

Article

Big Geodata Technology: Carbon Supply–Demand Balance Analysis of Ecological Service Systems

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Abstract

Amid intensifying global climate change and accelerating urbanization, maintaining a balance between carbon emission reduction has become essential for achieving sustainable development. This research investigates the spatiotemporal evolution and driving mechanisms of carbon sequestration services in the ecological development zone of northern Guangdong, China. By integrating Big Geodata technology with the InVEST model, the study quantitatively evaluates both the supply and demand dimensions of carbon sequestration services using land-use, nighttime light, and socioeconomic data. Carbon storage capacities were estimated for different land-use types (including cropland, forest, grassland, water body, built-up land, and undeveloped land), while carbon emissions were spatially distributed based on nighttime light intensity, providing a holistic perspective on the regional carbon budget. The findings indicate significant spatial heterogeneity: the western region exhibits an average carbon sequestration capacity approximately 20% higher than the eastern region, due to extensive forest and grassland coverage, whereas urban areas exhibit higher carbon demand coupled with insufficient supply. Through an analysis of land-use transfer matrices and contribution assessment, land-use transformations, particularly the conversion of ecological land to urban built-up areas, were quantitatively identified as the primary factor disrupting the regional carbon balance. This study proposes actionable territorial spatial planning strategies, such as prioritizing ecological conservation in high-carbon-supply areas and promoting low-carbon urban renewal in high-demand zones, directly derived from the spatial mismatch patterns revealed by the InVEST model outputs. These insights contribute significantly to regional sustainable development practices and global climate governance.

Keywords: InVEST model; land use data; nighttime light intensity; socioeconomic statistics

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1. Introduction

1.1. Research Background

In the context of rapid globalization and urbanization, the construction of an ecological civilization has become a cornerstone of national prosperity and long-term development [1]. The evolution of international climate governance, from the Kyoto Protocol [2] to the Paris Agreement [3] and the European Green Deal [4], has established a global framework for low-carbon transition. Within this context, China has committed to its “dual carbon” goals. As a leading economic powerhouse and a major energy consumer in the nation, Guangdong Province faces the distinctive challenge of maintaining robust growth while achieving deep

emission reductions, underscoring the critical importance of exploring localized pathways to carbon balance. China's "dual carbon" goals—peaking carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060—not only mark a profound transformation of the national development strategy toward green and low-carbon pathways but also pose new requirements and challenges for urban development. The Outline of the 14th Five-Year Plan and Long-Range Objectives Through 2035 further refines the pathway for green development and provides targeted guidance for advancing ecological civilization. However, the deepening of industrialization and urbanization has intensified ecological and environmental problems such as biodiversity loss and ecosystem degradation, which have become serious constraints on sustainable development. Confronted with these global challenges, the concept of sustainable development has gained worldwide recognition, and the construction of ecological civilization has emerged as a key solution [5]. As an important carrier of ecological civilization construction, territorial spatial optimization plays a crucial role in coordinating development and protection, thereby fostering harmony between humans and nature.

Land-use and land cover (LULC) are key drivers of the carbon supply–demand balance, directly influencing ecosystem carbon fluxes [6]. Terrestrial ecosystems act as significant global carbon sinks, absorbing approximately 20 billion [7] tons of carbon dioxide produced by human activities each year, with forests and wetlands playing dominant and critical supplementary roles, respectively. At the global scale, climate change and intensive human activities have been widely documented to drive significant mismatches between the supply of and demand for ecosystem services, including carbon sequestration [8]. However, land-use changes have increasingly disrupted carbon budgets, making them a core driver of climate change. Urbanization and agricultural expansion have disrupted surface cover and soil structure, weakening soils' capacity to sequester carbon. Quantitative studies in rapidly urbanizing regions of China suggest that urban expansion is often the predominant factor, accounting for over 65% of carbon stock loss due to land-use change [9], while agricultural expansion and intensification contribute approximately 20–25% [10]. Advanced analytical methods, such as explainable machine learning, are increasingly being applied to enhance the interpretability of complex urban environmental impacts, including those on the carbon cycle [11]. Additionally, the expansion of droughts and land degradation has exacerbated carbon release, with degraded lands worldwide emitting an estimated 4.4 billion tons of CO₂ annually [12]. Against this backdrop, optimizing territorial spatial structures based on the relationship between carbon emission reduction has become a key pathway for achieving sustainable, low-carbon development [13]. However, research on carbon balance in regions like northern Guangdong faces specific practical bottlenecks. Chief among these is the lack of fine-grained, spatially explicit data on carbon emissions at the township or county scale, as official energy consumption statistics are often aggregated at the prefectural or higher level. Additionally, while models like InVEST are valuable for estimating carbon stocks, their accuracy depends heavily on localized carbon density parameters, which are difficult and costly to obtain through comprehensive field surveys across large and topographically complex areas. Guangdong Province, characterized by a dense population, resource constraints, and high environmental pressure, has undergone profound ecological and socioeconomic changes during urbanization, resulting in prominent human–land conflicts. To address these specific data and resolution limitations, this study integrates nighttime light data as a spatially continuous proxy for human activity intensity. This approach allows for the downscaling of regional carbon emission totals and provides a high-resolution, cost-effective complement to traditional data sources, thereby enabling a more detailed analysis of the carbon supply–demand mismatch. There is thus an urgent need to enhance the matching of carbon service supply and demand through

spatial optimization to achieve sustainable development in ecological development zones. In the Chinese context, recent research employing spatial analysis to quantify and map the supply–demand mismatch of carbon sequestration services has provided a methodological foundation and confirmed the urgency of this issue [14]. This study focuses on the ecological development zone in northern Guangdong as a case study to explore pathways for optimizing territorial space based on carbon emission reduction relationships. The findings aim to provide scientific references for advancing regional ecological civilization construction and territorial spatial optimization in similar regions nationwide, as well as to contribute to global climate governance and regional sustainable development.

This study integrates theories of carbon emission reduction to analyze the interactive relationships between carbon services and social systems from a combined supply–demand perspective. This approach helps reveal the complex interconnections among human activities, land use, and the carbon cycle, offering new perspectives and methodologies for carbon service research and territorial spatial optimization. Furthermore, the study’s findings provide scientific evidence for understanding the interaction mechanisms between social and ecological systems, thereby enriching the theoretical framework of ecological civilization construction. Given the growing imbalance between carbon emission reduction, optimizing spatial development patterns in ecological development zones and advancing ecological civilization construction in an orderly manner have become urgent tasks of the current era. The 14th Five-Year Plan for the Protection and Development of Natural Resources in Guangdong Province emphasizes the high-level protection and efficient utilization of natural resources. Guided by the matching of carbon emission reduction, this study proposes strategies for optimizing territorial space to improve the regional ecological environment, safeguard ecological security, and promote sustainable economic and social development. These efforts aim to provide a scientific foundation and practical guidance for governmental decision-making.

