

Article

The Power of Forests: A Study on the Spatio-Temporal Patterns of China's Forestry Carbon Sinks from the Perspective of GIS-LCA Technology

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Abstract: Forest carbon sinks are a crucial component in achieving China's "dual carbon" goals. This study integrates GIS-LCA technology to systematically examine the spatiotemporal evolution of China's forest carbon sinks and quantitatively assess afforestation carbon sequestration efficiency and carbon sink influencing mechanisms. The research findings indicate: (1) From 2003 to 2022, China's total forest carbon sink increased from 11.78 billion tons to 19.76 billion tons, with an average annual growth rate of 2.9%. This overall upward trend corroborates the research findings of other domestic scholars. The center of forest carbon sinks is mainly located in Shaanxi Province, showing a clear southeastward migration trend. (2) Forest carbon sink capacity exhibits significant regional differentiation: cold spot areas in the northeast gradually weakened, while hot spot areas in the west peaked in 2015 and subsequently declined. This shift reflects the complex interplay between climate change and human activities on carbon sink capacity. (3) Provincial-level analysis of afforestation carbon sequestration efficiency based on GIS-LCA technology reveals notable spatial disparities, with a national average of 579 t CO₂/km². Eastern provinces performed the best, averaging 749.6 t CO₂/km², while central and western provinces showed similar efficiencies at 471.5 t CO₂/km² and 494.4 t CO₂/km², respectively. This study provides theoretical support for advancing the high-quality development of China's forest carbon sinks and achieving carbon neutrality goals.



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Keywords: forestry carbon sinks; dual carbon goals; high-quality development; GIS-LCA; spatiotemporal pattern

1. Introduction

Global climate change has emerged as one of the most severe challenges facing humanity in the 21st century. In response, countries worldwide have proposed carbon neutrality goals (Tian et al., 2025; Yao et al., 2025). Based on data from the United Nations Framework Convention on Climate Change (UNFCCC), as of 2023, a total of 130 countries had pledged to attain carbon neutrality, accounting for two-thirds of global carbon emissions (Gao et al., 2025; Hu et al., 2021). As the world's largest carbon emitter, China announced its "dual carbon" goals in 2020, aiming to "peak carbon emissions before 2030 and achieve carbon neutrality before 2060." This commitment not only underscores China's sense of responsibility in global climate governance but also adds new momentum into global efforts to combat climate change. Achieving these "dual carbon" goals requires a multi-pronged approach, among which forestry carbon sinks play an irreplaceable role as a critical carbon sequestration pathway. Forests, as the dominant component of terrestrial ecosystems, possess strong carbon sequestration capacity (T. Wang et al., 2024). Through photosynthesis, forests absorb carbon dioxide from the atmosphere and store it in vegetation and soil, thereby reducing greenhouse gas concentrations and mitigating climate change. Studies indicate that global forests annually absorb approximately 2 billion tons of carbon dioxide, equivalent to one-third of emissions from fossil fuel combustion (Pan et al., 2024). Thus, strengthening forestry carbon sinks

is of great significance for realizing China's "dual carbon" objectives. Currently, the major global forestry carbon sink projects, as shown in Table 1, provide valuable references for China (Zhang & Yao, 2024). In recent years, China has placed a high priority on forestry carbon sink development, implementing a series of policy measures to promote the development and trading of forestry carbon sink projects. In 2021, the State Council of China (2021) issued the "Guidelines on Accelerating the Establishment of a Green, Low-Carbon, and Circular Economic Development System," explicitly calling for "strengthening forestry carbon sink capacity building and promoting the development and trading of forestry carbon sink projects." Additionally, the National Forestry and Grassland Administration (2021) released the "Guidelines for validation and verification of forestry carbon projects," offering technical support and policy guidance for project development. By 2022, China had launched a nationwide network of forestry carbon sink pilot projects, aiming to enhance ecological carbon sequestration capacity through diversified afforestation and forest management initiatives.

Table 1. Major Global Forestry Carbon Sink Project.

Project Name	Start Time	Initiator	Main Purpose	Implementation Scope	Implementation Category	Land Eligibility Certificate Requirements	Average Issuance Duration
CDM (Millock & Ollivier, 2025)	2001	United Nations Framework Convention on Climate Change	Help developed countries achieve mandatory emission reduction targets set in the Kyoto Protocol	Global	Afforestation, Reforestation	Afforestation: Forestless land for over 50 years; Reforestation projects require forestless land before the end of 1989	Approximately 5 years
VCS (Yang & Park, 2025)	2006	Verified Carbon Standard (by Climate Group International, International Emission Trading Association, etc.)	Reduce costs for applicants and improve the quality and sustainability of emission reduction projects	Global	Afforestation, Reforestation, Vegetation Restoration, Improved Forest Management, Reduced Deforestation, and Forest Degradation	Afforestation, Reforestation, and Vegetation Restoration: Forestless land for at least 10 years before project initiation; Reduced Deforestation and Forest Degradation: Eligible as forest for at least 10 years before initiation	2–5 years
GS (Yang & Park, 2025)	2003	World Wide Fund for Nature (WWF) and other international non-governmental organizations	Improve the quality of emission reduction projects and enhance their sustainability	Global	Afforestation, Reforestation	Afforestation and Reforestation projects require forestless land for at least 10 years before project initiation	2–5 years

However, compared with developed countries, the development of forestry carbon sinks in China is still in its early stages and faces numerous challenges, such as an imperfect policy system, inadequate scientific and technological innovation capabilities, and an underdeveloped market-oriented mechanism (Hubbart et al., 2025; J. Zhang et al., 2025). Specifically, in terms of the policy system, although China has introduced a series of policies to support forestry carbon sink development, deficiencies remain in implementation details and supporting measures, resulting in limited policy effectiveness. Regarding scientific and technological innovation capabilities, China lags behind international advanced levels in forestry carbon sink monitoring, measurement, and verification technologies, which constrains the high-quality development of forestry carbon sink projects. In terms of market-oriented mechanisms, despite the formal relaunch of the CCER (Chinese Certified Emission Reduction) market in January 2024 (with the forestry carbon sink trading process illustrated in Figure 1), the listing of the first batch of CCERs in September, and the registration of the first CCER project in December, China's forestry carbon sink trading market remains immature (Nian et al., 2025; Xu, 2024). The pricing mechanism and trading rules for carbon sink projects require further refinement, which affects the enthusiasm of social capital to participate in forestry carbon sink projects.

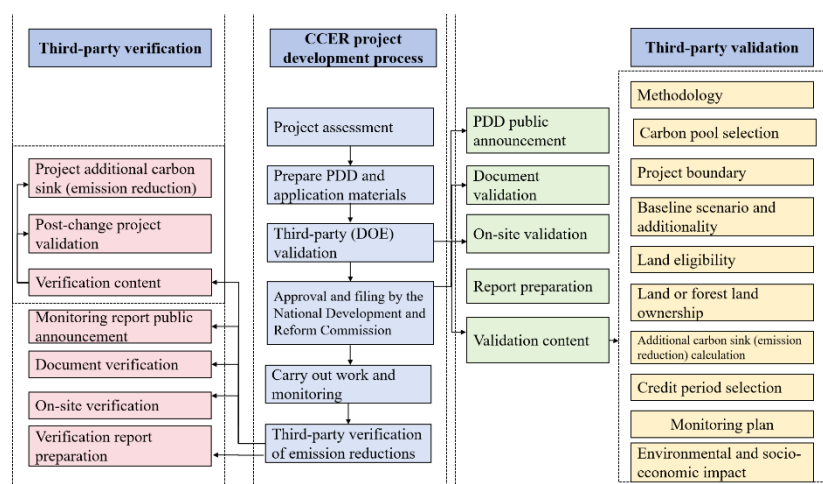


Figure 1. Flowchart for the Development of CCER Forestry Carbon Sink Projects.

