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Original Research

Spatio-Temporal Disparity of Ecosystem Carbon Sequestration Capacity in the Region of Chengde, China

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Abstract

Enhancing the carbon sequestration capacity of ecosystems in key regions, such as Chengde City, is crucial for achieving China's long-term goal of carbon neutrality. This study innovatively applies a comprehensive evaluation model to quantitatively evaluate the spatio-temporal disparity and key factors influencing the ecosystem carbon sequestration capacity in Chengde City over two decades, aiming to provide a solid scientific foundation for local policy formulation and to explore effective strategies for enhancing regional carbon sequestration potential. Based on Land Use and Land Cover Change data from 2000 to 2020, the study employs the carbon sequestration factor method from the "2006 IPCC Guidelines for National Greenhouse Gas Inventories" to quantitatively analyze the carbon sequestration ability of various kinds of ecosystems. Quantitative analysis revealed a 0.56% decrease in the annual carbon sequestration of Chengde's ecosystems from 17.8215 million tons in 2000 to 17.7214 million tons in 2020, indicating an average annual reduction of 0.0501 million tons. Forestlands and cultivated land, which are primary contributors to carbon sequestration, account for over 80% of the total capacity. Spatial distribution analysis identified Fengning County, Weichang County, and Longhua County as the areas with the most concentrated carbon sequestration capacity, together accounting for over 60% of Chengde's total annual carbon sequestration. The continuous decline in Chengde's ecosystem carbon sequestration capacity was closely linked to changes in land use, accelerated urbanization, and rapid economic development. To counteract this observed decline, the study recommends strengthening the construction and management of ecological conservation areas, holistically promoting sustainable agricultural practices, systematically advancing urban greening projects, and actively raising public environmental

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awareness. These comprehensive measures are expected to optimize land resource utilization, enhance the carbon sequestration functions of ecosystems, and improve ecological security and residents' quality of life, thereby providing robust support for the sustainable development of Chengde and its surrounding regions.

Keywords: ecosystem, carbon sequestration, land use and land cover change, sustainable development, Chengde city

Introduction

Climate change poses a universal challenge to human survival and development, warranting extensive concern within the international community [1]. According to the Sixth Assessment Report of the IPCC's Working Group I released in 2021, human activities have induced warming in the atmosphere, oceans, and land. The last five decades, dating back to 1970, have marked the warmest period in the past two millennia, with global CO_2 concentrations peaking at 410 ppm in 2019 — a level unprecedented in the last two million years. The frequency of extreme events such as high-temperature heatwaves, heavy precipitation, droughts, and typhoons has increased since the 1970s and is expected to continue; warming of the climate system is anticipated to persist through the mid-21st century. Over the next 20 years, global temperature is expected to reach or exceed 1.5°C. Concurrent occurrences of high-temperature heatwaves and droughts, extreme sea level events primarily characterized by storm surges, giant ocean waves, and tidal floods, along with compounded flooding events caused by heavy precipitation, are projected to intensify [2]. Climate change impacts natural ecosystems, socio-economic development, and human health. Consequently, countries around the world have established "carbon neutrality" goals to address climate change. In response to these challenges, nations worldwide have set ambitious 'carbon neutrality' targets to combat climate change. In September 2020, China announced its ambitious 'Dual Carbon' goals: striving to peak carbon emissions by 2030 and achieve carbon neutrality by 2060, accompanied by the release of the "Carbon Peak Action Plan by 2030," which comprehensively deploys efforts to realize these "Dual Carbon" goals. Achieving these goals requires efforts on both emission reduction and carbon sequestration, where consolidating and enhancing the carbon sequestration capacity of ecosystems is one of the most cost-effective methods currently available [3].

Terrestrial ecosystems possess tremendous carbon sequestration capacity, and strengthening this capacity is crucial for mitigating the rise in global CO_2 concentrations and global warming, playing an indispensable role in achieving "carbon neutrality" [4, 5]. China's terrestrial ecosystems, which account for 6.4% of the global land area, contribute 10%–30% of the global net CO_2 absorption [6], making it a focal region for global and regional carbon cycle research and modeling. The global land carbon sequestration increased from a weak carbon source of (-0.2±0.9) Pg C/a in the 1960s to a carbon sequestration of (1.9±1.1) Pg C/a in the 2010s [7], with China's terrestrial ecosystems showing an overall upward trend, averaging (0.213±0.030) Pg C/a [8]. Currently, China's land carbon sequestration strength is estimated at 0.20–0.25 Pg C/a, approximately offsetting 7–15% of anthropogenic CO_2 emissions [9], and is expected to reach 0.36 Pg C/a by 2050–2060, offsetting about 43% of the carbon emissions from fossil fuel combustion and industrial activities during the same period [10]. Therefore, it is essential to not only promote energy structure optimization and energy-saving and emission reduction but also to emphasize the "carbon fixing" function of ecosystems. By consolidating and enhancing the carbon sequestration capacity of key regional ecosystems, we can promote the "net zero growth" of carbon dioxide [11, 12].

Situated in the northern part of the Beijing-Tianjin-Hebei region, Chengde City plays a crucial role in this ecological and climatic context. With mountains covering about 80% of its total area, Chengde has long been considered an ecological security barrier for the capital, Beijing. In 2015, the Ministry of Environmental Protection and the Chinese Academy of Sciences revised the "National Ecological Function Zoning," classifying Chengde city as the Beijing-Tianjin-Hebei Water Conservation Function Area, further clarifying this region's ecological service functions to the Capital and the Beijing-Tianjin-Hebei urban agglomeration. Hence, preserving and bolstering its carbon sequestration capacity is imperative for safeguarding the ecological security and integrated development of the Beijing-Tianjin-Hebei region [13].

In recent years, as population growth and economic development have progressed, there have been considerable changes in the land use structure of Chengde City [14], manifesting as changes in land use types, patterns, and intensities. These changes have directly or indirectly impacted the regional ecosystem's carbon sequestration capacity. This dynamic context underscores the need for a comprehensive evaluation of the carbon sequestration capacity of ecosystems in the region, which is precisely the focus of our study. As Jin et al. (2019) noted in their analysis of land-use competition in the North China Plain, such transformations can have significant implications for sustainable land development [15].

