious changes in DLA unutilized land and high LUD values clustered in the lake area related to the land policy of returning farmland to the lake at that time.

LUT has an impact not only on human life and socioeconomic characteristics but also on the regional spatial environment (Dong et al., 2021). This research used a micro-grid scale to explore the fact that ecosystem services in neighboring regions are strongly correlated. The spillover effect makes land use transitions affect ecosystem services not only within the same region but also in neighboring regions (Feng et al., 2023). This study explores the effects of spatial spillovers on ecosystem service types at a grid scale, with different combinations of influencing factors that enhance the persuasive power of GWR. The results also showed that while sensible land use would enhance ESs in nearby areas, socio-economic development would inevitably lead to an increase in transition intensity. Furthermore, the LUI exhibited a negative spatial correlation with the majority of ESs at the grid scale. After 2013, the area had a sharp increase in both urban and rural development, and as a result of the loss of forest land and the accumulation of rural dwelling land, SC services started to diminish. High-value areas of LUD are primarily concentrated in areas with infrequent human activities, primarily in areas with higher elevation and lower LUI and LUD. In contrast, the distribution pattern of high-value areas of SC is different. These areas, including LUD, have a negative correlation with SC and a more homogeneous land structure with more intact soil, primarily composed of forested land.

4.2 Implications for LUT

From 2000 to 2010, the central and northern parts of Dongting Lake witnessed dramatic areas of land-use transformation, mainly in the form of the transfer of arable land to construction land and forest land, leading to a decline in the regional capacity to supply ecosystem services. From 2010 to 2020, the transformation of the Dongting Lake region was reduced, with the spread of aggregation from urban areas to peri-urban areas. In the future, the land use transformation of the Dongting Lake area will take land consolidation, reclamation, development, and urban and rural construction land increase/decrease linkage as a platform to promote the comprehensive improvement of fields, water, mountains, forests, and villages; control the proportion of arable land and forest land transferring to construction land; and enhance the sustainability of the land use structure (Gomersall, 2021). How to enhance ecosystem services through effective land management is a key issue for the sustainable development of Dongting Lake (Griggs et al., 2013). Different ecosystem service types showed different trends of change, except for FS and WY, which showed a decreasing trend. Among them, in terms of carbon stock and