To enhance the global reference value of this study, this section systematically compares the similarities and differences between mainstream international carbon sink projects, such as the Clean Development Mechanism (CDM) and Verified Carbon Standard (VCS), and China's Certified Emission Reductions (CCER) in terms of methodologies, verification costs, trading liquidity, and localization pathways:

- (1) In terms of methodologies, CDM/VCS has developed a modular and dynamically updatable system that covers diverse forest types and incorporates risk buffers. In contrast, CCER suffers from outdated updates and insufficient support for complex systems like mixed forests. China can draw on the modular approach of CDM/VCS to develop refined, region-specific, and dynamically adjustable methodologies tailored to its context.
- (2) Regarding verification costs and accessibility, while international projects entail high third-party fees and cumbersome processes, digital monitoring and “simplified procedures” have emerged to lower the barriers for small-scale projects. CCER still needs to shorten verification cycles and enhance transparency. It is recommended to promote simplified procedures integrating remote sensing, the Internet of Things, and smallholder farmer engagement to improve inclusivity.
- (3) Concerning trading liquidity, VCS benefits from global carbon finance, offering a rich array of derivatives and mature price discovery mechanisms. In contrast, the revived CCER market remains small in scale, lacking market makers and financial instruments. To address this, China should accelerate the development of a national-level platform, introduce market makers and futures/options, and increase the offset ratio of allowances to stabilize demand.
- (4) The localization challenges stem from the incompatibility of international additionality benchmarks and private capital models with China's collective forest tenure and government-led ecological projects. A “absorb-transform-innovate” strategy is needed: absorbing scientific methodologies and transparent mechanisms, transforming them to align with China's institutional framework, and innovating to form a forestry carbon sink governance system that combines international standards with Chinese characteristics. This approach will enable refined methodologies, intelligent verification, and market-oriented trading without blindly replicating international models, significantly enhancing the influence of China's CCER in global climate governance.

Scholars both domestically and internationally have conducted extensive research on forestry carbon sinks. In terms of strategy selection, based on real-world forestry carbon sink financing mechanisms, scholars have constructed three financing model frameworks: bank carbon sink expected earnings pledge, industrial investment funds, and BOT (Build-Operate-Transfer; [He & Ren, 2023](#); [J. Yang et al., 2025](#); [Zhou et al., 2025](#)). They have also considered moral hazards during project development and the supervisory intensity of regulatory authorities, establishing a stochastic differential game model between project development enterprises and forest farmers. Regarding carbon trading, based on the “dual carbon” goals, scholars have studied the impact of incorporating forestry carbon sinks into the carbon trading framework on China's regional carbon reduction costs ([X. Li et al., 2022](#)). They have found that numerous constraints exist in the forestry carbon sink pledge loan financing process, including limited pledged underlying assets, the absence of a unified accounting and evaluation system for pledged assets, an imperfect credit risk compensation mechanism, a lack of relevant institutional guarantees, and the absence of a comprehensive financial

service system (Begemann et al., 2025; Mohan, 2025; von Lüpke et al., 2025). In terms of optimization strategies, scholars have explored the comparison, constraints, and optimization strategies of forestry carbon sink insurance models, as well as the practical patterns and desirable approaches to determining the ownership of certified emission reductions from forestry carbon sinks. These studies provide theoretical support and practical guidance for improving the development of forestry carbon sinks in China. However, further theoretical research and refined practical pathways are still needed to better address the challenges.

Against this backdrop, the role of GIS-LCA carbon footprint assessment software is particularly critical. As an integration of Geographic Information System (GIS) and Life Cycle Assessment (LCA) technologies, this software provides robust technical support for the development and management of forestry carbon sink projects (García-Pérez et al., 2018; Guillén-Lambea et al., 2023). By integrating spatial data analysis, carbon sink measurement models, and life cycle assessment methods, the GIS-LCA software can accurately calculate the carbon sequestration capacity of forest ecosystems, evaluate the carbon reduction potential of forestry projects, and offer a scientific basis for carbon sink trading. Specifically, it plays a significant role in precise monitoring and measurement, carbon footprint assessment, policy support, and decision optimization, as well as the establishment of market-oriented mechanisms. For instance, by integrating remote sensing data, ground monitoring data, and climate models, the software enables dynamic monitoring and precise measurement of forest carbon sinks, identifies carbon sink hotspots, and optimizes project layouts. Meanwhile, its full life cycle carbon footprint assessment function covers stages such as afforestation, tending, harvesting, and reuse, enhancing project transparency and credibility while providing reliable data support for carbon sink trading. Additionally, the GIS-LCA software can simulate carbon sequestration potential under different policy scenarios, offering scientific evidence for policymakers to optimize carbon sink development goals and incentive mechanisms. By providing precise carbon sink data, it also promotes transparency and standardization in the carbon sink trading market, attracting social capital participation.

Building on this, this paper, grounded in the realities of China's forestry carbon sink development and utilizing GIS-LCA carbon footprint assessment software, aims to systematically evaluate the carbon reduction potential and full life cycle carbon footprint of forestry carbon sink projects. The application of the GIS-LCA platform is intended to identify and connect a full life cycle pathway, thereby enabling an integrated analysis of the carbon footprint across each stage of forestry carbon sink projects. It explores effective pathways for optimizing the layout of forestry carbon sink projects, improving carbon sink measurement accuracy, and facilitating market-oriented transactions, thereby providing scientific evidence and policy recommendations to drive high-quality development of China's forestry carbon sinks. The innovative aspects of this paper are primarily reflected in the following two dimensions: First, by integrating GIS spatial analysis techniques with LCA life cycle assessment methods, it constructs a carbon footprint assessment framework tailored to China's forestry carbon sink projects, addressing deficiencies in spatial precision and systemicity inherent in traditional approaches. Second, based on multi-source data integration and scenario simulation, it proposes innovative pathways for optimizing the layout of forestry carbon sink projects and designing market-oriented mechanisms, offering new theoretical support and practical references for relevant policy formulation and implementation.

2. Materials and Methods

2.1. Research Data

This study focuses on data related to forest stock volume, with the specific numerical unit of forest stock volume being 10,000 cubic meters. These data are primarily collected from the China Statistical Yearbook and the China Forestry and Grassland Yearbook. Compiled by relevant national departments, these two yearbooks offer a high degree of assurance in terms of data accuracy and authority, providing solid data support for the research. In terms of time span, the study selects data spanning two decades from 2003 to 2022. This period covers multiple important stages in China's forestry development, encompassing both the initial exploration and adjustment phase of forestry policies and the subsequent rapid development phase of forestry ecological construction. Through a systematic analysis of the data from these two decades, we can gain a more comprehensive and in-depth understanding of the dynamic trends in China's forest stock volume, explore the influencing factors behind these trends, and provide robust data evidence and decision-making references for formulating scientific and rational forestry development policies and promoting sustainable forestry development. Additionally, the data related to the GIS-LCA software primarily originates from various data documents collected by the platform, which have not been disclosed in publicly available information.

2.2. Evaluation of Forestry Carbon Sink Potential

In terms of carbon sink accounting, various methods already exist, such as the biomass method, carbon turnover model method, remote sensing technology method, and micrometeorological method. However, these methods still have certain limitations, including high technical requirements, difficulties in data acquisition, or reliance on research findings from other fields, which make them challenging to implement. In contrast, the volume method is considered a relatively straightforward approach, as it accounts for ecological factors such as stand growth and litterfall and features a more mature calculation system. Therefore, this paper selects the volume method to calculate carbon sinks across different regions. The volume method specifically comprises two components: First, based on forest stock volume, it calculates the biomass carbon sink primarily attributed to trees using parameters such as the stock volume expansion factor, bulk density, and carbon content rate (Ji et al., 2025). Second, on this basis, it further calculates the carbon sinks of understory vegetation and forest land by utilizing proportional relationships and conversion coefficients. The calculation model is presented as follows:

$$\begin{aligned} C_f &= C_b + C_v + C_s \\ &= V \times \delta \times \rho \times \gamma + \alpha(V \times \delta \times \rho \times \gamma) + \beta(V \times \delta \times \rho \times \gamma) \end{aligned} \quad (1)$$

Equation (2) illustrates the calculation method for the total forestry carbon sink. Here, C_f represents the total forestry carbon sink, C_b denotes the carbon sink of trees, C_v signifies the carbon sink of understory vegetation, and C_s indicates the carbon sink of forest land. The calculations of these carbon sinks are all based on the forest stock volume V , biomass expansion factor δ , bulk density ρ , and carbon content rate γ . In the equation, α and β represent the carbon sink conversion coefficients for understory vegetation and forest land, respectively. Their values are referenced from the study by Xue et al. (2017), with $\alpha = 0.195$ and $\beta = 1.244$. Additionally, the equation provides the values of the carbon content rate $\gamma = 0.500$, biomass expansion factor $\delta = 1.900$, and bulk density $\rho = 0.500$. By utilizing these parameters and the equation, we can calculate the total forestry carbon sink of forests, which holds significant importance for assessing forests' carbon storage capacity and formulating relevant carbon sink policies.