1.2. Advances in Research: Domestic (China) and Global Perspectives

Early Chinese studies primarily focused on assessing the carbon sequestration capacity of wetland ecosystems. For instance, Song Changchun highlighted the unique role of wetlands in the carbon cycle and emphasized the significance of wetland restoration in enhancing carbon sink functions [15]. As research advanced, the carbon sequestration services of forests, grasslands, and other ecosystems gradually received increased attention. Liu Weiwei et al. reviewed the carbon storage and sequestration capacity of forest ecosystems across different climatic zones and geographical regions, examined the effects of land-use changes on forest carbon sequestration, and discussed the sources of uncertainty in estimating forest carbon sequestration [16]. In recent years, the growing application of ecosystem service supply–demand theory has shifted research toward understanding the balance between carbon sequestration service supply and demand. Xu Qian et al. constructed an assessment framework for carbon sequestration service supply and demand, analyzed spatial disparities across Guangdong Province, and provided a scientific basis for policy formulation [17]. Zhao Yiqi et al. investigated the coupled dynamics among land-use and land cover changes, carbon emissions, and ecosystem service values at the oasis–agricultural scale [18]. Liu Jinyan et al. proposed an integrated “assessment-construction-optimization” method for island cities, establishing an innovative paradigm for the deep integration of ecosystem services (ES) and urban spatial planning [19]. From the early focus on wetland carbon sequestration capacity, through the mid-term expansion toward collaborative research on multi-ecosystem studies, to the recent emphasis on the balance between carbon sequestration service supply and demand and its integration with spatial planning, research on ecosystem carbon sequestration services has evolved substantially. This continuous

deepening and broadening of research have provided a robust scientific basis and practical guidance for addressing global climate change and advancing sustainable development.

Territorial space forms the foundation for regional production, living, and ecological functions, and optimizing its development pattern is crucial for promoting regional sustainable development [20]. In the international research arena, scholars have established an early and relatively comprehensive understanding of regional territorial space development [21]. Guttenberg defined key spatial concepts and analyzed challenges in spatial planning [22], while Koomen explored the relationship between land-use changes and spatial policy implementation [23]. The Chinese academic community has mainly focused on optimizing territorial space patterns from the perspective of production–living–ecological spaces. Theoretical studies have expanded the connotation and framework of this concept, while empirical research has examined the spatiotemporal evolution of territorial space patterns and the spatial differentiation of development and utilization efficiency. At the same time, models for evaluating carrying capacity and coordinating territorial space development at different spatial scales have been established. At the methodological level, traditional mathematical programming models have been combined with emerging algorithms, resulting in diversified spatial optimization and allocation methods [24,25]. However, existing research on territorial space optimization based on ES still exhibits a major limitation—most studies emphasize the supply side while neglecting the demand side. In the context of carbon sequestration services, this imbalance has led to mismatches between carbon emission reduction [26,27]. Such imbalances not only waste resources but may also trigger a range of ecological and environmental issues, causing delays and inaccuracies in territorial space optimization. Therefore, there is an urgent need to strengthen research that integrates both supply and demand perspectives to achieve efficient and sustainable territorial development.

This study focuses specifically on the supply–demand relationships of carbon sequestration services within ecological development zones. Guided by the goal of achieving a dynamic balance between carbon sequestration service supply and demand, it seeks to optimize and regulate territorial space through a scientific and systematic approach. Considering the distinct ecological background, socioeconomic characteristics, and complex human–land conflicts typical of these zones, the northern ecological development zone of Guangdong Province was selected as the research area. This region possesses diverse ecological environments and abundant forest resources, yet also faces ecological pressures from human activities—especially rapid urbanization—making it an ideal area for studying carbon sequestration service dynamics. Using the spatiotemporal evolution of ecosystem service supply and demand under urbanization as a starting point, this study investigates the spatiotemporal dynamics of ecosystem carbon sequestration services at the municipal scale across urban–rural gradients. Advanced data analysis techniques and models are employed to quantitatively measure the supply and demand for carbon sequestration services across regions and time periods, revealing the underlying spatiotemporal mechanisms of their evolution.

In addition, this study analyzes the driving mechanisms behind the evolution of carbon sequestration service supply and demand, considering both natural factors (e.g., climate, soil) and human factors (e.g., population growth, economic development, policy guidance). This study aims to develop a set of models to optimize and regulate territorial space in the ecological development zone of northern Guangdong, China (encompassing Qingyuan, Shaoguan, Heyuan, and Meizhou), based on supply-and-demand relationships. This proposed model will fully consider the balance between the supply and demand of carbon sequestration services, enabling the rational planning of land-use types and

spatial layouts. Ultimately, it seeks to achieve the coordinated development of ecological, economic, and social systems. The data sources used in this study are shown in Table 1.

Table 1. Summary of data sources and descriptions.

Data Name	Data Description	Data Source
Land-Use Data	Used for calculating the supply and demand of multiple ecosystem services and simulating future land-use changes.	Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn/DOI ; accessed on 16 November 2025)
Nighttime Light Data	Primarily used to calculate carbon sequestration service demand in the northern Guangdong development region.	Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn/DOI ; accessed on 16 November 2025)

2. Materials and Methods

2.1. Geographic and Socioeconomic Characteristics of the Study Region

This study focuses on the northern ecological development zone of Guangdong Province, China, as a representative research area. The zone encompasses four prefecture-level cities—Qingyuan, Shaoguan, Heyuan, and Meizhou (Figure 1). Located in the mountainous region of northern Guangdong, it functions as a crucial ecological security barrier and an important water conservation area for the province. According to 2024 statistical data, the zone covers 68,900 square kilometers, accounting for 38% of Guangdong’s total land area, and has a population of 14.02 million, representing 10.9% of the province’s total population [28]. The region lies within a subtropical monsoon climate zone, characterized by an average annual temperature of 21–23 °C and annual precipitation of 1300–2500 mm. Extensive and contiguous areas of ecological land are distributed throughout the region, with high ecological connectivity and limited human disturbance, providing stable and high-quality habitats for diverse wildlife species.

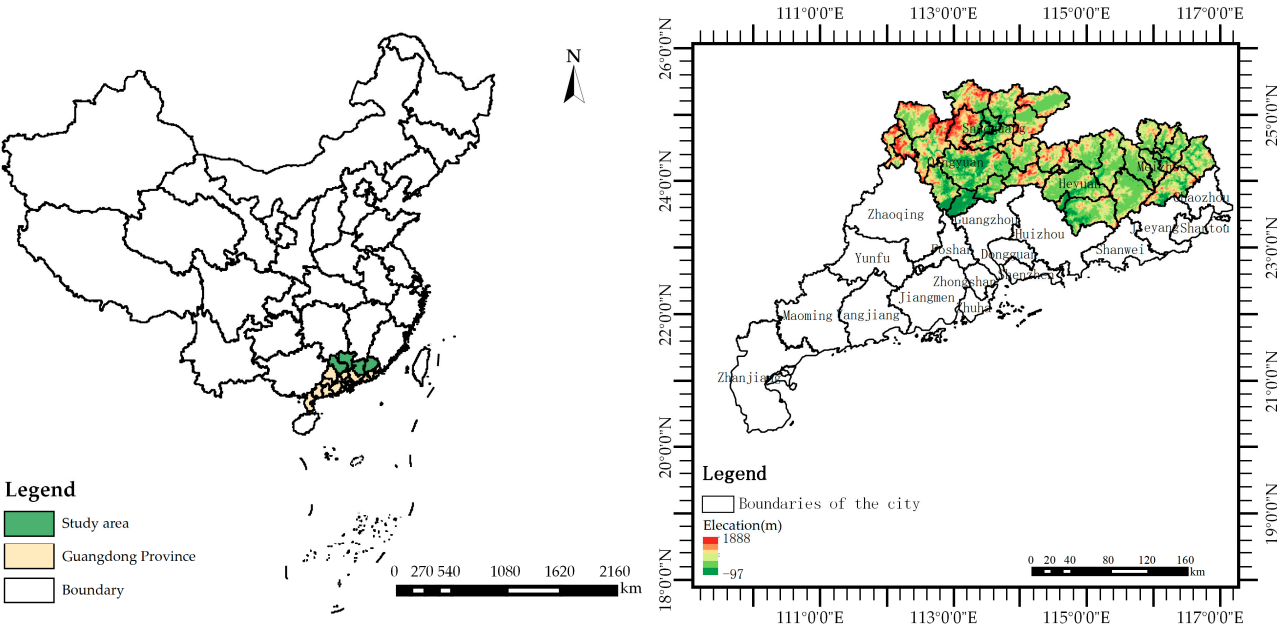


Figure 1. Geographic scope of the research area.