Our study introduces an innovative comprehensive evaluation model that quantitatively assesses the spatio-temporal disparity of ecosystem carbon sequestration capacity over two decades. This model not only provides a detailed analysis of the current state of carbon sequestration but also offers strategic recommendations for enhancing the region's carbon sequestration potential in line with sustainable development goals. Our approach integrates multi-year land use data with the carbon sequestration factor method, offering a more nuanced understanding of carbon dynamics in the context of rapid urbanization and economic development. Furthermore, we propose strategic pathways for enhancing carbon sequestration that align with the sustainable development goals of the region. This study, therefore, contributes to the broader understanding of ecosystem services in the context of climate change mitigation and the pursuit of carbon neutrality.

Amid the escalating impacts of global climate change and within the framework of the Beijing-Tianjin-Hebei coordinated development strategy, the ecological role and carbon sequestration function of Chengde have risen to prominence. Guided by the ecological civilization concept of 'building a community of life for man and nature,' our research into Chengde's carbon sequestration capacity is not only paradigmatic but also pioneering. By leveraging multi-year land use data and an ecosystem carbon sequestration capacity evaluation model specific to Chengde, we systematically assess the carbon sequestration capacity of its ecosystems, considering the city's unique resource endowments and socio-economic conditions. As highlighted by Peng et al. (2024), ecological restoration is a multifaceted challenge that requires addressing key issues such as reference state, size threshold, and cultural resilience [16]. Our study's innovative approach lies in its ability to integrate these diverse data sources, providing a nuanced understanding of carbon dynamics and offering strategic recommendations for enhancing carbon sequestration in line with sustainable development goals. This contributes to the broader understanding of ecosystem services in the context of climate change mitigation and the pursuit of carbon neutrality.

Materials and Methods

Overview of the Study Area

Chengde City, renowned for its rich historical and cultural heritage as well as its unique ecological significance, is located in the northeastern part of Hebei Province, China. It spans geographic coordinates ranging from 40°12' to 42°37' North latitude and from 115°54' to 119°15' East longitude. This city serves as a crucial transitional zone between North China and Northeast China and is located directly north of Beijing, making it a vital ecological buffer for the Beijing-Tianjin-Hebei region, underscoring its importance in ecological and environmental conservation

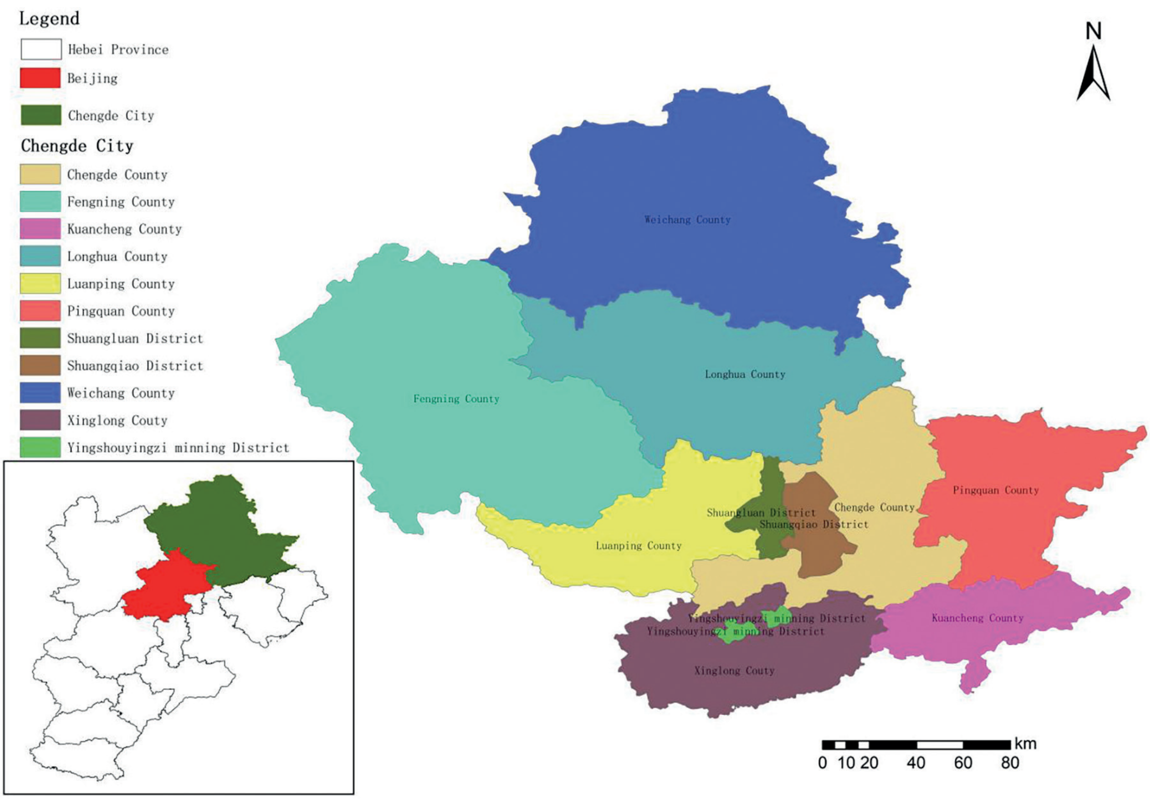

Fig. 1. Study area.