2.3. GIS-Based Spatial Distribution and Potential Assessment of Forestry Carbon Sinks

The concept of the “center of gravity” in physics, in brief, refers to the equilibrium point of an object’s mass distribution. Its calculation involves first summing the products of the masses of individual particles and their respective positions, and then dividing by the total mass. This concept has been borrowed by geography and statistics to describe the concentrated areas of various elements (such as population density, intensity of economic activities, and resource allocation) within a specific geographical region, with a particular focus here on the concentrated areas of grain production. The gravity model plays a crucial role in this context, as it efficiently evaluates the match between various indicators of regional development and central point analysis, revealing the mobility and agglomeration characteristics of these elements in geographical space. The displacement of the center of gravity over time visually illustrates the transfer paths of regional development elements, making the model highly valuable for understanding the trajectories and trend changes of these elements (Chen et al., 2025; J. Wang et al., 2022). The specific calculation steps are as follows:

$$\bar{x} = \frac{\sum_{i=1}^n T_i X_i}{\sum_{i=1}^n T_i} \quad (2)$$

$$\bar{y} = \frac{\sum_{i=1}^n T_i Y_i}{\sum_{i=1}^n T_i} \quad (3)$$

In the formula: x and y represent the longitude and latitude values, respectively, of the centroid coordinates for a certain attribute within the study area; n denotes the number of sub-units; X_i and Y_i are the geographic centroid coordinates of the i -th sub-unit; T_i indicates the value of a certain attribute in the region, which, in this paper, refers to the gross domestic product (GDP) and the area of urban construction land. From the centroid coordinates, the distance of spatial movement of the

centroid for a certain attribute within the study area can be calculated using the following formula (L. Li et al., 2023):

$$d = \rho \sqrt{(x_{i+t} - x_i)^2 + (y_{i+t} - y_i)^2} \quad (4)$$

In the formula: d represents the distance of centroid movement; (x_i, y_i) and (x_{i+t}, y_{i+t}) are the centroid coordinates of a certain attribute in the i -th and $(i+t)$ -th years, respectively; ρ is the conversion rate between planar coordinates and geographic coordinates, typically taken as a constant value of 111.11 km.

2.4. Hotspot Analysis

The hotspot analysis employs the Getis-Ord G_i^* index, proposed by British mathematicians Getis and Ord in 1992, for its analytical framework. Initially developed as a new analytical theory to address the spatial independence issues that global Moran's I statistics failed to properly reveal, this method can reflect the clustering effects of high and low values within spatial data over a certain range. By calculating each feature in the dataset, it identifies locations where high or low values spatially cluster (Iamtrakul et al., 2025). Statistically, a feature with a high value does not automatically signify a significant hotspot; it only qualifies as such when surrounded by other features with similarly high values (Kato, 2025).

$$G_i^* = \frac{\sum_{j=1}^n W_{ij} - \bar{X} \sum_{j=1}^n W_{ij}}{\sqrt{\frac{n \sum_{j=1}^n W_{i,j} - (\sum_{j=1}^n W_{i,j})^2}{n-1}}};$$

$$\bar{X} = \frac{\sum_{j=1}^n X_j}{n};$$

$$S = \sqrt{\frac{\sum_{j=1}^n X^2}{n} - \bar{X}^2} \quad (5)$$

In the formula: X_j is the attribute value of spatial feature j ; $W_{i,j}$ is the spatial weight between features i and j , defined as 1 if they are adjacent and 0 otherwise; n is the total number of spatial features; \bar{X} is the mean of the spatial features' attribute values; S is the standard deviation of the spatial features' attribute values; G_i^* statistic is represented as a z-score. A higher z-score indicates tighter clustering of high values among spatial features, while a lower z-score indicates tighter clustering of low values. Through GIS maps, the spatial locations of these attribute values can be visualized, allowing for an analysis of whether they exhibit clustering effects. From the map, the Getis-Ord z-value for the selected attribute of a geographic object can be observed. A higher z-value, represented by a color trending towards red, indicates that the attribute is a spatial hotspot; conversely, a lower z-value, represented by a color trending towards blue, indicates that the attribute is a spatial cold spot.

2.5. GIS-LCA Carbon Footprint Assessment

The "GIS-LCA Carbon Footprint Assessment Software" (<https://lca.qibebt.ac.cn/#/index>), originally developed by the team led by Academician Xie Kechang and Director Tian Yajun from the Pan-Energy Big Data and Strategic Research Center of the Chinese Academy of Sciences (hereinafter referred to as the "Center"), represents the first in-depth integration of Geographic Information System (GIS) and Life Cycle Assessment (LCA) technologies. This innovation enables precise carbon footprint accounting and spatial traceability. The tool is capable of tracking the entire life cycle of a product, from raw material acquisition, production and processing, usage, to final disposal, conducting quantitative analysis of greenhouse gas emissions at each stage, and scientifically evaluating their potential impacts on climate change. This study systematically analyzed the carbon sequestration efficiency of afforestation across various provinces in China based on GIS-LCA carbon footprint assessment technology.

3. Analysis of the Current Development Status of Forestry Carbon Sinks in China

3.1. Assessment of Forestry Carbon Sink Potential

Through a temporal analysis of China's total forestry carbon sink (Cf, in units of 100 million tons) and its constituent elements—carbon sink of trees (Cb), carbon sink of understory vegetation (Cv), and carbon sink of forest land (Cs)—from 2003 to 2022, the study reveals that China's forestry carbon sink system exhibits significant phased growth characteristics (Figure 2). During the research period, Cf steadily increased from 11.78 billion tons in 2003 to 19.76 billion tons in 2022, with an average annual growth rate of 2.9%. Specifically, the growth process of Cf can be divided into three distinct phases: a rapid growth period (2003–2006), during which Cf increased from 11.78 billion tons to 14.02 billion tons; a plateau period (2006–2009), when the total carbon sink remained relatively stable; and a sustained growth period (after 2009), reaching two interim peaks of 17.12 billion tons in 2013 and 19.76 billion tons in 2018. In terms of carbon sink composition, forest land carbon sink (Cs) consistently dominated, contributing 10.08 billion tons in 2022, accounting for 51.0% of the total; tree carbon sink (Cb) followed with 8.1 billion tons (41.0%); although understory vegetation carbon sink (Cv) had the smallest share (1.58 billion tons, 8.0%), its growth trend remained synchronized with Cb and Cs, indicating its non-negligible role in the carbon sink function of forest ecosystems. These findings corroborate the research results of scholars such as Wu Weiguang, Xue Longfei, and Zhang Xufang, further confirming the reliability of the study's conclusions (Wu et al., 2024; X. Zhang et al., 2016; Xue et al., 2017). The results demonstrate that China's forestry carbon sink system has achieved qualitative improvements over the past two decades, reflecting significant achievements in sustainable forest resource management and the continuous enhancement of ecosystem service functions. The improvement in China's forestry carbon sink capacity not only provides crucial support for the realization of domestic carbon neutrality goals but also makes a positive contribution to global climate governance and ecological sustainable development.

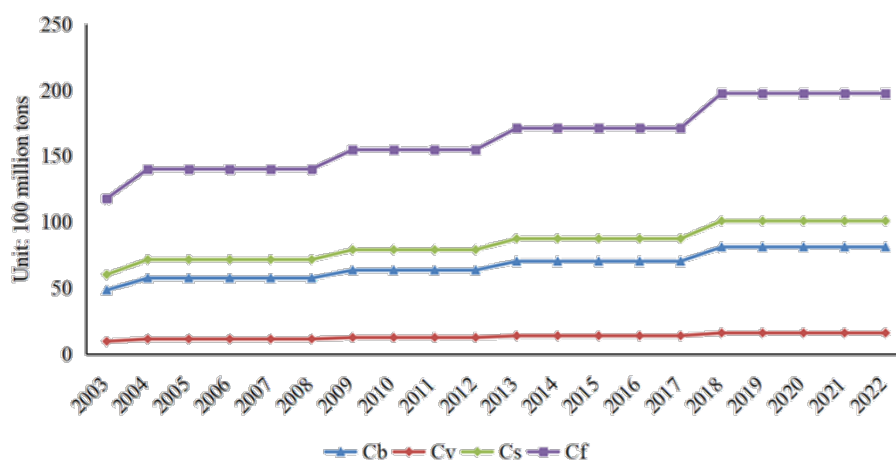


Figure 2. Trends in China's Forestry Carbon Sink from 2003 to 2022.