The northern ecological development zone of Guangdong is renowned for its abundant forest resources, with forest coverage exceeding 70%. It serves as a vital carbon sink

area not only for Guangdong Province but also for China as a whole. However, rapid urbanization and sustained economic growth have imposed multiple pressures on the region, including land-use changes, reductions in ecological land, and rising carbon emissions. A pronounced conflict exists between ecological protection and economic development among the four cities—Qingyuan, Shaoguan, Heyuan, and Meizhou. Local governments face the challenge of balancing fiscal revenues and expenditures while fostering economic growth and utilizing the region's natural resource advantages.

Nevertheless, the extensive mode of economic growth has led to severe ecological degradation. The continued encroachment of urban and industrial development into ecological lands has impaired ecosystem service functions, resulting in a noticeable decline in carbon sequestration capacity. Concurrently, carbon emissions have continued to increase, exacerbating regional climate pressures. This conflict between ecological preservation and economic development underscores the urgent need for green transformation and sustainable development within the Northern Ecological Development Zone of Guangdong. The distribution of land area and population is shown in Table 2.

Table 2. Summary characteristics of the study area.

Region	Land Area (10,000 km ²)	Population (10,000 Persons)	Carbon Emission (t)
Qingyuan City	1.90	398.90	46,088,254.10
Shaoguan City	1.84	334.91	40,435,735.31
Heyuan City	1.57	283.70	19,509,525.97
Meizhou City	1.58	384.16	16,071,644.74

Data Source: Guangdong Provincial Statistical Yearbook [28].

Significant differences exist in the carbon emission reduction characteristics among the different prefecture-level cities within the study area. Qingyuan City and Shaoguan City, as the major cities in the study region, feature concentrated construction land and frequent industrial activities, leading to relatively high carbon emissions. In contrast, forest-covered areas function as strong carbon sinks, playing a crucial role in maintaining regional carbon balance. Heyuan and Meizhou, with their predominantly ecological landscapes, possess abundant carbon sequestration resources. However, some regions are experiencing imbalances between carbon emission reduction during urbanization, characterized by the reduction in ecological land and the increase in carbon emissions.

The ecological quality of the northern Guangdong ecological development zone not only directly influences the environmental security of surrounding regions, such as the Pearl River Delta, but also has a significant impact on the environmental quality of the Guangdong–Hong Kong–Macao Greater Bay Area. Owing to the mismatch between cities that provide ecosystem services and those that benefit from them, as well as the public nature of ecological environment, the service-providing cities often fail to receive adequate ecological compensation. Consequently, the value of ecosystem services and ecological capital remains underrecognized. Therefore, it is both crucial and urgent to conduct an in-depth analysis of the carbon service supply–demand relationship in the northern Guangdong ecological development zone. Guided by the principles of ecological priority and green development, this study aims to promote high-quality development, ensure high-level ecological protection, and rationally optimize the spatial layout of territorial space.

2.2. Approaches to Quantifying the Supply and Demand of Carbon Sequestration Services

Since the Industrial Revolution, human dependence on fossil fuels and the rapid pace of urbanization have continuously increased greenhouse gas emissions, leading to global warming and frequent extreme rainfall events that seriously threaten sustainable

development [29,30]. Terrestrial ecosystems such as forests, grasslands, and wetlands store substantial amounts of carbon dioxide through vegetation and soil, exerting a significant influence on climate change driven by atmospheric carbon concentrations. However, when these ecosystems are disturbed by factors such as wildfires, pests, diseases, or land-use changes, they release considerable amounts of carbon dioxide into the atmosphere, disrupting the carbon balance. Falahatkar et al. argue that land use and land cover are among the most critical factors influencing global climate change and altering carbon cycles [31,32]. Land-use and land-cover changes are directly affected by urbanization. While most developed countries have entered a post-urbanization stage, some developing countries remain in the early stages of urbanization, characterized by low efficiency and high energy consumption [33]. According to data from the International Energy Agency (IEA), urbanization accounts for over 70% of global carbon emissions. Therefore, urbanization can be considered as a significant factor contributing to the continuous increase in greenhouse gas emissions [34].

This study uses the Carbon Storage and Sequestration module in InVEST 3.9.0 (Stanford, CA, USA) to assess the carbon sequestration service supply in the northern Guangdong ecological zone. The model estimates carbon storage by considering four main carbon pools: aboveground biomass, belowground biomass, soil, and dead organic matter. Aboveground biomass refers to the total carbon stored in all living plant material above the soil surface, including bark, trunks, branches, and leaves, but it does not include volatile carbon stored in grasslands and short-cycle crops. Belowground biomass is more difficult to estimate because it is influenced by complex factors such as soil structure and moisture. It primarily refers to the carbon stored in plant root systems. The soil carbon pool, one of the largest carbon reservoirs in ecosystems, stores substantial organic matter and is typically defined as the organic carbon in mineral soils. Dead organic matter includes litter, fallen trees, standing dead trees, and similar material. Harvested wood products (HWPs), such as building materials or furniture, also represent a fifth carbon pool. However, this pool is not included in the model because it represents carbon sequestered in products that do not re-enter the atmosphere.

The carbon sequestration service supply in the ecological development zone of northern Guangdong was calculated using the carbon storage module of the InVEST model. This module determines ecosystem carbon storage by multiplying the average carbon density of four carbon pools (aboveground, belowground, soil, and dead organic matter) for each land-use type by its corresponding area. The calculation formula is as follows:

$$C_{\text{total}} = C_{\text{above}} + C_{\text{below}} + C_{\text{soil}} + C_{\text{dead}} \quad (1)$$

where

C_{total} represents total carbon storage (t/ha);

C_{above} denotes aboveground carbon storage;

C_{below} denotes belowground carbon storage;

C_{soil} indicates soil carbon storage;

and C_{dead} refers to dead organic matter carbon storage.

Measured data, survey data, and published literature were the main sources of carbon density data. Due to the difficulty of obtaining measured and survey data, this study collected relatively accurate carbon density data by reviewing a substantial number of studies conducted in areas adjacent to the northern Guangdong ecological zone [35–37]. A precipitation–carbon-density relationship model and the biomass factor conversion method were then employed to refine these data, resulting in a table of carbon densities for different land-use types in the region (Table 3).