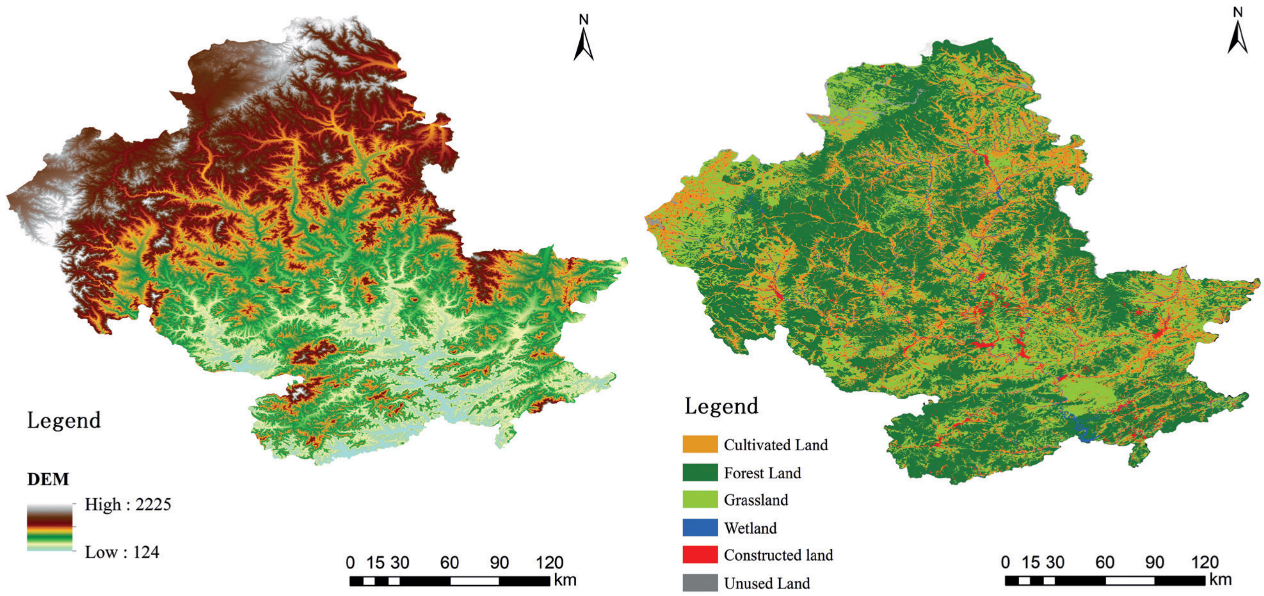

Fig. 2. Map of topography and vegetation distribution in Chengde City.

efforts (Fig. 1). Covering a substantial north-to-south distance of 269 km and a west-to-east span of 280 km, Chengde's extensive area of 39,511.89 km^2, which represents 21.19% of Hebei Province's total area, includes diverse topographical features such as mountains, plains, and rivers, providing a unique environment for various vegetation types to thrive. This diverse landscape is integral to understanding the complex interactions between land use, ecosystem services, and carbon sequestration capacity, which are central to this study. To provide a clearer understanding of the geographical and ecological context of the study area, topographical maps, and vegetation distribution maps are included, illustrating the diverse landscape of Chengde City. The included topographical and vegetation maps offer a visual representation of the study area in Chengde City, highlighting its unique environmental attributes (Fig. 2).

Data Sources

This study primarily focuses on five major land types within the Chengde area — forestland, grassland, cultivated land, wetlands, and unused land — as the subjects for assessing ecosystem carbon sequestration capacity. The land use data employed is sourced from the Land Use and Cover Remote Sensing Monitoring Database of the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. This database meticulously records various primary land classifications, including forestland and cultivated land, as well as secondary classifications such as timber forestland and paddy fields.

The selected dataset includes land cover data at five time points: 2000, 2005, 2010, 2015, and 2020. The dataset was specifically selected to commence from the year 2000, with subsequent evaluations conducted at five-year intervals to capture the dynamic changes within the ecosystems up to the year 2020. This temporal framework was chosen to systematically assess and illustrate the trends and transformations in land use over two decades, providing a robust basis for analyzing the impact of land management practices on carbon sequestration capacities. To ensure the consistency and comparability of the data, some of the secondary classification data were reorganized and restructured according to the land use classification standards provided by the '2006 IPCC Guidelines for National Greenhouse Gas Inventories' to meet the analysis requirements of this study.

Evaluation Methodology

Based on the carbon sequestration factor method provided in the "2006 IPCC Guidelines for National Greenhouse Gas Inventories," combined with domestic and international methods for assessing carbon sequestration capacity [17], this model evaluates the carbon sequestration capacity of various ecosystems. The evaluation is conducted within the scope of each ecosystem type, using land use area and carbon sequestration coefficients. The model is expressed as follows:

$$C_s = \Sigma_{i=0}^{n} S_i = \Sigma_{i=1}^{n} L_i \gamma_i \quad (1)$$

where C_s represents the total carbon sequestration, S_i represents the carbon sequestration produced by the ith type of land use, L_i represents the area of the ith type of land

Table 1. Ecosystem carbon sequestration capability estimation coefficients of Chengde City.

Primary Category	Secondary Category	Carbon Sequestration Coefficient (tons/hectare/year)
Forest Land	Forested Land	8.7
	Shrubland	2.25
	Sparse Forest	4.05
	Other Forest Land	4.05
Cultivated Land	Paddy Field	11.85
	Dry Land	6.15
Grassland	High Coverage Grassland	1.5
	Medium Coverage Grassland	0.75
	Low Coverage Grassland	0.15
Wetland	River Channel	6.75
	Lake	6.75
	Reservoir Pond	3
	Beach	6.75
	Marsh	3.45
Unused Land	Sand Land	0.045
	Bare Land	0.045
	Bare Rocky Land	0.045

use (such as forestland, grassland, cultivated land, etc.), γ_i represents the carbon sequestration coefficient for the ith land use type.

Determination of Carbon Sequestration Coefficients

Based on domestic and international research on ecosystem carbon calculations, including local climatic, soil characteristics, and water resource considerations, this paper determines the carbon sequestration capacity coefficients applicable to various ecosystems in Chengde City. These coefficients are compiled in Table 1 for different ecosystem types, facilitating the evaluation of Chengde City's carbon sequestration capacity.