In recent years, China's forestry carbon sink has played an increasingly important role in addressing climate change and achieving carbon neutrality goals. Based on an analysis of spatial distribution maps of forestry carbon sinks at four time points—2003, 2009, 2015, and 2022—the dynamic trends and regional distribution characteristics of China's forestry carbon sink can be systematically assessed. In 2003, China's forestry carbon sink was primarily concentrated in the northeastern, southeastern, and southwestern regions, covering major forest areas such as the Northeast Forest Region and key forest areas in the south. By 2009, the spatial distribution of forestry carbon sinks exhibited significant changes, with an increase in carbon sinks in the southwestern region and a decline in some central areas. By 2015, carbon sinks in the southeastern region further increased, and the central region also showed recovery. The latest data from 2022 indicate that carbon sinks in the northeastern, southeastern, and southwestern regions remain at high levels, with an overall distribution tending towards equilibrium. These changes reflect significant temporal and spatial differences in China's forestry carbon sinks, with factors such as policy changes (e.g., the Natural Forest Protection Program and the Grain for Green Program), climate change, and shifts in land use patterns exerting important influences on carbon sink variations.

3.2. Current Status and Trends of Forest Resources

As shown in Figure 3, from 2003 to 2022, the centroid of China's forestry carbon sink remained primarily within Shaanxi Province, exhibiting a pronounced southeastward shift. This spatial trajectory not only reflects the dynamic redistribution of carbon sequestration capacity but also signals underlying shifts in ecological governance, land use transitions, and regional development strategies. Initially centered in central Shaanxi in 2003, the centroid's southeastward migration—particularly pronounced in 2009, 2015, and 2022—coincides temporally with key national ecological initiatives. These include the sloping land conversion program and the Natural Forest Protection Program, which were intensified in the Loess Plateau and its surrounding regions during the mid-2000s and 2010s. The 2015 peak and subsequent decline in western hotspot regions may reflect not only the maturation of early-planted forests but also the exhaustion of marginal lands suitable for afforestation, compounded by drought-induced mortality during extreme climate events. Additionally, the southeastward shift aligns with increasing human activity pressure in the northwest—such as expanded infrastructure development and agricultural intensification—which may have undermined local carbon sink stability. Mechanistically, these policy-climate-human interactions likely reconfigured the regional balance of carbon uptake, driving the observed centroid migration.

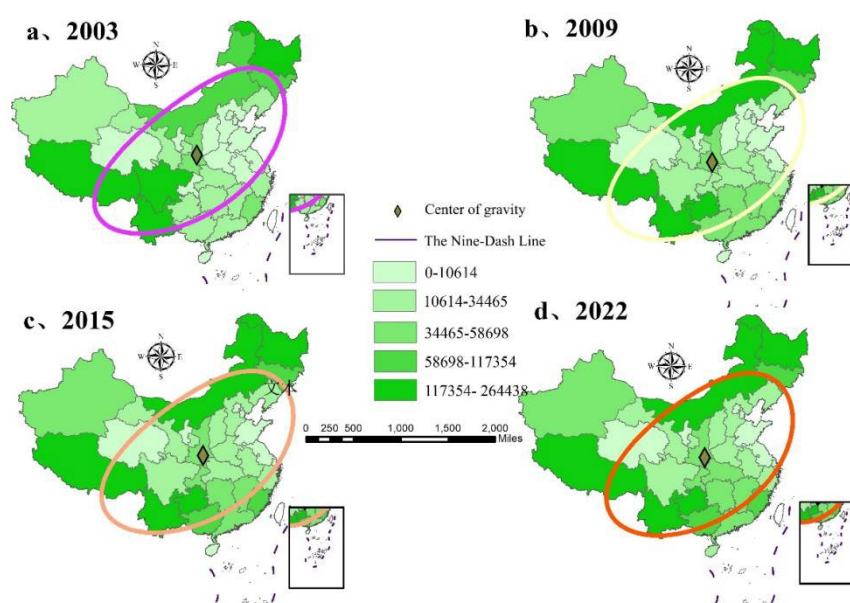


Figure 3. Spatial Evolution Trend of China's Forestry Carbon Sink from 2003 to 2022.

The standard deviational ellipse analysis further elucidates the directional asymmetry of this redistribution. The Y-axis dispersion (18.644) significantly exceeds that of the X-axis (9.556), indicating a north-south elongated pattern of carbon sink distribution. This anisotropy may reflect the orographic and bioclimatic gradient along the Loess Plateau-Qinling transition zone, where afforestation programs were disproportionately implemented along elevation and precipitation gradients. The rotation angle (64.46°) aligns closely with the northeast-southwest orientation of this topographic transition, suggesting that geo-ecological constraints—rather than administrative boundaries—have shaped the macro-scale configuration of carbon sinks. Thus, the spatial evolution of China's forestry carbon sink is not merely a descriptive pattern but a composite signature of policy intervention, climate variability, and anthropogenic land use dynamics, warranting region-specific attribution in future mechanism-focused studies.

3.3. Evolution Characteristics of Forest Resources

By analyzing hotspot and coldspot maps across different years, the dynamic changes in carbon sink capacity and their significance in various regions can be clearly observed. As illustrated in Figure 4, in 2003 (Figure 4a), northeastern China exhibited a prominent coldspot area (dark blue), indicating low forestry carbon sink capacity with a confidence level as high as 99%. The remaining regions were primarily classified as non-significant areas (yellow), suggesting that the carbon sink capacities in these areas were not statistically significant. By 2009 (Figure 4b), the extent of the coldspot in northeastern China had diminished, while a significant hotspot (dark orange) emerged in a western province, with a confidence level of 90%, indicating a notable increase in forestry carbon sink capacity in that region. The rest of the areas remained predominantly non-significant.

In 2015 (Figure 4c), the coldspot in northeastern China further weakened, and the hotspot area in the west expanded significantly, with the confidence level rising to 95% and reaching its peak at 99% that year, demonstrating a continuous enhancement in forestry carbon sink capacity in the western region. By 2022 (Figure 4d), the coldspot in northeastern China had nearly vanished, and while the hotspot area in the west persisted, its color lightened, and the confidence level decreased. Additionally, some new coldspot areas (grayish-blue) emerged, with a confidence level of 90%, indicating a reduction in carbon sink capacity and weakened statistical significance in these regions.

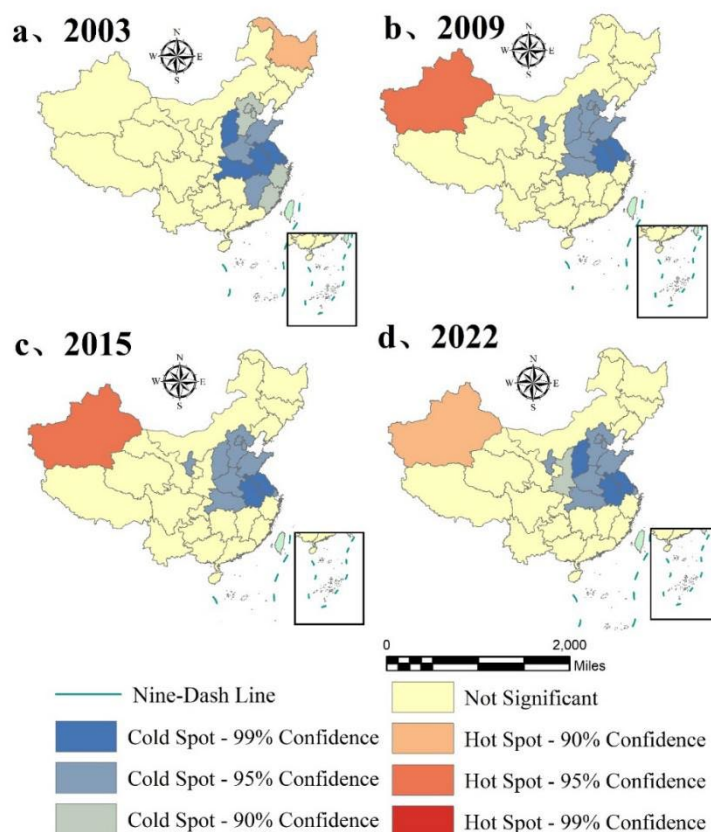


Figure 4. Spatial Distribution of Cold and Hot Spots in China's Forestry Carbon Sink from 2003 to 2022.