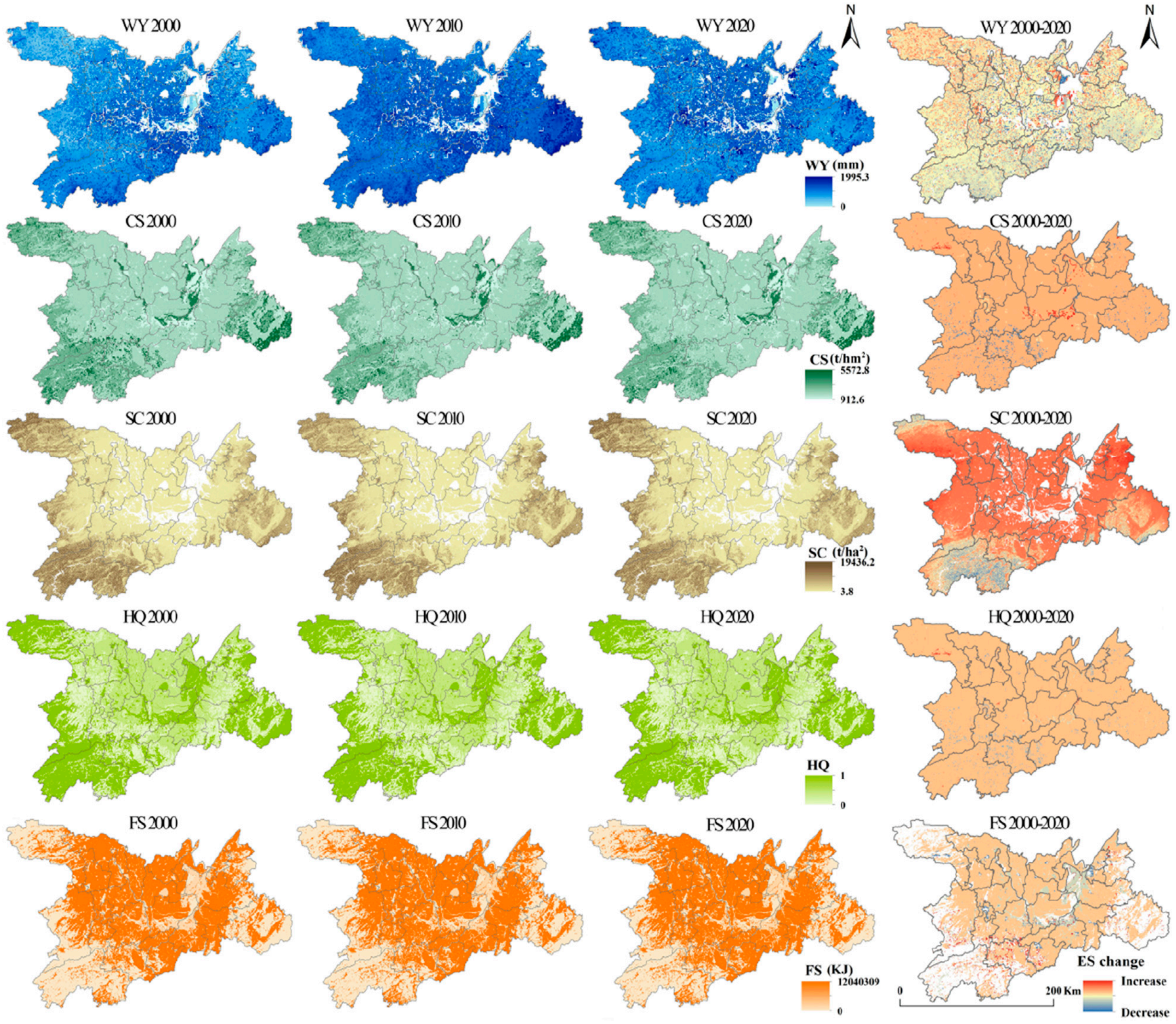

FIGURE 4
Changes in various types of ecosystem services, 2000–2020.

habitat quality, among different land use types, forest land was the main contributor to CS in the study area, while the expansion of construction land was the main reason for the decrease in CS. Therefore, the protection and restoration of forest ecosystems should be strengthened in the Dongting Lake area. For soil and water conservation, slope and vegetation cover in natural conditions determine the ability of soil and water conservation, and since the slope length is not easy to change, improving the vegetation cover on the ground surface can weaken the influence of slope length on soil erosion and reduce the spatial heterogeneity of soil erosion. When carrying out soil erosion control, corresponding soil erosion control measures can be formulated for the dominant factors of erosion differentiation in different regions. In terms of food production, arable land should be further protected, the scale of high-standard farmland should be expanded, and at the same time, agricultural production technology should be upgraded. In terms of water production, water ecology monitoring should be strengthened, wetland shrinkage and degradation should be controlled, and ecological restoration projects for wetland protection should be carried out. Overall, the Dongting Lake area needs to improve rural production, living conditions, and ecological environment and promote the development of large-scale agricultural management, centralized population living, and industrial agglomeration so as to mitigate the impacts of human activities and climate change on ecosystem services and improve the sustainability of the land space in the Dongting Lake area.

4.3 Shortcomings and future study

To explore the impact of LUT on the spatial and temporal changes in ecosystem services, this paper selected GWR to reflect the partial spatial characteristics. Among them, mountainous areas and waters are intuitively more sensitive than built-up areas, causing variations in ecosystem services related to carbon sequestration and water yield services different from other areas. This, in turn, affects