Table 3. Carbon stock density in the ecological region of northern Guangdong.

Land Cover Type	Lucode	Aboveground Carbon Stock (t/ha)	Belowground Carbon Stock (t/ha)	Soil Carbon Stock (t/ha)	Dead Organic Matter Carbon Stock (t/ha)
Cropland	10	16.44	4.11	10.84	0
Forest	20	19.99	5.00	19.57	0
Grassland	30	2.12	9.55	9.99	0
Waterbody	60	0	0	0	0
Undeveloped Land	70	18.32	1.83	0.84	0
Built-up Land	80	1.14	0.11	17.97	0

Vegetation biomass is the primary determinant of carbon density [38,39]. Based on vegetation type maps of China from the 1980s and 2000, Chuai Xiaowei et al. found that if land-use types had remained unchanged, there would have been no significant alterations in vegetation types across China during that period [40]. Although land management practices and climatic conditions may have changed, these variations were insufficient to significantly alter vegetation and soil carbon densities under different land-use patterns [41]. Therefore, this study posits that the carbon density of a specific land-use type remains constant over time and changes only when the land is converted to another type.

Numerous studies have shown that nighttime light data can effectively reflect the intensity of human activities and exhibit a significant linear relationship with regional carbon emissions [42–45]. Accordingly, this study allocates carbon emission data in the northern Guangdong ecological zone based on the ratio of the nighttime light index for each grid to the total nighttime light index, thereby estimating the total demand for carbon sequestration services at the township scale. The calculation Formula (2) is as follows:

$$C_{\text{demand}} = \sum \frac{NL_i}{NL_{\text{sum}}} \times C_{\text{emission}} \quad (2)$$

where

C_{demand} represents the demand for carbon sequestration services;

NL_i denotes the nighttime light index of grid cell i ;

NL_{sum} indicates the total nighttime light index;

C_{emission} signifies the total carbon emissions.

This study applied the Carbon Storage and Sequestration module of the InVEST model to systematically evaluate the supply of carbon sequestration services in the ecological development zone of northern Guangdong. By quantifying aboveground biomass, belowground biomass, soil carbon pools, and dead organic matter carbon pools, the region's total carbon storage was accurately calculated. Meanwhile, nighttime light data were used as a proxy for human activity intensity to allocate regional carbon emissions and estimate the corresponding demand for carbon sequestration services. This integrated approach not only improves understanding of the regional carbon budget but also provides a scientific basis for formulating effective carbon management strategies and optimizing territorial spatial planning. It holds significant relevance for promoting coordinated ecological, economic, and social development.

2.3. Big Geodata Technology and ArcGIS-Based Visualization Analysis Methods

In studying the supply–demand relationship for carbon sequestration services in the northern Guangdong ecological development zone, the combined use of Big Geodata technology (geographic big data information technology) and ArcGIS 10.8 software (GeoScene Information Technology Co., Ltd., Beijing, China) played a key role. This section details how these advanced tools were used for data visualization and spatial analysis to reveal

the spatiotemporal evolution and driving mechanisms of carbon sequestration supply and demand.

This study integrated multi-source datasets, including land-use data, nighttime light data, socioeconomic statistics, and measured and surveyed carbon density data. The land-use data, obtained from the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences, provided detailed information on the spatial distribution of land-use types across different years. Nighttime light data from the same source reflected the intensity and spatial patterns of human activities. Socioeconomic data encompassed key indicators such as population and GDP. The raw data underwent preprocessing steps such as data cleaning, format conversion, and coordinate unification. Land-use data were reclassified to match research needs and to ensure accuracy and consistency across various land-use types. Nighttime light data necessitated standardized processing of brightness values to facilitate subsequent analysis and comparison.

1. Spatial Data Loading and Visualization

The preprocessed spatial datasets—such as land-use and nighttime light data—were loaded into ArcGIS. Display styles for each layer (e.g., color, symbol, transparency, etc.) were customized as needed. For instance, different land-use types were visualized using distinct colors, while the intensity of human activities was represented through brightness gradient maps from the nighttime light data.

2. Spatial Analysis and Modeling

The specific steps for calculating the supply of carbon sink services are as follows:

Defining carbon pools: Four basic carbon pools were considered—aboveground biomass, belowground biomass, soil, and dead organic matter.

Assigning carbon density values: Based on the literature review and measured data, carbon density values were assigned to different land-use types.

Calculating carbon storage: ArcGIS's Raster Calculator or Model Builder was used to automate the calculation of carbon sequestration service supply.

Calculation of Carbon Sequestration Service Demand: Based on nighttime light data and total carbon emission data, the carbon sequestration service demand for each region was computed using Formula (2).

Specific steps include the following:

Calculating nighttime light index: The Raster Statistics function in ArcGIS was used to calculate the nighttime light index for each grid cell.

Allocating demand: The total carbon emissions were distributed among the grid cells according to the ratio of each cell's nighttime light index to the total nighttime light index.

3. Visualization and Interpretation of Results

ArcGIS's powerful mapping and visualization tools were used to generate a series of thematic maps representing carbon sequestration service supply and demand. These maps include spatial distribution maps of supply, spatial distribution maps of demand, and supply–demand matching index maps. Different numerical ranges were represented using distinct colors and symbols, making the results more intuitive and understandable. By combining these thematic maps with relevant statistical data, an in-depth analysis of the spatiotemporal evolution of the supply–demand relationship for carbon sequestration services was conducted, along with an exploration of the driving mechanisms. Both natural factors (e.g., climate, soil) and human factors (e.g., population growth, economic development, policy orientation) were examined for their influence on the supply–demand dynamics.

These visualization results offer robust support for a deeper understanding of the supply–demand relationship of carbon sequestration services in the northern Guangdong ecological development zone.

By leveraging Big Geodata technology and ArcGIS, large volumes of spatial data can be efficiently processed and analyzed, allowing the complex patterns and driving mechanisms of the carbon supply–demand relationship to be revealed through intuitive visual representations. This approach provides a solid scientific basis and practical guidance for the optimization and regulation of territorial spatial planning.

3. Results and Discussions

3.1. Supply–Demand Characteristics of Carbon Sequestration Services

The land-use map (Figure 2) illustrates the distribution of different land-use types within the study area, including farmland, forest, grassland, wetland, water bodies, unused land, and built-up land. As shown, forests and grasslands dominate the land-use pattern in northern Guangdong. These two types together account for over 81.12% of the total area, forming the foundation of regional carbon sequestration. Forests, as the most significant terrestrial carbon sinks, possess the highest carbon stock density, reaching 44.56 t/ha (sum of aboveground, belowground, and soil carbon pools), which is approximately 2–3 times that of cropland or grassland. In particular, the extensive contiguous forestlands in the western part, corresponding to the high-value zones in the carbon supply distribution, exhibit the highest sequestration potential. This is quantitatively confirmed by the results in Table 4, where forest-rich counties like Xinfeng and Fengshun recorded carbon supplies exceeding 475 t/ha.