The observed peak and subsequent decline of the western hotspot after 2015 suggest that the enhancement of carbon sink capacity in this region may have encountered limiting factors. Potential mechanisms could include:

- (1) Policy implementation cycles—if the region had undergone large-scale afforestation or ecological restoration projects prior to 2015, the maturation of these forests or reduced post-project maintenance could lead to growth saturation or degradation;
- (2) Climate variability—periods of drought or extreme temperature events after 2015 could have suppressed vegetation growth and carbon uptake efficiency;
- (3) Human activity interference—increased land use pressure or infrastructure development in the region may have fragmented forest landscapes, undermining their carbon sequestration function. In summary, from 2003 to 2022, China's forestry carbon sink capacity exhibited significant regional variations: the coldspot in northeastern China gradually weakened, while the hotspot in the west peaked in 2015 before experiencing a decline. These changes reflect the dynamic evolution of forestry management and carbon sink capacity across different regions, providing crucial scientific insights for formulating regional carbon sink policies and addressing climate change.

3.4. Analysis of the Differences in Carbon Sequestration Effects of Afforestation Among Chinese Provinces from the GIS-LCA Perspective

Against the backdrop of global climate change, forests, as the largest carbon reservoirs in terrestrial ecosystems, play a crucial role in achieving carbon neutrality goals due to their carbon sequestration capacity. This study developed a visualization model for the carbon sequestration

effects of provincial afforestation based on the GIS-LCA software platform (as shown in Figure 5). Through the GIS-LCA platform, a full life cycle pathway was identified, enabling the integration of all stages of afforestation into a coherent framework to analyze the carbon footprint across each stage. With “forest land use” as the core node, the afforestation processes of various provinces were linked to the same “forest land use” process. By utilizing this “forest land use” node, connections were established among the afforestation processes of 31 provinces in China, quantifying the differences in carbon sequestration efficiency per unit area (1 km²) during the afforestation process across provinces (higher values indicate greater carbon sequestration efficiency during afforestation).

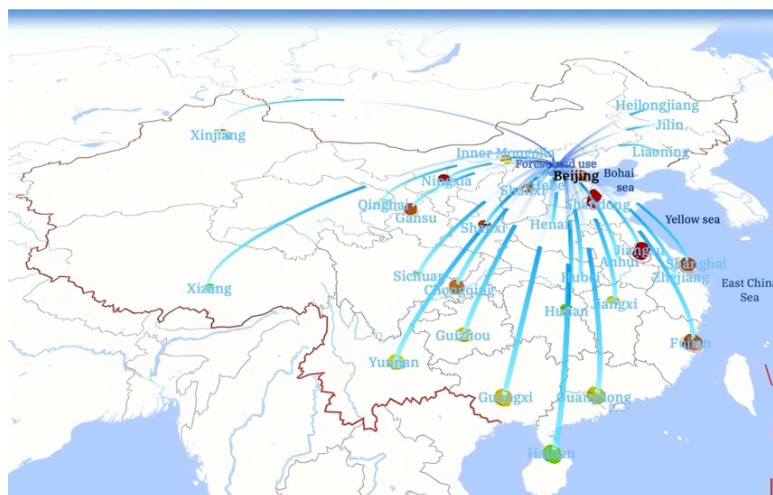


Figure 5. Visualization Model of Provincial Afforestation Carbon Sequestration Efficiency Based on GIS-LCA.

From the perspective of the bar chart heights and colors in the afforestation carbon sequestration efficiency model, where higher values represent stronger efficiency, provinces with high efficiency include Shandong, Jiangsu, and Ningxia; those with relatively high efficiency are Shaanxi, Tianjin, and Shanghai, among others; provinces with moderate efficiency include Beijing, Inner Mongolia, and Hebei, among others; while provinces with relatively low efficiency include Qinghai and Sichuan, among others. This phenomenon may be related to the climatic suitability of each region. Shandong is located in the warm temperate sub-humid climatic region, and Jiangsu is situated in the northern subtropical humid climatic region. The suitable temperatures and soil moisture levels in these areas are likely reasons for their high carbon sequestration efficiency. Similarly, Shaanxi and Tianjin, like Shandong, are located in the warm temperate sub-humid climatic region, demonstrating relatively high afforestation carbon sequestration efficiency on a national scale. In contrast, Qinghai is located in the plateau subfrigid sub-arid climatic region, where the low temperatures in the frigid zone and arid climate have a certain impact on tree growth, thereby affecting the carbon sequestration efficiency of afforestation.

As shown in Table 2, the model results indicate that the afforestation carbon sequestration efficiency of various provinces exhibits significant regional differentiation characteristics. Again, larger numerical values correspond to higher carbon sequestration efficiency. The average afforestation carbon sequestration efficiency across the 31 provinces in China is 579 t CO₂/km². From the perspective of the three major regions—eastern, central, and western China—the eastern provinces demonstrate the most outstanding performance in afforestation carbon sequestration efficiency, with an average of 749.6 t CO₂/km². Among them, Shandong ranks first nationwide with a carbon sequestration efficiency of 1,925 t CO₂/km², followed by Jiangsu with 1,543 t CO₂/km². The afforestation carbon sequestration efficiencies of the central and western provinces are relatively close, at 471.5 t CO₂/km² and 494.4 t CO₂/km², respectively. In the central region, Shanxi, Henan, and Anhui exhibit relatively high carbon sequestration efficiencies, while in the western region, Ningxia, Shaanxi, and Gansu perform relatively well. In contrast, Sichuan’s carbon sequestration efficiency is only 83 t CO₂/km², less than half of that of Shandong, making it one of the provinces with the lowest carbon sequestration efficiency nationwide. This regional differentiation characteristic may be closely related to factors such as climatic conditions, soil types, and afforestation policies, providing a scientific basis for further optimizing regional afforestation strategies.

Table 2. Results of Carbon Sequestration Efficiency of Provincial Afforestation Based on GIS-LCA.

Eastern Region	kg CO ₂ /km ²	Central Region	kg CO ₂ /km ²	Western Region	kg CO ₂ /km ²
Shandong	1,925,000	Shanxi	751,000	Ningxia	1,173,000
Jiangsu	1,543,000	Henan	719,000	Shaanxi	890,000
Tianjin	882,000	Anhui	606,000	Gansu	776,000
Shanghai	802,000	Heilongjiang	444,000	Chongqing	686,000
Fujian	758,000	Hubei	390,000	Inner Mongolia	552,000
Beijing	552,000	Jilin	343,000	Xinjiang	511,000
Hebei	515,000	Jiangxi	327,000	Guangxi	454,000
Zhejiang	487,000	Hunan	192,000	Guizhou	421,000
Guangdong	396,000			Yunnan	331,000
Liaoning	233,000			Qinghai	120,000
Hainan	153,000			Sichuan	83,000
				Xizang	64,000

4. Conclusions and Prospects

4.1. Research Conclusions

Through multi-dimensional analysis, this study draws the following key conclusions:

- (1) China's total forestry carbon sink has experienced significant growth, with its spatial distribution pattern demonstrating dynamic evolution characteristics. From 2003 to 2022, China's total forestry carbon sink increased from 11.78 billion tons to 19.76 billion tons, with an average annual growth rate of 2.9%, indicating a steady improvement in China's forestry carbon sink capacity. In terms of spatial distribution, the centroid of forestry carbon sinks is primarily concentrated within Shaanxi Province, exhibiting a notable southeastward migration trend. In 2003, the centroid was located in central Shaanxi Province and subsequently shifted southeastward gradually, with particularly pronounced migration characteristics observed in 2009, 2015, and 2022. This evolutionary pattern reveals the combined influence of multiple driving factors, including regional development disparities, policy guidance, and natural conditions.
- (2) The forestry carbon sink capacity exhibits significant regional differentiation characteristics. During the study period, the spatial heterogeneity of China's forestry carbon sink capacity was prominent. Cold spot areas in Northeast China demonstrated a gradual weakening trend, indicating an improvement in the region's carbon sink capacity. In contrast, hot spot areas in western China peaked in 2015 before experiencing a certain degree of decline, potentially related to the impacts of climate change and human activities. These changes in spatial distribution characteristics provide an important basis for a deeper understanding of the spatiotemporal evolution patterns of China's forestry carbon sink.
- (3) Analysis of provincial afforestation carbon sequestration efficiency based on the GIS-LCA software platform. Against the backdrop of global climate change, forests, as the largest carbon reservoirs in terrestrial ecosystems, play a crucial role in achieving carbon neutrality goals due to their carbon sequestration capacity. This study constructed a visualization model for the carbon sequestration effects of provincial afforestation based on the GIS-LCA platform, with "forest land use" as the core node, and quantified the differences in carbon sequestration efficiency per unit area (1 km²) during the afforestation process across 31 provinces in China. The results showed significant regional differentiation in afforestation carbon sequestration efficiency among provinces, with a national average of 579 t CO₂/km². Eastern provinces performed the best, with an average of 749.6 t CO₂/km², with Shandong (1,925 t CO₂/km²) and Jiangsu (1,543 t CO₂/km²) demonstrating the highest efficiency. Central and western provinces had similar efficiencies, at 471.5 t CO₂/km² and 494.4 t CO₂/km², respectively, with provinces such as Shanxi, Henan, Ningxia, and Shaanxi performing relatively well, while Sichuan (83 t CO₂/km²) had lower efficiency. Climatic conditions are a crucial factor influencing carbon sequestration efficiency, with warm temperate and subtropical humid climate zones, such as those in Shandong and Jiangsu, being suitable for tree growth, while arid climate zones in plateau subfrigid regions, such as Qinghai, exhibit lower efficiency.