Forestland Carbon Sequestration Coefficients: Extensive studies, such as those by Wang et al. (2019) and Fang et al. (2018) in the Inner Mongolia and Ningxia Hui Autonomous Regions, have explored the carbon sequestration potential of forests [18, 19]. Synthesizing these findings, we have established carbon sequestration coefficients for various forest types in Chengde, such as 8.7 tons/hectare/year for forested land, 2.25 tons/hectare/year for shrubland, and 4.05 tons/hectare/year for both sparse forestland and other forest land.

Cultivated land Carbon Sequestration Coefficients: Researchers like Tang have discussed the productivity of different scales and types of cultivated land ecosystems and calculated the carbon sequestration coefficients for paddy fields, irrigated lands, and drylands [20, 21]. Based on this, combined with the distribution of different types of cultivated land in Chengde City, the final carbon sequestration coefficients for paddy fields and drylands have been set at 11.85 tons/hectare/year and 6.15 tons/hectare/year, respectively.

Grassland Carbon Sequestration Coefficients: Grasslands play a crucial ecological and productive role, storing about 34% of the organic carbon in global terrestrial ecosystems, with approximately 90% of this carbon stored in plant roots and soils. However, 90% of China's natural grasslands have suffered various degrees of degradation due to overgrazing, unreasonable exploitation, and climate change. Piao et al. and Liu et al. have listed the biomass carbon stocks of China's grasslands derived from different research methods and calculated the carbon sequestration of grasslands in Inner Mongolia under various growth conditions [22, 23]. After integrating these findings, the carbon sequestration coefficients for high coverage grassland, medium coverage grassland, and low coverage grassland have been determined to be 1.5 tons/hectare/year, 0.75 tons/hectare/year, and 0.15 tons/hectare/year, respectively.

Wetland Carbon Sequestration Coefficients: Wetland ecosystems, one of the most important carbon sequestration systems on earth, play a vital role in the global carbon cycle. Through unique biogeochemical processes, they effectively store and sequester large amounts of organic

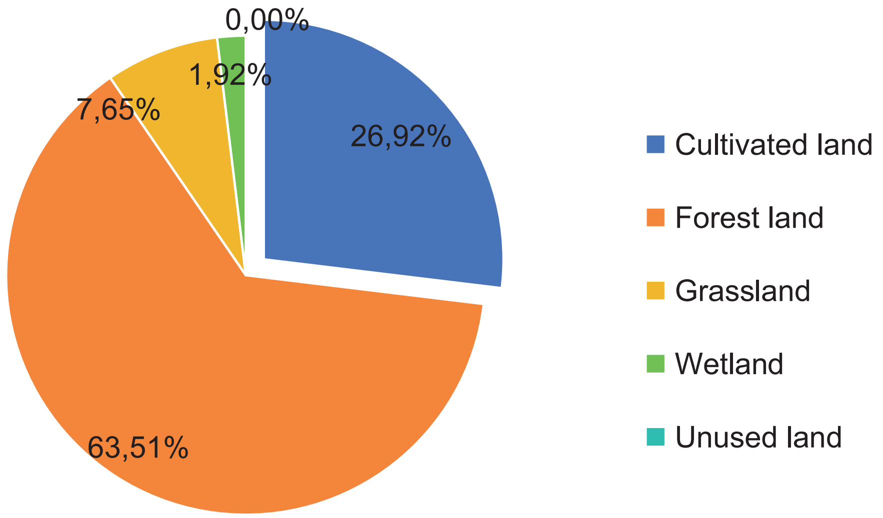

Fig. 3. Proportions of carbon sequestration in various types of ecosystems.

carbon, thereby reducing atmospheric carbon dioxide concentrations and actively combating global climate change. Given the diversity of wetland types and the large variation in conditions, research on wetland carbon sequestration coefficients needs to be refined for specific wetland types. The main types of wetlands in Chengde City, due to its relatively poor water resources and uneven spatial distribution, include rivers, lakes, reservoirs, beaches, and marshes. Researchers have studied the ecological function values of carbon sequestration in key wetland areas in Gansu Province and the Ningxia Hui Autonomous Region [24–26]. Combining these studies with the types of wetlands in Chengde, the carbon sequestration coefficients for river channel, lake, reservoir pond, beach, and marsh have been selected to be 6.75 tons/hectare/year, 6.75 tons/hectare/year, 3 tons/hectare/year, 6.75 tons/hectare/year, and 3.45 tons/hectare/year, respectively.

Other Unused Lands: Studies indicated that unused lands such as bare soil and bare rocky gravel have a weak capacity for carbon absorption. Therefore, the carbon sequestration coefficient for other unused lands has been set at 0.045 tons/hectare/year [27].

Results and Discussion

Carbon Sequestration Characteristics of Ecosystems in Chengde City

This paper focuses on assessing the carbon sequestration capacity of regional ecosystems in Chengde City and its potential enhancement pathways. By utilizing land use data and carbon sequestration coefficients for various ecosystems, this study reveals the current state and trends of Chengde City's ecosystem carbon sequestration capacity and discusses influencing factors and possible countermeasures to provide a scientific basis for enhancing the city's ecosystem capabilities.

Structural Characteristics of Types

In 2020, the total annual carbon sequestration of natural ecosystems in Chengde City reached 17.7214 million tons. Further analysis based on this data indicates that cultivated land and forestlands are the dominant types contributing to Chengde's ecosystem carbon sequestration. These two ecosystem types have collectively contributed more than 80% to the carbon sequestration in Chengde, Hebei Province. In 2020, the shares of carbon sequestration from forestlands and cultivated land were 63.51% and 26.92%, respectively (Fig. 3). The dominance of these land types is largely due to their extensive coverage and the region's favorable climate and topographical conditions, which enhance their carbon sequestration capabilities, and the implementation of ecological projects such as returning farmland to forest has direct impacts on the region's carbon sequestration capacity.