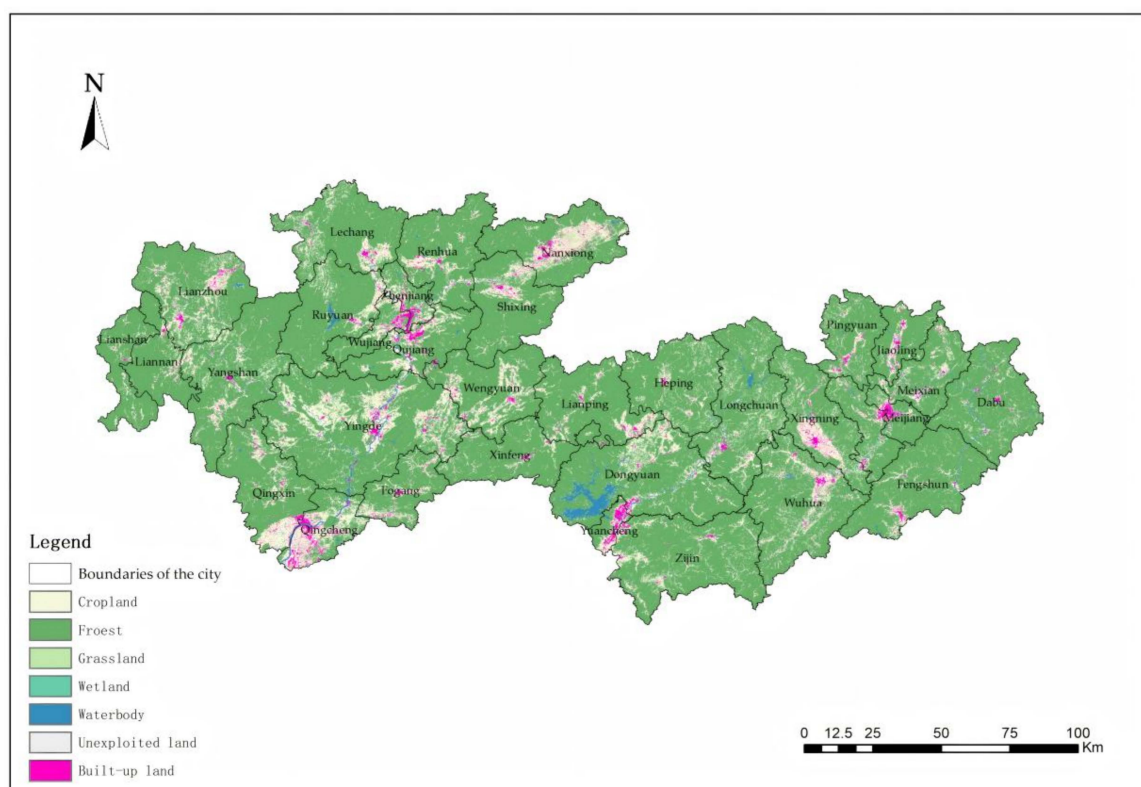


Figure 2. Land-use map of the Guangdong ecological zone in 2024.

Although grasslands have slightly lower carbon sequestration capacity than forests, they remain vital for regional carbon balance. Through vegetation growth and soil organic matter accumulation, grassland ecosystems continuously absorb and store atmospheric carbon dioxide. While total carbon storage in grasslands is lower than in forests, grasslands provide unique benefits, including biodiversity protection, soil erosion prevention, and indirect support for regional ecosystem stability, thereby sustaining regional carbon sequestration.

Table 4. Summary of high- and low-supply units for carbon sequestration services in the ecological zone of northern Guangdong in 2024.

High Supply Scenario (2024)		Low Supply Scenario (2024)	
County	Carbon Supply (t/ha)	County	Carbon Supply (t/ha)
Xinfeng County, Shaoguan	481.32	Wujiang District, Shaoguan	440.17
Fengshun County, Meizhou	476.18	Dongyuan County, Heyuan	436.32
Heping County, Heyuan	475.18	Zhenjiang District, Shaoguan	419.19
Zijin County, Heyuan	474.98	Yuancheng District, Heyuan	386.79
Dabu County, Meizhou	472.54	Qingcheng District, Qingyuan	382.52

In contrast, built-up land serves as the primary source of carbon emissions, with its expansion having a significant positive correlation with total carbon emissions. Accelerated urbanization has transformed ecological lands in central urban areas and industrial regions into built-up areas, sharply increasing carbon emission intensity.

Figure 3 shows the spatial distribution of light brightness across the study area. Colors closer to red indicate higher brightness, suggesting more active economic and human activities; colors closer to blue indicate lower brightness, suggesting less activity. As an effective proxy for human activity intensity, nighttime light data clearly reveal the strong connection between high-brightness areas—typically urbanized and economically active—and total carbon emissions.

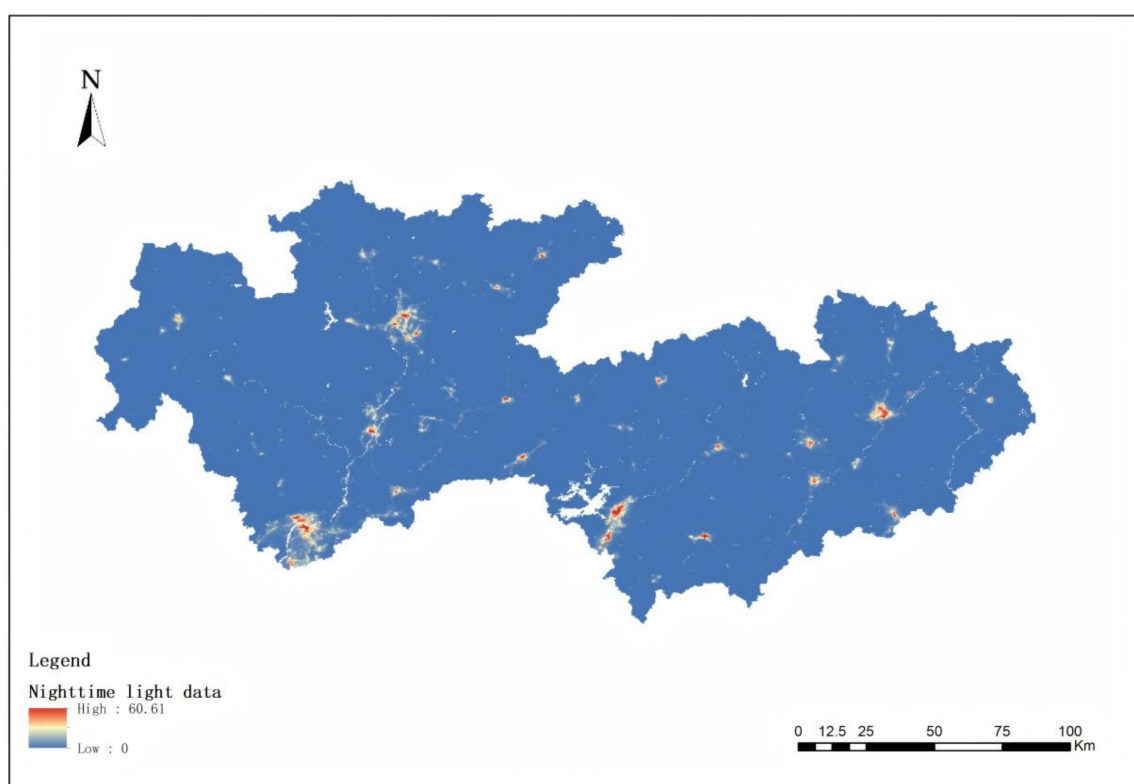
**Figure 3.** Nighttime light data map of the Guangdong ecological zone in 2024.