4.2. Prospects

Combining the deficiencies identified during this research process, future research can further explore the following key aspects to promote the continuous development of this field in depth.

4.2.1. Deepening Research on the GIS-LCA Model

Although the GIS-LCA model was applied in this study, there is still room for in-depth exploration in terms of model details. Future research should focus on refining the technical framework of the GIS-LCA model, detailing and elaborating its technical framework diagram to clearly illustrate the entire process from data collection and processing to final carbon sink measurement. Particularly, it is essential to delve into the specific setting basis and interrelationships of various parameters within the model. For instance, in the construction method of Life Cycle Inventory (LCI), clarify the dynamic variation patterns of parameters under different forest types and management measures to enhance the model's applicability across diverse geographical regions and forest management scenarios. Simultaneously, conducting extensive model validation work is crucial. By comparing and analyzing with field monitoring data and results from other authoritative models, the accuracy and reliability of the GIS-LCA model can be assessed. In-depth cause analysis should be carried out for the model's performance discrepancies in different regions and forest ecosystems, followed by targeted model optimization to improve its universality and scientific rigor.

4.2.2. Strengthening Data Management and Quality Assessment

Data serves as the foundation for forestry carbon sink research. While this study has elaborated on data sources and quality assessment to some extent, further strengthening is needed. In the future, a more comprehensive data management system should be established, integrating multi-source data, including national forest resource inventory data, satellite remote sensing data, and ground survey data, to achieve real-time data updates and sharing. By constructing a unified data platform, data acquisition efficiency and utilization value can be enhanced, providing more comprehensive and accurate data support for forestry carbon sink research. In terms of data quality assessment, stricter and more detailed standards should be formulated. Not only should data accuracy be evaluated, but also data completeness, consistency, and timeliness. Advanced data analysis techniques, such as data mining and machine learning, should be employed to identify and correct anomalies and errors in the data. Simultaneously, uncertainty analysis of data quality should be conducted to quantify the impact of different data sources and measurement methods on research results, providing stronger guarantees for the reliability of research conclusions.

4.2.3. Comprehensively Analyzing Factors Influencing Carbon Sink Efficiency

This study has preliminarily explored differences in carbon sink efficiency at the provincial level. However, the analysis of numerous factors influencing carbon sink efficiency is not yet comprehensive and in-depth enough. Future research needs to systematically identify and quantify the contributions of different factors to carbon sink efficiency, constructing a comprehensive influencing factor model. From the perspective of natural factors, in-depth research should be conducted on the impact mechanisms of soil type, texture, and nutrient content on forest growth and carbon sink capacity, analyzing differences in carbon cycling processes within forest ecosystems under different soil conditions. Simultaneously, consider topographic and geomorphic factors such as altitude, slope, and aspect on the spatial distribution of forest carbon sinks, revealing the intrinsic connections between geographical environments and carbon sink efficiency. In terms of human factors, detailed assessments should be made on the long-term impacts of forest management and operation measures on carbon sink efficiency, including different afforestation methods, thinning intensities, and forest pest and disease control measures on the dynamic changes in forest biomass growth and carbon storage. Furthermore, in-depth research should be conducted on the guiding role of policy incentives in the development of forestry carbon sinks, analyzing the impacts of various ecological compensation policies and carbon trading policies on the enthusiasm and behavioral choices of forest farmers and enterprises participating in forestry carbon sink projects, providing theoretical bases for formulating more scientifically effective policies.

4.2.4. In-Depth Exploration of the Formation Mechanisms of Carbon Sink Hotspot Regions

This study has identified hotspot and coldspot regions for carbon sinks, but in-depth analysis of the formation mechanisms of hotspot regions still needs strengthening. Future research should combine socioeconomic, policy implementation, and natural environmental factors in the regions to conduct in-depth mechanistic studies. For carbon sink hotspot regions, analyze the specific implementation effects and pathways of regional policies. For example, study the differences in implementation intensities, funding inputs, and management models of major ecological projects such as the "Grain for Green Program" and the "Natural Forest Protection Program" in different regions, and how these differences affect forest carbon sink growth. Simultaneously, consider the impacts and recovery mechanisms of extreme climate events on the carbon sink capacity of hotspot regions,

assessing the stability and sustainability of carbon sinks in hotspot regions under a climate change background. Additionally, attention should be paid to the impacts of human activity intensity on carbon sink hotspot regions. Research the changes in forest ecosystem structures and functions caused by human activities such as urbanization, agricultural expansion, and infrastructure construction, and how these changes feed back into the carbon sink process. By establishing a coupled model of human activities-forest ecosystems-carbon sink capacity, the complex mechanisms underlying the formation of carbon sink hotspot regions can be deeply revealed, providing targeted strategies for regional ecological protection and carbon sink enhancement.

5. Development Suggestions

As illustrated in Figure 6, under the backdrop of the “dual carbon” goals, promoting high-quality development of China’s forestry carbon sink requires collaborative efforts across four key dimensions: mechanism refinement, technological innovation, scientific planning and innovative management, and deepening international cooperation.

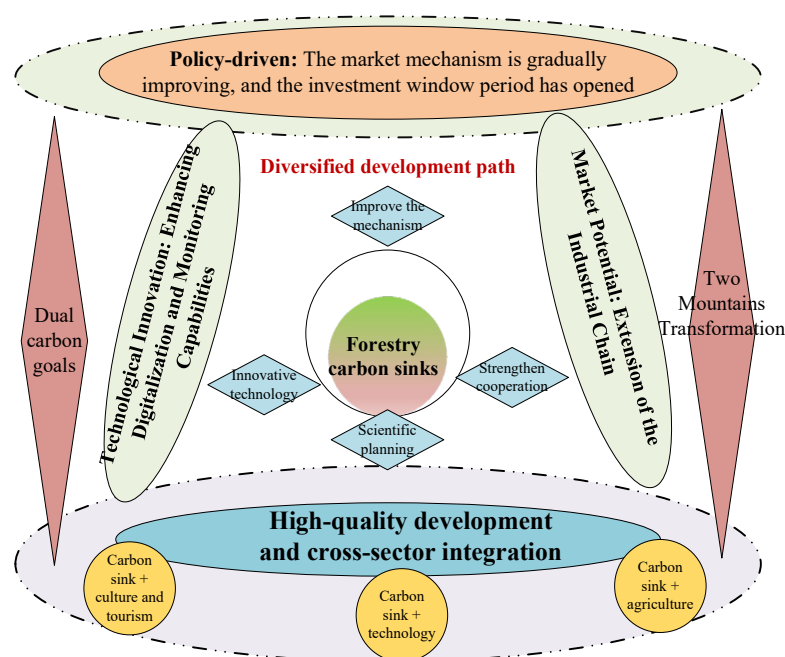


Figure 6. Schematic Diagram of the Development Pathway for China’s Forestry Carbon Sinks.