Among all secondary categories, forested land, dry land, shrubland, and high coverage grassland rank in the top four for carbon sequestration capacity, at 9.1643 million tons/year, 4.7206 million tons/year, 1.7133 million tons/year, and 1.1198 million tons/year, respectively. These figures correspond to 51.71%, 26.64%, 9.67%, and 6.32% of the total carbon sequestration capacity (Fig. 4). These findings reflect the carbon sequestration efficiency of various ecosystem types to some extent, suggesting that forestlands dominated by woody plants are a relatively efficient carbon storage medium under the continental climate conditions of North China. The elevated carbon sequestration capabilities observed in these ecosystems

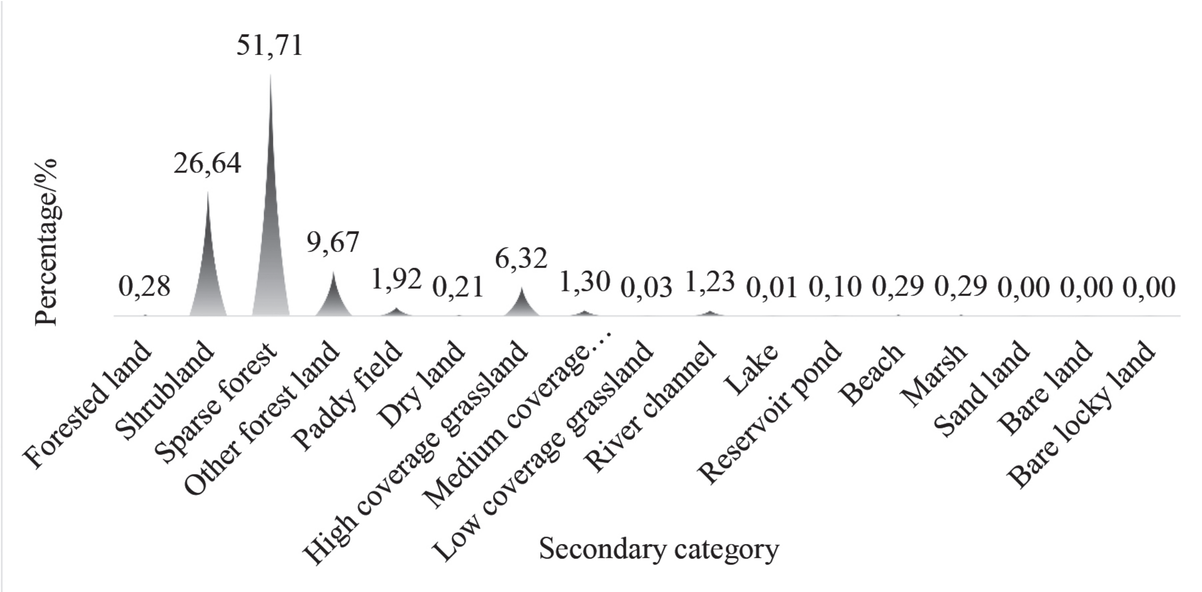

Fig. 4. Comparison of carbon sequestration capacity among secondary categories of ecosystems.

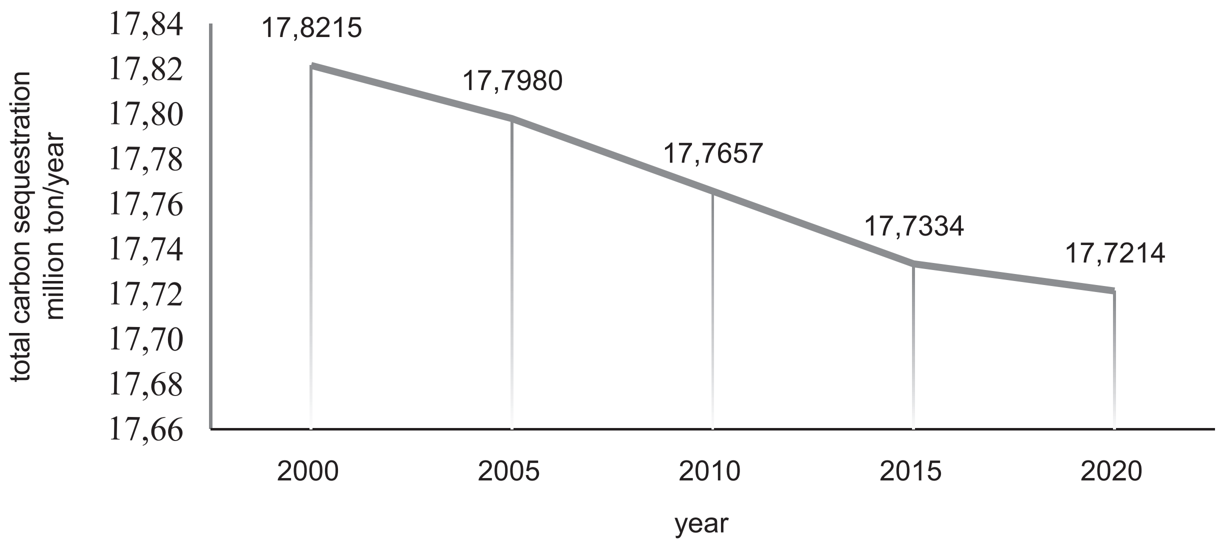

Fig. 5. Trend of Carbon Sequestration Capacity in Chengde City from 2000 to 2020.

are predicated upon a multifaceted array of determinants, encompassing climatic conditions, terrestrial stewardship protocols, edaphic profiles, and phytogenic attributes.

Forested ecosystems, characterized by their sylvan biomass, are particularly advantaged by the continental climatic regime of North China, which fosters vigorous vegetative expansion and subsequent carbon sequestration. The implementation of land management strategies, notably reforestation initiatives and silvicultural conservation measures, substantially augments the carbon sequestration efficacy within these forested domains. Concurrently, the carbon sequestration propensity of arid soils, shrublands, and grasslands with high vegetation density is modulated by soil hydration levels, thermal regimes, and the intricate subterranean root architectures that facilitate the sequestration of carbon in the soil matrix. Comprehensive apprehension of these interrelated factors is indispensable for the formulation of efficacious strategies aimed at maximizing carbon sequestration potential across the region's diverse ecosystems.