Figure 3 indicates that areas with higher light brightness are concentrated in locations such as the Yuancheng District of Heyuan City and the Qingcheng District of Qingyuan City. These regions, characterized by dense populations and frequent industrial activity, exhibit high nighttime light intensity and significantly higher carbon emissions than other regions.

Nighttime light data holds unique advantages in reflecting the intensity and spatial distribution of human activities. By processing and analyzing this data in ArcGIS, spatial disparities in human activity within the study area can be clearly observed. High-brightness

areas generally correspond to regions with higher urbanization levels and more intense economic activities, often serving as hotspots for carbon emissions. Further analysis demonstrates a significant correlation between nighttime light intensity and land-use types. Areas dominated by built-up land typically show high nighttime light brightness and elevated carbon emission intensity, whereas regions covered by ecological land, such as forests and grasslands, show low nighttime brightness and low carbon emissions. This correlation confirms the effectiveness of nighttime light data as a proxy for human activities and provides crucial data support and analytical methods for subsequent research.

Figure 4 illustrates the spatial distribution of total carbon emissions across various sub-regions within the study area. Darker colors indicate higher carbon emissions. The central region displays significantly higher carbon emissions than the surrounding areas, suggesting it may be an industrial hub or a high-energy-consuming area.

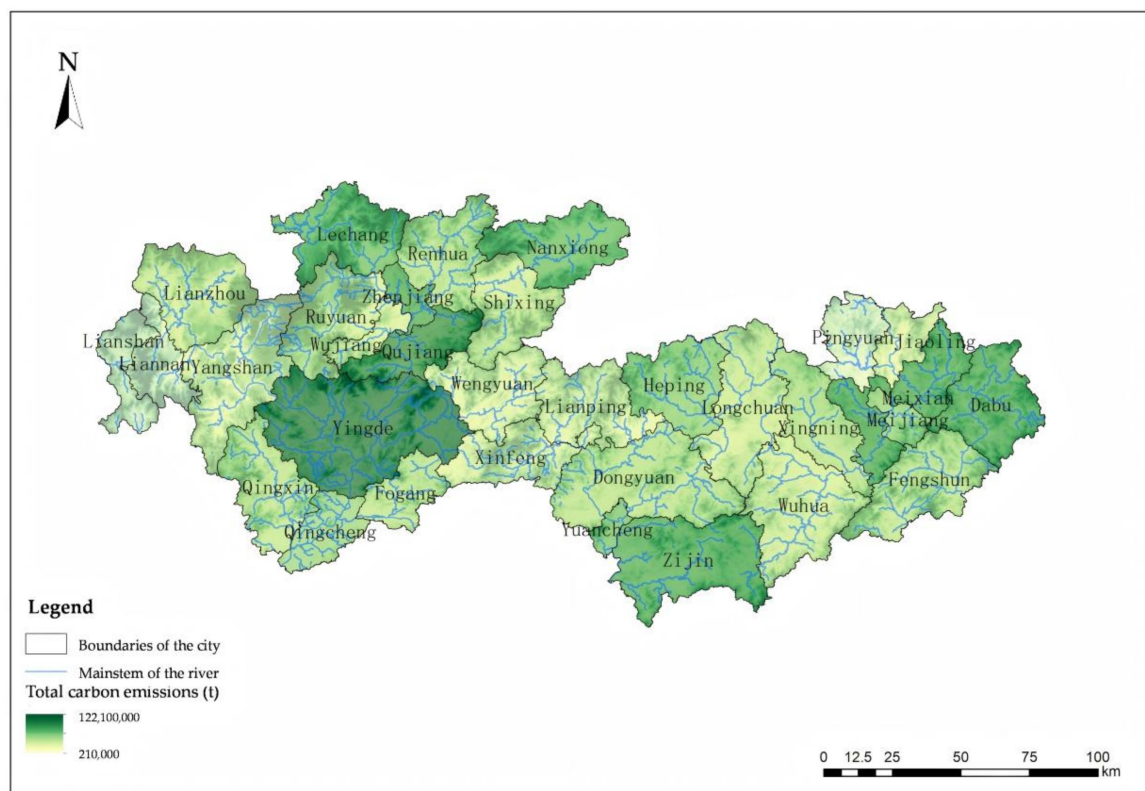


Figure 4. Spatial distribution map of total carbon emissions in the ecological zone of northern Guangdong in 2024.

Figure 4 highlights variations in the spatial distribution of total carbon emissions across administrative units using different shades of green. The results reveal significant spatial heterogeneity in emissions. Central and eastern regions, such as Yingde, appear in dark green, indicating high-emission zones likely driven by industrial agglomeration, dense populations, and substantial energy consumption. In contrast, peripheral regions like Lianzhou display lighter shades, reflecting lower emissions, likely due to their predominance of agricultural or ecological land and limited industrial activity.

3.2. Carbon Sequestration Service Supply

As shown in Table 4, the total carbon sequestration service supply in the Ecological Zone of Northern Guangdong in 2024 reached 31.75×10^8 tons. The unit with the highest per-unit-area carbon sequestration service supply was Xinfeng County, Shaoguan City, at 481.32 tons/ha. This high supply is attributed to extensive vegetation coverage and

a substantial proportion of forestland. Other administrative units with relatively high per-unit-area supply include Fengshun County (Meizhou City), Heping County (Heyuan City), and Zijin County (Heyuan City), characterized by low urbanization and abundant forest, grassland, or cultivated land.

Conversely, the lowest per-unit-area supply was observed in Qingcheng District, Qingyuan City, at 382.52 tons/ha. This district is highly urbanized, with built-up land as the dominant land-use type and relatively low vegetation coverage, resulting in a lower per-unit-area carbon sequestration service supply. Other administrative units with low per-unit-area supply include Yuancheng District (Heyuan City), Zhenjiang District (Shaoguan City), Dongyuan County (Heyuan City), and Wujiang District (Shaoguan City).

From a spatiotemporal distribution perspective (Figure 5), the supply of carbon sequestration services exhibits pronounced regional disparities. The western region, with extensive forestland and grassland, exhibits a relatively high carbon sequestration supply, forming contiguous high-value zones. In contrast, the southern region has a patchy distribution, though specific counties such as Fengshun County (Meizhou City) and Heping County (Heyuan City) also show relatively high supply levels. Urbanization has caused some contraction of high-value areas, particularly around urban peripheries and in the eastern region, reflecting the direct impact of ecological land reduction on carbon sink capacity. By comparison, the southern region shows a predominantly patchy distribution of carbon sequestration services, with certain counties and districts, such as Heping County and Zijin County in Heyuan City, showing relatively high supply values. This is attributed to effective local ecological conservation and forest coverage, although the overall supply remains lower than in the western region.