5.1. Mechanism Refinement: The Fundamental Guarantee for the Implementation of Forestry Carbon Sink Projects

Establishing a policy framework and innovating market mechanisms are crucial for promoting the sustainable development of forestry carbon sinks. First, a legal and regulatory system centered on a Forestry Carbon Sink Law should be established to clarify the legal status and rights and responsibilities of various stakeholders in the development, trading, and supervision of carbon sink projects (He et al., 2025; Liu et al., 2023). This system should integrate international measurement methodologies with local conditions to refine technical standards for carbon sink monitoring and accounting, ensuring scientific rigor and transparency. Furthermore, policies should be regionally differentiated and tailored to local ecological conditions. In high-efficiency eastern provinces (e.g., Shandong, Jiangsu), afforestation efforts should be scientifically expanded in non-agricultural areas, promoting integrated models such as “urban forests + carbon sinks” to enhance synergistic benefits between carbon sequestration and ecosystem services. In ecologically fragile yet potentially high-yield regions of central and western China (e.g., Shanxi, Ningxia), enhanced policy support should be provided to promote adaptive afforestation based on water resource availability, advancing ecological protection and restoration in tandem. In ecologically sensitive or low-efficiency areas such as Sichuan and Qinghai, conservation should take precedence, with pilot adaptive afforestation projects carefully implemented based on local climatic and ecological conditions, and carbon sink initiatives advanced prudently. Second, market mechanisms must be innovated by establishing a unified national forestry carbon sink trading platform, leveraging blockchain technology to enhance transaction transparency and credibility, and developing financial instruments such as carbon sink futures, options, and pledge financing to invigorate the market. Additionally, a carbon sink price stabilization fund should be established, regional trading alliances promoted, cross-

border trading mechanisms explored, and China's pricing power in the global carbon market strengthened.

5.2. Technological Innovation: The Core Driving Force for High-Quality Development of Forestry Carbon Sinks

Technological innovation serves as the core driving force for the high-quality development of forestry carbon sinks, permeating all aspects from basic research and technological application to talent cultivation (Wise & Parker, 2025). In the field of basic research, it is crucial to establish national major science and technology projects focused on forestry carbon sinks, break through key technological bottlenecks, and construct national key laboratories to promote deep interdisciplinary integration and build a big data platform for forestry carbon sinks. Simultaneously, introduce blockchain technology to ensure data credibility and transparency, develop an intelligent carbon sink management platform based on GIS-LCA for dynamic optimization and precise management of carbon sink projects, and accelerate the application and commercialization of new technologies. In talent cultivation, establish interdisciplinary forestry carbon sink programs to train compound talents, set up talent training bases, implement the "Forestry Carbon Sink Young Talent Program," and attract high-level overseas talents.

5.3. Scientific Planning and Management: The Key Pathway for the Implementation of Forestry Carbon Sink Projects

Establish a comprehensive carbon sink potential assessment system in China, prioritizing project deployment in ecologically fragile areas and regions with high carbon sink potential to achieve efficient resource allocation and maximize ecological benefits. Simultaneously, adopt a "multi-plan integration" approach to align carbon sink project planning with national land use, ecological protection, and other relevant plans, avoiding conflicts and resource waste. Introduce participatory planning to incorporate the opinions of local communities and stakeholders, enhancing project sustainability and social acceptance. Additionally, refine the environmental impact assessment system to scientifically evaluate ecological impacts, ensuring a balance between ecological and economic benefits and minimizing negative environmental impacts. Innovating management models is central to the efficient implementation of projects. It is essential to implement full lifecycle management, establishing a comprehensive regulatory mechanism from project initiation to operation to ensure orderliness across all stages. Introduce third-party certification bodies to objectively assess implementation effects, enhancing transparency and credibility. Establish a performance evaluation system to regularly conduct effect assessments, providing data support for subsequent project optimization. Develop an intelligent management platform that integrates big data and artificial intelligence technologies to achieve precise management and dynamic optimization, improving management efficiency. The monitoring system is a crucial safeguard for the smooth implementation of projects. Construct a national-provincial-municipal three-tier monitoring network to achieve comprehensive monitoring, ensuring data accuracy and completeness. Develop an intelligent monitoring platform that combines remote sensing, Internet of Things, and artificial intelligence technologies to enable real-time monitoring and dynamic assessment of carbon sinks. Additionally, establish a data-sharing mechanism to promote data openness and sharing, improving utilization efficiency. Further enhance monitoring capabilities through technical training and equipment upgrades to ensure scientific and reliable results, providing a solid data foundation for the sustainable development of projects.

5.4. Deepening International Cooperation: A Strategic Pathway to Enhance the International Competitiveness of Forestry Carbon Sinks

By actively participating in the formulation of carbon sink rules under the UNFCCC framework, promote the establishment of unified carbon sink measurement and trading standards, enhancing the normativity and transparency of the international carbon sink market (Nasiritousi et al., 2025; Yang & Park, 2025). Simultaneously, deepen cooperation with countries along the Belt and Road Initiative to explore international markets and optimize regional carbon sink resource allocation. Actively engage in shaping international carbon sink standards to strengthen China's voice and influence in the global carbon market. Expand international collaboration by forging in-depth partnerships with developed nations in carbon sink technology, management, and policy, leveraging their best practices, while enhancing support for developing countries through technical assistance and financial aid to foster mutual benefits and win-win outcomes—reinforcing China's leadership in global climate governance. Establishing robust international exchange platforms is equally critical. Host global forestry carbon sink forums to facilitate knowledge sharing and technological collaboration, establish international carbon sink technology transfer centers to accelerate the dissemination of innovations, and participate in mutual recognition mechanisms for carbon sink

certification to promote the seamless circulation of carbon credits. Together, these efforts will significantly enhance the international competitiveness, market reach, and global influence of China's forestry carbon sink initiatives.

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Abbreviations

The following abbreviations are used in this manuscript:

GIS-LCA	Geographic Information System-based Life Cycle Assessment
UNFCCC	United Nations Framework Convention on Climate Change
CCER	China Certified Emission Reduction
GIS	Geographic Information System
CDM	Clean Development Mechanism
VCS	Verified Carbon Standard
GS	Gold Standard
BOT	Build-Operate-Transfer

References

- Begemann, A., Dolriis, C., Onatunji, A., Chimisso, C., & Winkel, G. (2025). The politics of sustainable finance for forests: Interests, beliefs and advocacy coalitions shaping forest sustainability criteria in the making of the EU Taxonomy. *Global Environmental Change*, 92, 103001. <https://doi.org/10.1016/j.gloenvcha.2025.103001>
- Chen, P., Duan, J., & Wang, Y. (2025). Spatio-temporal evolution and driving forces of urban gravity centers and ecological security risk gravity centers in China. *Ecological Indicators*, 170, 113025. <https://doi.org/10.1016/j.ecolind.2024.113025>
- Gao, D., Gao, W., Ma, Z., Zhu, L., Tian, J., Liu, S., Yu, Y., Zhang, G., & Gao, Q. (2025). Trends and characteristics of global CH₄ emissions: Insights from UNFCCC greenhouse gas inventories. *Atmospheric and Oceanic Science Letters*, 18(5), 100637. <https://doi.org/10.1016/j.aosl.2025.100637>
- García-Pérez, S., Sierra-Pérez, J., & Boschmonart-Rives, J. (2018). Environmental assessment at the urban level combining LCA-GIS methodologies: A case study of energy retrofits in the Barcelona metropolitan area. *Building and Environment*, 134, 191–204. <https://doi.org/10.1016/j.buildenv.2018.01.041>
- Guillén-Lambea, S., Sierra-Pérez, J., García-Pérez, S., Montealegre, A. L., & Monzón-Chavarrías, M. (2023). Energy Self-Sufficiency Urban Module (ESSUM): GIS-LCA-based multi-criteria methodology to analyze the urban potential of solar energy generation and its environmental implications. *Science of the Total Environment*, 879, 163077. <https://doi.org/10.1016/j.scitotenv.2023.163077>
- He, X., Huang, H., & Hu, W. (2025). Analyzing the impact of government subsidies and other socioeconomic factors on blue carbon sinks in the coastal regions. *Ecological Economics*, 237, 108718. <https://doi.org/10.1016/j.ecolecon.2025.108718>
- He, Y., & Ren, Y. (2023). Can carbon sink insurance and financial subsidies improve the carbon sequestration capacity of forestry? *Journal of Cleaner Production*, 397, 136618. <https://doi.org/10.1016/j.jclepro.2023.136618>
- Hu, Y., Chen, Y., & Wu, S.-H. (2021). Synergy between the Convention on Biological Diversity and the UNFCCC in China. *Advances in Climate Change Research*, 12(2), 287–295. <https://doi.org/10.1016/j.accr.2021.03.011>
- Hubbart, J. A., Comacho, F., Gazal, K., Martins, L., Stephan, K., & Wood-Turner, K. (2025). Growing opportunities: Considering a thriving agroforestry industry in Appalachia, USA. *Agricultural & Rural Studies*, 3(2), 12. <http://doi.org/10.59978/ar03020007>
- Iamtrakul, P., Chayphong, S., & Gao, W. (2025). Geospatial analytics for promoting a healthy peri-urban city: A Health-Cartographic Perspective. *Journal of Urban Management*. <https://doi.org/10.1016/j.jum.2025.05.013>
- Ji, Y., Li, M., Zhao, Q., Geng, J., Liu, J., & Yu, K. (2025). Forest carbon stock ecological risk assessment in Minjiang River basin based on the adaptive cycle model. *Ecological Indicators*, 176, 113668. <https://doi.org/10.1016/j.ecolind.2025.113668>