Temporal Variation Characteristics

Since 2000, Chengde City's annual total carbon sequestration from natural ecosystems has shown a consistent downward trend. From an initial sequestration

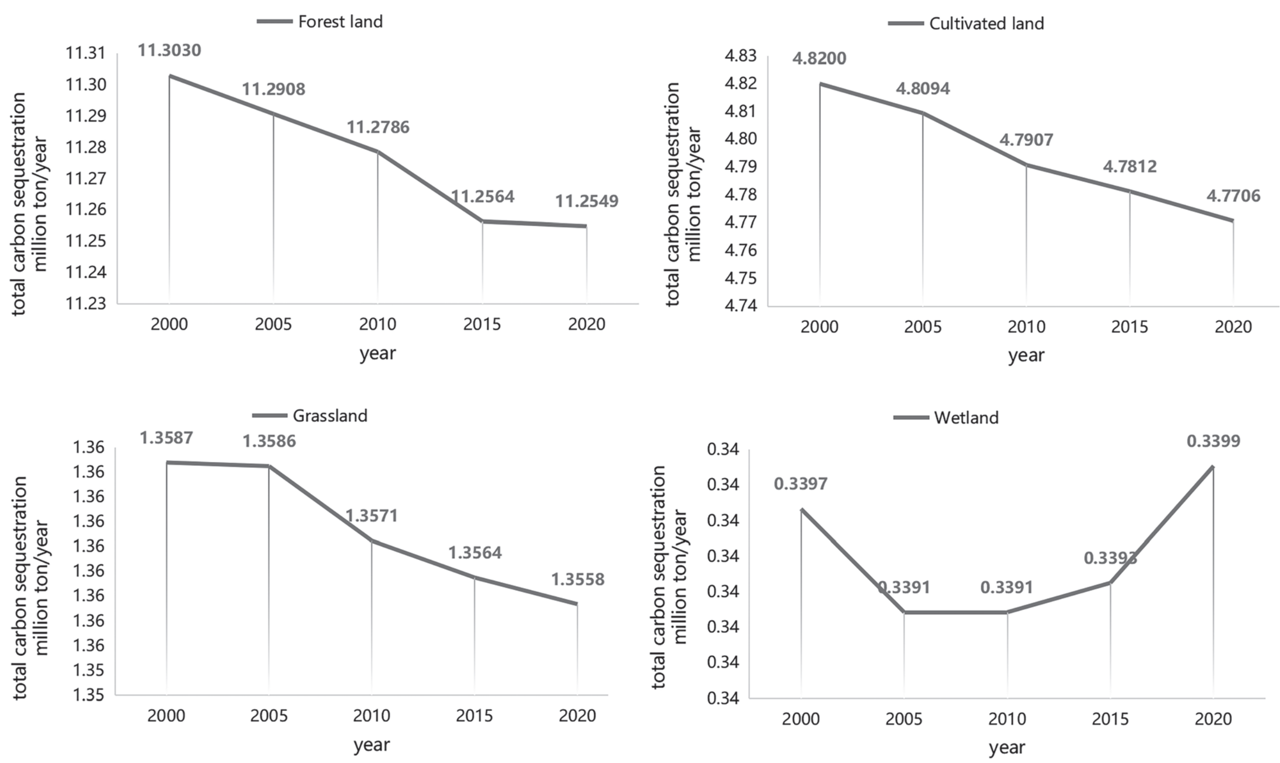

Fig. 6. Trend of carbon sequestration capacity in various types of ecosystems.

of 17.8215 million tons, there has been a slight decrease to 17.7214 million tons by 2020, indicating an annual average decrease of approximately 0.1001 million tons (Fig. 5). This trend, likely driven by urban expansion and diminishing capacities in cultivated land, grasslands, and forestland, suggests a regional reduction in carbon sequestration abilities. The significant decline in the carbon sequestration capacity among forestland and cultivated land can be attributed to multiple factors, including changes in land management practices and the impacts of climate variability, such as shifts in temperature and precipitation patterns that affect plant growth and soil carbon dynamics.

Specifically, among various ecosystems, the carbon sequestration capacity of forestland and cultivated land has shown the most significant decline. Forestland decreased from 11.3030 million tons in 2000 to 11.2549 million tons in 2020, a reduction of 0.0481 million tons. Cultivated land also exhibited a similar trend, decreasing from 4.8200 million tons to 4.7706 million tons, a decrease of 0.0494 million tons. The carbon sequestration capacity of grasslands slightly declined, from 1.3587 million tons to 1.3558 million tons. The carbon sequestration capacity of wetlands shows a trend of first decreasing and then increasing, as shown in Fig. 6. This fluctuation in wetland carbon sequestration may be linked to variations in hydrological conditions and efforts in wetland conservation and restoration initiatives.

Analysis of the trends in various carbon sequestrations revealed that the capacities of forestland, cultivated land, and grasslands to sequester carbon decreased in tandem with the overall regional total. In contrast, the carbon sequestration capacity of wetlands initially decreased and then showed a slight increase, while the carbon sequestration capacity of unused land has remained largely unchanged, with a slight increase observed in 2020. As economic development progresses, Chengde City's industrialization and urbanization levels have risen, accelerating economic growth, expanding urban population size, and increasing land demand. Consequently, some forestland, cultivated land, and grasslands have been converted into construction lands, further contributing to the decline in carbon sequestration capacity of these land types. The conversion of these lands not only affects the immediate carbon storage capacity but also disrupts the ecological balance, leading to a loss of biodiversity and alterations in ecosystem services that are crucial for carbon cycling.