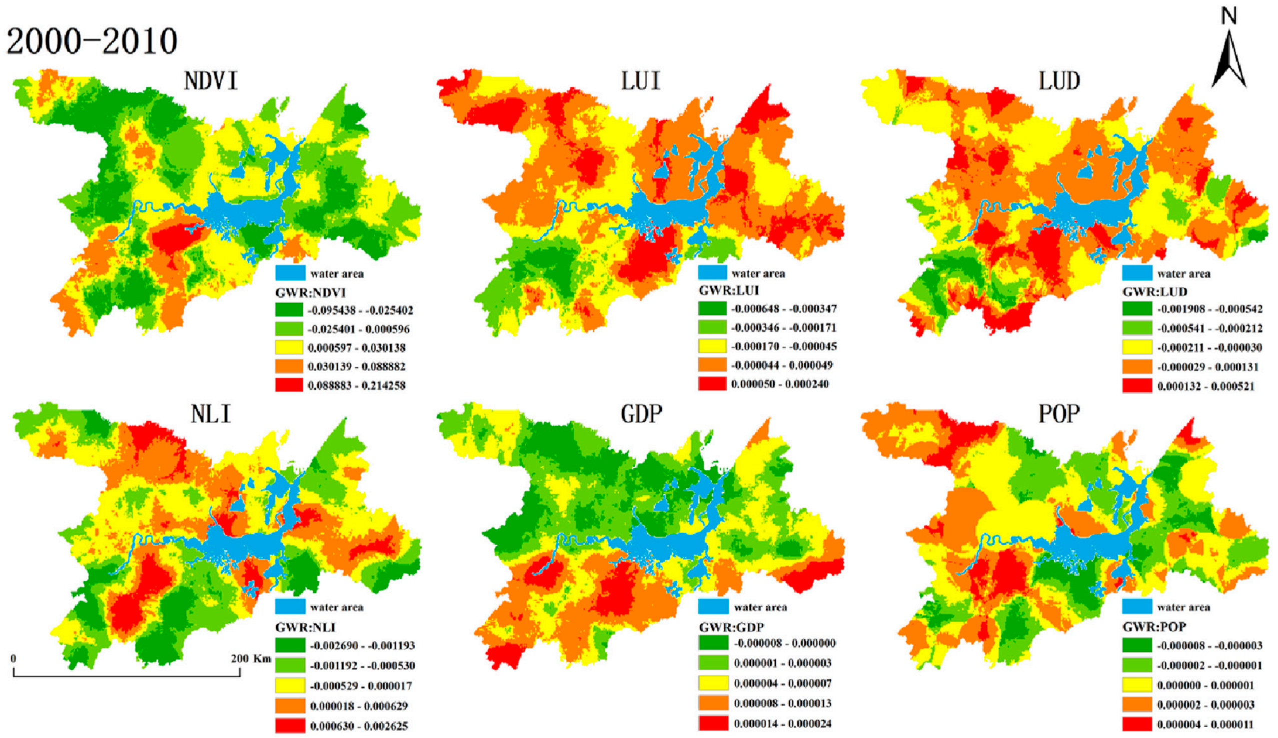

FIGURE 5
Changes in the coefficients of the role of different influencing factors, 2000–2010.