- Kato, H. (2025). Spatial patterns and geographic characteristics of tourism-accommodation intensity hotspots in Kyoto city. *Annals of Tourism Research Empirical Insights*, 6(1), 100178. <https://doi.org/10.1016/j.annale.2025.100178>
- Li, L., Li, J., Wang, X., & Sun, S. (2023). Spatio-temporal evolution and gravity center change of carbon emissions in the Guangdong-Hong Kong-Macao greater bay area and the influencing factors. *Heliyon*, 9(6), e16596. <https://doi.org/10.1016/j.heliyon.2023.e16596>
- Li, X., Ning, Z., & Yang, H. (2022). A review of the relationship between China's key forestry ecology projects and carbon market under carbon neutrality. *Trees, Forests and People*, 9, 100311. <https://doi.org/10.1016/j.tfp.2022.100311>
- Liu, J., Ren, Y., Hong, Y., & Glauben, T. (2023). Does forest farm carbon sink projects affect agricultural development? Evidence from a Quasi-experiment in China. *Journal of Environmental Management*, 335, 117500. <https://doi.org/10.1016/j.jenvman.2023.117500>
- Millock, K., & Ollivier, H. (2025). The clean development mechanism. In T. Lundgren, M. Bostian, & S. Managi (Eds.), *Encyclopedia of energy, natural resource, and environmental economics* (2nd Edition) (pp. 22–30). Elsevier. <https://doi.org/10.1016/B978-0-323-91013-2.00017-4>
- Mohan, P. S. (2025). International climate finance in land use, land use change and forestry in Caribbean Small Island Developing States. *Forest Policy and Economics*, 170, 103383. <https://doi.org/10.1016/j.forpol.2024.103383>
- Nasiritousi, N., Buylova, A., & Linnér, B.-O. (2025). Matching supply and demand? Exploring UNFCCC reform options. *Earth System Governance*, 23, 100241. <https://doi.org/10.1016/j.esg.2025.100241>
- National Forestry and Grassland Administration. (2021). *Guidelines for validation and verification of forestry carbon projects*. <https://openstd.samr.gov.cn/bz/gk/std/newGbInfo?hcno=3CF8EE0F34DB617CF904AD930703D55E>
- Nian, H., Wang, H., & Zhang, Z. (2025). Carbon credit and credibility in lawsuit: Evidence from CCER firms in China. *Energy Economics*, 146, 108480. <https://doi.org/10.1016/j.eneco.2025.108480>
- Pan, Y., Birdsey, R. A., Phillips, O. L., Houghton, R. A., Fang, J., Kauppi, P. E., Keith, H., Kurz, W. A., Ito, A., Lewis, S. L., Nabuurs, G.-J., Shvidenko, A., Hashimoto, S., Lerink, B., Schepaschenko, D., Castanho, A., & Murdiyarso, D. (2024). The enduring world forest carbon sink. *Nature*, 631(8021), 563–569. <http://doi.org/10.1038/s41586-024-07602-x>
- State Council of China. (2021). *Guidelines on Accelerating the Establishment of a Green, Low-Carbon, and Circular Economic Development System*. https://www.gov.cn/zhengce/content/2021-02/22/content_5588274.htm?5xyFrom=site-NT
- Tian, S., Wu, W., Chen, S., Li, Z., & Li, K. (2025). Global mismatch between ecosystem service supply and demand driven by climate change and human activity. *Environmental Science and Ecotechnology*, 26, 100573. <https://doi.org/10.1016/j.es.2025.100573>
- von Lüpke, H., Mármárosi, B., Aebischer, C., Trushin, E., Bolaños, M., Webb, T., Nascimento, E., Suroso, D., & Breviglieri, G. (2025). Does international climate finance contribute to the adoption of zero deforestation policies? Insights from Brazil and Indonesia. *Forest Policy and Economics*, 174, 103480. <https://doi.org/10.1016/j.forpol.2025.103480>
- Wang, J., You, K., Qi, L., & Ren, H. (2022). Gravity center change of carbon emissions in Chinese residential building sector: Differences between urban and rural area. *Energy Reports*, 8, 10644–10656. <https://doi.org/10.1016/j.egyr.2022.08.208>
- Wang, T., Li, H., & Accatino, F. (2024). A theoretical framework for value co-creation analysis in carbon sink projects. *Journal of Cleaner Production*, 477, 143854. <https://doi.org/10.1016/j.jclepro.2024.143854>
- Wise, A., & Parker, H. (2025). Innovation in global forestry: Evolution towards a diversified industry. *Journal of Business Research*, 189, 115140. <https://doi.org/10.1016/j.jbusres.2024.115140>
- Wu, W. G., Xu, Q. Q., Yang, L. Y., & Liu, Y. (2024). Analysis on the potential of forest carbon sequestration and its economic impact on carbon neutrality in China. *Journal of Agrotechnical Economics*, (08), 128–144. (In Chinese)
- Xue, L. F., Luo, X. F., Li, Z. L., & Wu, X. R. (2017). Spatial spillover effects and influencing factors of forest carbon sinks in China: A spatial econometric analysis based on forest resource inventory data from 31 provinces (municipalities and autonomous regions) in mainland China. *Journal of Natural Resources*, 32(10), 1744–1754. (In Chinese)
- Xu, S. (2024). Forestry offsets under China's certificated emission reduction (CCER) for carbon neutrality: Regulatory gaps and the ways forward. *International Journal of Climate Change Strategies and Management*, 16(1), 140–156. <https://doi.org/10.1108/IJCCSM-04-2022-0047>
- Yang, D., & Park, H. (2025). Integrity challenges in carbon markets: Comparing UNFCCC and voluntary REDD+ verification in the Amazon Biome. *Environmental Science & Policy*, 169, 104080. <https://doi.org/10.1016/j.envsci.2025.104080>
- Yang, J., Fang, C., Zhang, L., & Yang, Y. (2025). Carbon sink potential and contributions to dual carbon goals of the grain for green program in the arid regions of Northwest China. *Resources, Conservation and Recycling*, 220, 108355. <https://doi.org/10.1016/j.resconrec.2025.108355>
- Yao, T., Wu, C., Yeh, P. J.-F., Hu, B. X., Jiao, Y., Li, Q., & Niu, J. (2025). Widespread global enhancement of vegetation resistance to compound dry-hot events due to anthropogenic climate change. *Ecological Indicators*, 178, 113880. <https://doi.org/10.1016/j.ecolind.2025.113880>
- Zhang, J., Dong, Y., Liu, Y., Kang, Y., Xie, S., & Xu, H. (2025). Knowledge domain and emerging trends in monitoring of forest fires using remote sensing: A scientometric review based on CiteSpace analysis. *Agricultural & Rural Studies*, 3(2), 29. <http://doi.org/10.59978/ar03020008>
- Zhang, X., Yang, H., & Zhang, X. (2016). China's forestry carbon pool level and development trend from 1993 to 2033. *Resources Science*, 38(02), 290–299. (In Chinese)
- Zhang, X., & Yao, S. (2024). Spatial convergence and differentiation characteristics of ecological efficiency of forestry carbon sink: Evidence from China. *Geosystems and Geoenvironment*, 3(1), 100241. <https://doi.org/10.1016/j.geogeo.2023.100241>
- Zhou, Y., He, L., Zhang, E., Lu, D., & Lin, A. (2025). Impact of cropland use transformation on ecosystem carbon sinks in a typical agroforestry mixed region: An analysis from explicit and implicit perspectives. *Environmental Impact Assessment Review*, 115, 107979. <https://doi.org/10.1016/j.eiar.2025.107979>

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