Land use changes in Chengde City were a significant factor affecting the region's carbon sequestration capacity. From 2000 to 2020, the extensive conversion of forest and cultivated land to construction land led to reduced vegetation cover and soil erosion, similar to situations faced globally [28]. Forests and cultivated land, important for carbon sequestration, have shown a declining trend year by

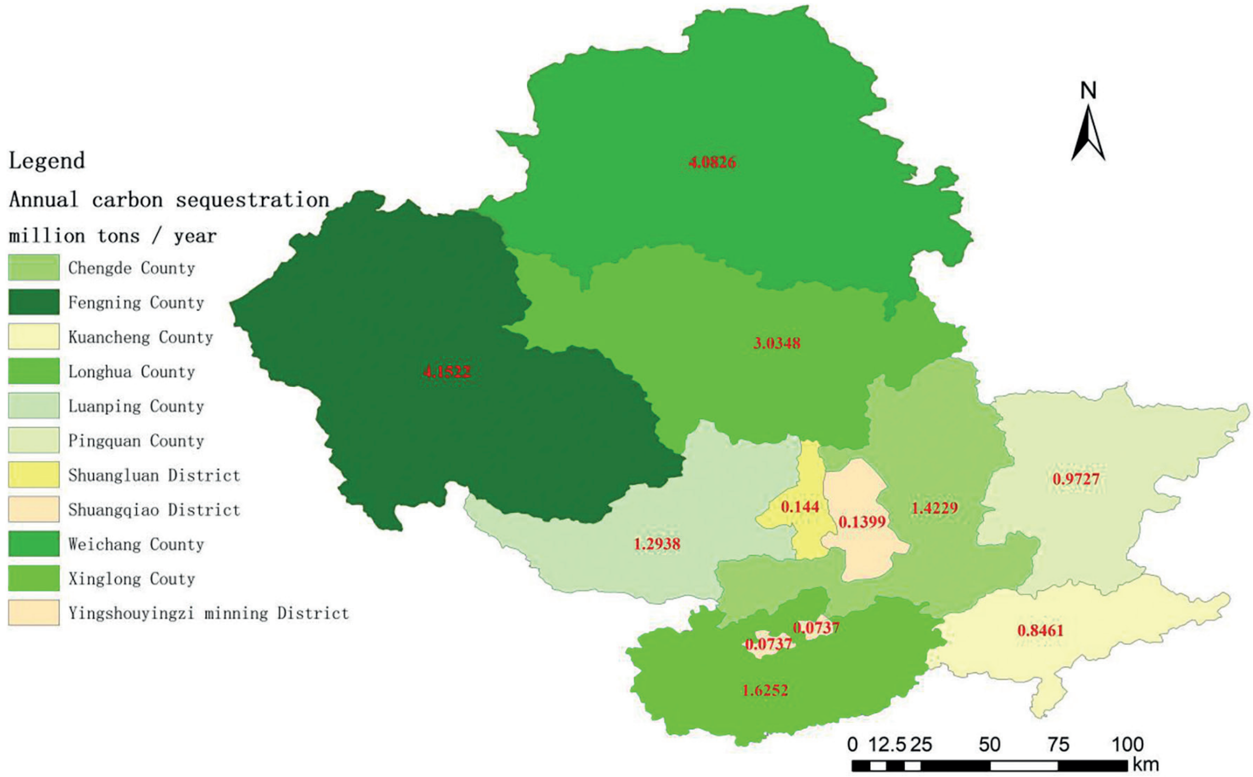

Fig. 7. Comparison of annual average carbon sequestration capacity among Counties.

year. Although Chengde City has implemented measures to protect these lands, their effectiveness is limited under the pressures of economic development and urban expansion. Climate change poses a global challenge, and Chengde City faces the added challenges of rising temperatures and changing precipitation patterns. Studies suggest that rising temperatures may accelerate the decomposition of soil organic matter, reducing the stability of the soil carbon pool [29]. Furthermore, irregular precipitation can affect plant growth cycles and productivity, thereby impacting carbon absorption capacity [30]. These climate-induced alterations highlight the necessity for adaptive management strategies that consider the resilience of ecosystems and their capacity to sequester carbon under varying environmental conditions. Additionally, the role of species composition and diversity in maintaining the carbon sequestration potential of ecosystems should be examined, as certain species may offer greater carbon storage benefits due to their growth habits, longevity, or adaptability to changing conditions.

Spatial Distribution Characteristics

From 2000 to 2020, the spatial distribution of carbon sequestration capacity in Chengde City showed a concentration trend, with Fengning County, Weichang County, and Longhua County serving as the primary hubs, together accounting for over 60% of the city's total annual carbon sequestration. Specifically, Fengning County averaged 4.1522 million tons, Weichang County 4.0826 million tons, and Longhua County 3.0348 million tons annually in carbon sequestration (Fig. 7).

During the same period, the carbon sequestration capacities across Chengde's various counties generally followed a slowly declining trend, with Luanping County experiencing the most significant reduction at an average annual decrease of about 19.80 thousand tons. This was closely followed by declines in Kuancheng County, Shuangluan District, Pingquan City, and Chengde County, which saw decreases of 16.90 thousand tons, 14.00 thousand tons, 11.20 thousand tons, and 9.70 thousand tons, respectively (Fig. 8).

The industrialization and urbanization of Chengde City have had a significant dual impact on carbon sequestration. In areas with high carbon sequestration values, there is a pressing need to integrate environmental considerations into regional planning and development strategies. On one hand, carbon emissions from industrial activities and transportation directly contribute to atmospheric pollution. On the other hand, urban expansion often leads to a reduction in green spaces, diminishing the region's