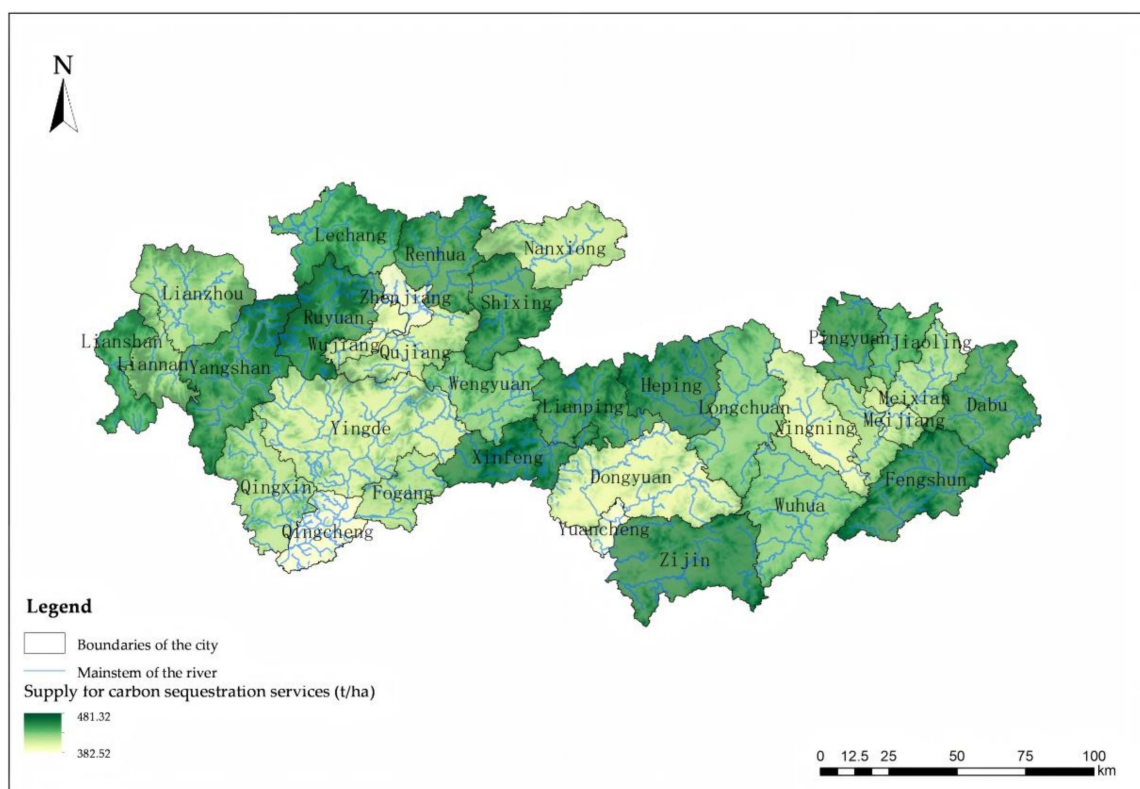


Figure 5. Spatial distribution map of carbon sequestration service supply in the ecological zone of northern Guangdong in 2024.

Comparing the spatial distribution of supply and demand reveals a significant mismatch within the study area. The western region exhibits ample carbon sequestration

service supply but relatively low demand, whereas urban areas and the eastern region show high demand but insufficient supply. This imbalance highlights challenges for regional carbon balance and sustainable development.

3.3. Carbon Sequestration Service Demand

As shown in Table 5, the total carbon sequestration service demand in the Guangdong Ecological Zone in 2024 reached 62.48×10^5 tons. The unit with the highest per-unit-area demand was Yuancheng District, Heyuan City, at 9.95 tons/ha, primarily due to its high population density and intense economic activities. Other areas with relatively high demand included Yingde City (Qingyuan), Zhenjiang District (Shaoguan), Qujiang District (Shaoguan), and Qingcheng District (Qingyuan).

Table 5. Summary of high- and low-demand units for carbon sequestration services in the Guangdong ecological zone (2024).

High Demand Scenario (2024)		Low Demand Scenario (2024)	
County	Carbon Supply (t/ha)	County	Carbon Supply (t/ha)
Xinfeng County, Shaoguan	481.32	Wujiang District, Shaoguan	440.17
Fengshun County, Meizhou	476.18	Dongyuan County, Heyuan	436.32
Heping County, Heyuan	475.18	Zhenjiang District, Shaoguan	419.19
Zijin County, Heyuan	474.98	Yuancheng District, Heyuan	386.79
Dabu County, Meizhou	472.54	Qingcheng District, Qingyuan	382.52

Nighttime light data, a reliable proxy for human activity intensity, confirm that urban and eastern regions exhibit significantly higher demand for carbon sequestration services, reflecting concentrated populations and intensive industrial activity. Conversely, areas dominated by ecological land, such as Yangshan County and Lianshan Zhuang and Yao Autonomous County (Qingyuan), show lower demand due to sparse populations and limited economic activities. These regions maintain relatively stable ecosystems and favorable carbon balance conditions.

The demand for carbon sequestration services is primarily concentrated in urban areas and along transportation corridors, where populations are dense and economic activities are frequent. As shown in Figure 5, regions such as Yuancheng District (Heyuan City), Yingde City (Qingyuan City), and Zhenjiang District (Shaoguan City) exhibit high per-unit-area demand, highlighting a strong need for carbon sink services. Nighttime light data corroborate these patterns. Areas with high brightness typically coincide with regions of higher carbon sequestration service demand, confirming that economically active regions are major contributors to carbon emissions and consequently exhibit greater demand for carbon sequestration services.

From a spatiotemporal perspective (Figure 6), the supply of carbon sequestration services displays significant spatial heterogeneity. Some counties in the western region, such as Yingde and Lianzhou, exhibit relatively high levels of supply due to extensive ecological land, forests, and grasslands. These high-value areas form a contiguous high-supply belt. In contrast, the southern region primarily features a patchy distribution, with some counties showing elevated supply values, benefiting from robust ecological conservation and forest coverage.

However, due to urbanization, some high-value patches are at risk of shrinkage, reflecting the trend of increasing construction land and decreasing ecological land. As shown in Figure 6, the supply of carbon sequestration services in urban areas and certain counties in the eastern part of the northern Guangdong ecological development zone is relatively low. This reduction is linked to urban expansion, which has encroached on ecological land. Overall, the spatial distribution of carbon sequestration service supply is shaped by

land-use changes, ecological restoration measures, and urbanization, resulting in significant regional disparities and polarization.