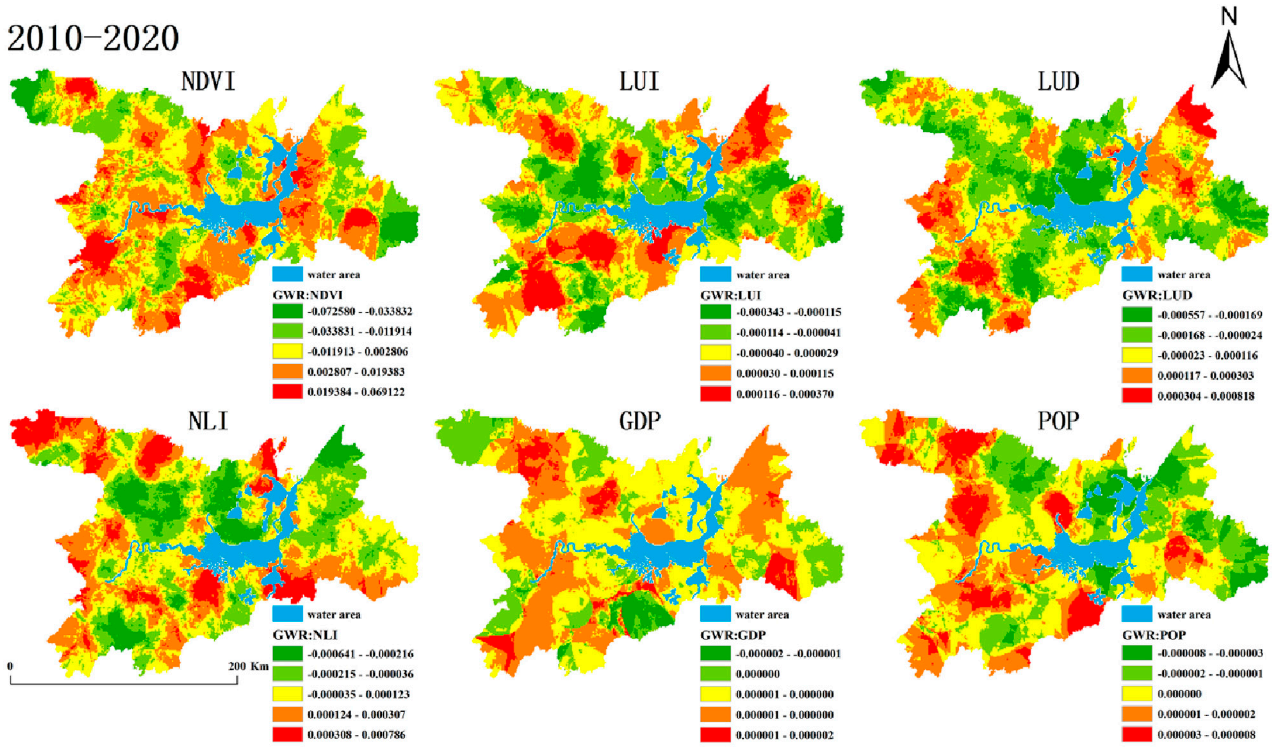

FIGURE 6
Changes in the coefficients of the role of different influencing factors, 2010–2020.

the median values of the corresponding coefficients of variation, which are usually used to characterize the overall GWR results (Chen et al., 2019). Future studies should refine the limitations to quantitative methods, owing to data accuracy. For example, this study measured five types of ecosystem services, which cannot fully reflect the regional ecosystem pattern. In addition, factors such as ecological protection policies should be considered in the future to improve the mechanism of ecosystem service changes.

5 Conclusion

In this paper, the Dongting Lake Ecological and Economic Zone serves as the focal point of our investigation, utilizing remote sensing images from 2000, 2010, and 2020 as primary data sources. Employing grid analysis alongside InVEST and GWR models, we examine the repercussions of LUT on ESs within the study area, spanning from 2000 to 2020. The principal conclusions are outlined as follows:

During the period 2000–2020, the rapid expansion of construction land in the study area led to a significant LUT. The result demonstrates that the mean value of intensity changed from 237.99 in 2000 to 238.92 in 2020. In particular, the high intensity of LUT is mainly distributed around the Dongting Lake Basin, while the low intensity is mainly distributed in the mountainous areas at the edge of the area. Additionally, the dynamics of LUT changed from 5.58 in 2000–2010 to 5.62 in 2010–2020. Among them, the high dynamics in 2000–2010 were mainly distributed in the coastal areas in the northeastern part of Dongting Lake and urban construction areas. On the other hand, the high dynamics in 2010–2020 were mainly located on the outskirts of cities and rural areas.

Different types of ecosystem services displayed spatial and temporal heterogeneity. To be specific, carbon sequestration services, habitat quality services, and soil conservation have similar spatial characteristics, and the high values are primarily distributed in high-elevation mountain areas. In contrast, food production services presented the opposite features, with high values mainly distributed in plain areas. Soil conservation declined first and then ascended. The low value of water services is related to the distribution of watersheds.

There are differences in the factors that influence ecosystem services in different periods. Compared with 2010–2020, NDVI coefficients had the largest value of change in 2000–2010 and the strongest impact on ecosystem services. Notably, the high values in 2000–2010 converge on the west side of Dongting Lake, while the high-value areas in 2010–2020 are scattered all over the research area. Furthermore, LUI and LUD had more grids with high values in 2000–2010, but the number of grids with high values decreased in 2010–2020. The NLI has a higher impact coefficient in the high-value range of 2000–2010 compared to 2010–2020. However, GDP and POP have the smallest coefficients, implying that they have the lowest explanatory validity compared to other impact factors. The findings have significant implications for understanding the relationship and evolutionary processes between land use transition and ecosystem services.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

XS: conceptualization, methodology, software, supervision, validation, and writing–original draft. QN: funding acquisition, project administration, validation, and writing–original draft. ZL: software, supervision, validation, visualization, and writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

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