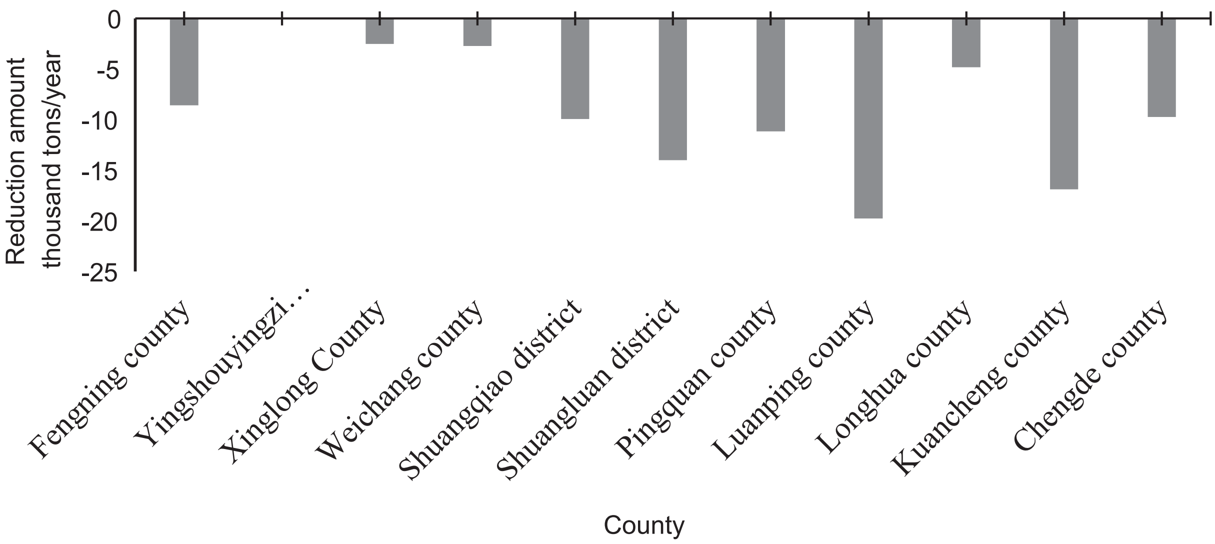

Fig. 8. Changes in carbon sequestration capacity among Counties.

capacity for carbon absorption. Moreover, this loss of greenery can potentially alter local climate conditions, fostering the development of urban heat islands, which in turn exacerbate carbon emissions [31].

Proposed Pathways for Enhancing Carbon Sequestration Capacities in Chengde City

To achieve "carbon neutrality," optimizing the ecological spatial layout of Chengde City and scientifically implementing ecological restoration is key. This process must be based on nature-based climate solutions, respecting natural laws, adapting to natural conditions, and utilizing natural processes [32, 33]. The spatial layout of ecosystems should be coordinated with national land space functional zoning, identifying and prioritizing the protection and restoration of important carbon sequestration functions and ecologically sensitive areas. Planning should aim to enhance carbon sequestration functions based on ecological protection and system restoration and advance from the intrinsic mechanisms of ecosystems to promote overall protection, systematic restoration, and integrated management of terrestrial ecosystems, thus enhancing their carbon sequestration capacity and quality [34–36].

A scientific understanding of the mechanisms of ecosystem carbon sequestration is crucial for enhancing carbon fixation capabilities. The carbon sequestration function of an ecosystem is its dynamic response to environmental changes, becoming "sinks" when the amount of CO_2 absorbed through photosynthesis and carbon cycling processes exceeds its emissions. Both global and Chinese terrestrial ecosystems are currently significant carbon sinks [37], a phenomenon partly due to increased atmospheric CO_2 concentrations and ecological projects implemented over the past decades, such as returning farmland to forest. However, as forest age increases, the carbon sequestration capacity of forests may gradually decline [38–40]. To maintain high carbon sequestration capacity over the long term, scientific management measures are needed. Understanding and improving the carbon fixation mechanisms of ecosystems and their response to environmental changes are foundational for enhancing their carbon sequestration capacity through diverse technological and management models.

Strengthening the investigation, monitoring, and accounting of Chengde City's ecosystem carbon sequestration is critical. Current challenges include uncertainties in carbon sequestration estimates and weak research on climate-sensitive areas like wetlands and deserts. To improve the stability of predictions for terrestrial ecosystem carbon sequestration, it is necessary to develop integrated "sky-earth-space" monitoring systems and carbon sequestration prediction models [41]. Additionally, unifying technical standards and strengthening scientific and technological efforts, establishing a robust data-sharing mechanism, promoting significant carbon-enhancing technologies, and developing verifiable carbon sequestration accounting and assessment standards are essential to provide scientific support and assurance.

By implementing these strategies, Chengde City can not only enhance its ecosystem's carbon sequestration capacity but also contribute to global climate change mitigation while improving regional ecological security and residents' quality of life. These measures will provide a solid foundation for the sustainable development of Chengde City, ensuring it plays an active role in global environmental governance.

Conclusions

This study presents a comprehensive analysis of the spatio-temporal disparity in ecosystem carbon sequestration capacity in Chengde City, leveraging data from 2000 to 2020. The findings highlight several key insights that are pivotal for informing local environmental policy and management strategies.

1. Persistent Decline in Carbon Sequestration Capacity: The study reveals a gradual decline in the total carbon sequestration capacity of Chengde's ecosystems, dropping from 18.907 million tons in 2000 to 18.8046 million tons in 2020. This trend underscores the need for targeted interventions to arrest the decline and enhance the region's carbon sequestration potential.
2. Dominance of Forestland and Cultivated Land: Forestlands and cultivated land, which are primary contributors to carbon sequestration, account for over 80% of the total capacity. Their reduction significantly impacts the city's carbon sequestration capacity. To address this, we recommend focusing on sustainable land management practices that prioritize the protection and restoration of these critical ecosystems.
3. Spatial Distribution Inequality: The spatial distribution of carbon sequestration capacity in Chengde City shows a significant concentration trend, with Fengning County, Weichang County, and Longhua County as the main concentrated carbon sequestration areas, contributing over 60% of the carbon sequestration. This highlights the need for regionally tailored strategies to enhance carbon sequestration, such as targeted reforestation and afforestation projects in these areas.
4. Impact of Land Use Changes: The conversion of forest and cultivated lands to urban and industrial uses is a major driver of the observed decline in carbon sequestration capacity. This trend underscores the urgency of sustainable land management practices. We suggest implementing policies that encourage urban greening and the preservation of green spaces within urban areas to mitigate this impact.

Based on these conclusions, it is recommended that Chengde City focus more on integrated management and land use optimization in future environmental management and policy-making. This includes exploring new strategies and technologies to enhance carbon sequestration, such as carbon capture and storage technologies and agroforestry systems. Additionally, public education and participation play a key role in improving the efficiency of regional carbon sequestration management. Through these measures, support can be provided for the sustainable development of Chengde City and the broader region.

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Conflict of Interest

The authors declare no conflict of interest.

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