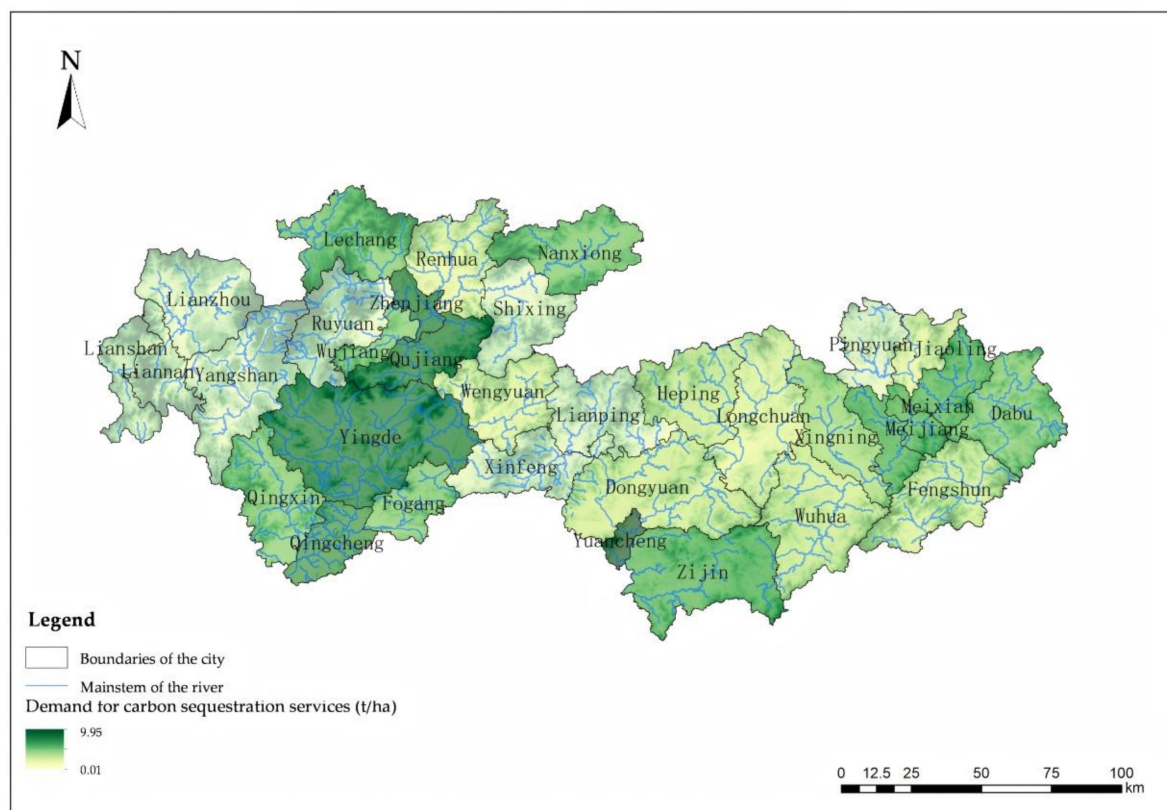


Figure 6. Spatial distribution map of carbon sequestration service demand in the Guangdong ecological zone in 2024.

A comparison of the spatial distribution maps of carbon sequestration service supply and demand reveals a notable mismatch within the study area. The western region exhibits ample supply but relatively low demand, whereas urban areas and the eastern region exhibit high demand with insufficient supply. This supply–demand contradiction poses challenges for regional carbon balance and sustainable development. To address these issues, it is recommended to implement territorial space optimization and regulation strategy guided by the alignment of ecosystem service supply and demand. Rational planning of land-use types and spatial layouts can promote a better balance and coordinated development of carbon sequestration services. Simultaneously, strengthening ecological restoration and environmental protection measures will enhance overall carbon sequestration capacity, providing robust support for achieving sustainable development across the region.

4. Conclusions and Prospects

4.1. Conclusions

This study conducted an in-depth analysis of the supply–demand relationship of ecosystem services in the ecological development zone of northern Guangdong, with a particular focus on carbon sequestration services. Using remote sensing image processing platforms (ArcGIS) and the InVEST model, the study quantitatively assessed the supply and demand of carbon sequestration services in 2024 and examined their spatiotemporal characteristics and driving mechanisms.

1. Supply Characteristics of Carbon Sequestration Services: The supply of carbon sequestration services in the ecological development zone of northern Guangdong exhibited

significant spatial disparities. The western region, dominated by extensive forests and grasslands, demonstrated a high carbon sequestration capacity, forming contiguous high-value zones. In contrast, the southern region showed a more fragmented, patchy distribution, although several counties also displayed relatively high supply values. With the acceleration of urbanization, some high-value areas have contracted, particularly around urban peripheries and in the eastern region, where the supply of carbon sequestration services has significantly declined.

2. **Demand Characteristics of Carbon Sequestration Services:** Demand for carbon sequestration services was concentrated mainly in urban areas and along transportation corridors with dense populations and frequent economic activities. Nighttime light data, used as a proxy for human activity intensity, effectively reflected regional demand patterns. Urban and eastern areas, characterized by higher population densities and industrial activity, exhibited significantly higher demand for carbon sequestration services compared to other regions.
3. **Influencing Factors and Driving Mechanisms:** The study further examined the main factors influencing the supply–demand relationship of carbon sequestration services, including natural factors (such as elevation, slope, and vegetation cover) and socioeconomic factors (such as population size, GDP, and land-use change). Using the Geodetector model, the study quantified the explanatory power of each factor on the spatial distribution of the carbon sequestration service supply–demand matching index. The results indicated that land-use change and urbanization are the key factors shaping the supply–demand balance. As the extent of urban built-up land continues to increase, ecological land and cultivated lands have been reduced correspondingly, leading to a decline in their capacity to provide carbon sequestration services.
4. **Optimization and Regulation of Territorial Space:** Based on these findings, the study proposed optimization and regulation strategies for territorial space guided by the matching relationship between ecosystem service supply and demand. Specific regulatory strategies were proposed for both urban and rural areas to promote the coordinated development of ecosystem service supply and demand and improve residents' well-being.

4.2. Prospects

Although this study has yielded important insights into the supply–demand relationship and spatiotemporal evolution of carbon sequestration services in the ecological development zone of northern Guangdong, several aspects still warrant further refinement and expansion in future research.

1. **Enhancement of Data Precision and Timeliness:** The current research primarily relies on remote sensing imagery and socioeconomic statistical data, which have certain limitations in precision and timeliness. Future studies should incorporate higher-resolution remote sensing images and real-time monitoring data to improve the accuracy, timeliness, and reliability of ecosystem service supply–demand assessments.
2. **Multi-Scenario Simulation and Prediction:** Although this study simulated territorial space development under different development scenarios, future uncertainties—such as climate change and policy adjustments—may have profound impacts on the supply–demand relationship of ecosystem services. Therefore, future research should strengthen multi-scenario simulations and predictions to account for these potential changes and assess their impacts on the supply–demand balance of ecosystem services.
3. **Cross-Regional Collaboration and Policy Support:** Given the spatial spillover effects of ecosystem services, optimizing and regulating a single region in isolation often fails to

achieve optimal results. Future research should expand toward cross-regional collaborative optimization and regulation to explore mechanisms for matching ecosystem service supply and demand across regions. Meanwhile, stronger policy support plays a crucial role in promoting territorial space optimization and enhancing ecosystem services, highlighting the need for continued development and refinement of relevant governance policies.

4. **Public Participation and Educational Promotion:** Effective management and protection of ecosystem services require broad public participation and support. Future research should emphasize mechanisms that promote public awareness and conservation consciousness regarding the value of ecosystem services. Simultaneously, educational campaigns and related initiatives should be used to guide the public toward adopting green and low-carbon lifestyles, thereby jointly promoting the sustainable development of regional ecosystems.

In conclusion, this study provides a solid scientific basis and decision-making support for optimizing territorial space and managing ecosystem services in the ecological development zone of northern Guangdong and broader regions. Future research should continue to deepen and expand investigations in related fields to make greater contributions to the sustainable development of regional ecosystems.

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Abbreviations

The following abbreviations are used in this manuscript:

LULC	Land use and land cover
IEA	International Energy Agency
HWPs	Harvested wood products
GDP	Gross Domestic Product

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