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Spatiotemporal Evolution and Land Disturbance Analysis of Ecological Carbon Sinks in the Yangtze River Delta

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Abstract: ***Ecological carbon sinks are vital for climate adaptation and carbon neutrality, yet their integration into national plans is hindered by challenges in identifying social attributes and boundaries. This study develops a Net Ecosystem Productivity (NEP)-based model and a land disturbance framework for the Yangtze River Delta (YRD). Results reveal significant spatial heterogeneity ("rich south, scarce north"; "high west, low east"). Of the 49.3 Mt CO_2 total increment, ecological protection contributed 91%, cropland management (dominated by agricultural activities) accounting for over 83%. Notably, carbon degradation (-1.03 Mt CO_2) occurred in regions remaining as forest land. These findings underscore that for megacity clusters, strengthening the boundary determination of carbon sink projects is essential to identify such dynamic incremental space available for inclusion in carbon neutrality initiatives.***

Keywords: Ecological carbon sink, Yangtze River Delta, Land-use disturbance, Carbon neutrality.

1. Introduction

Amid the global response to climate change, enhancing terrestrial ecosystem carbon sinks represents more than a natural science challenge. It is also a profound issue of social governance. From a social perspective, enhancing carbon sinks involves artificially boosting the carbon sequestration capacity of ecosystems. This is achieved through social mechanisms, including policy guidance, management interventions, economic incentives, and community participation. Land-use management serves as a critical entry point for social interventions. Scientific spatial planning can restrict the expansion of construction land. Consequently, this effectively protects existing carbon sinks in wetlands and croplands (Zhang et al., 2022). Management interventions within the land sector are projected to contribute approximately 30% of the emission reduction potential required to meet global temperature targets. Meanwhile, large-scale forest restoration initiatives provide society with clear, actionable goals.

Ecological restoration and landscape optimization yield significant carbon sink gains in specific regions. In ecologically sensitive areas, such as the Yellow River Delta, changes in land-use structure directly affect carbon emission intensity (Zhang et al., 2022). Reducing the extent of idle, unutilized land and controlling urban expansion can effectively safeguard wetland carbon sequestration functions. In mining site restoration, traditional random soil dumping is being replaced by scientific soil reconstruction (Feng et al., 2019). This shift restores carbon sink attributes through landform reshaping and subsequent vegetation succession. At the macro scale, comprehensive land sector management can contribute approximately 30% of the mitigation needed for global climate targets (Roe et al., 2019). Furthermore, it generates multiple synergistic benefits for sustainable development (Chiriacò et al., 2025). Forests represent the primary component of terrestrial carbon sinks. Globally, there are approximately 900 million hectares of potential space for forest restoration (Bastin et al., 2019). However, anthropogenic disturbances have caused substantial losses in global vegetation biomass. This loss highlights a critical reality: improving management practices can significantly unlock the carbon sequestration potential of existing ecosystems (Erb et al., 2018).

Agricultural systems are central to how human activities alter land-use patterns and ecological carbon sinks. Transitioning to diversified crop rotations improves the ecological resilience of farmlands. Additionally, it significantly enhances the stability of soil organic carbon (Zou et al., 2024). In agroforestry systems, multi-tiered management models allow communities and farmers to achieve higher carbon sequestration efficiency (Fahad et al., 2022). Concurrently, promoting management practices like conservation tillage and straw return requires policy and subsidy support from local governments. This support provides the necessary social momentum for soil carbon sequestration (Bekhit et al., 2025). Biotechnological tools, such as the application of arbuscular mycorrhizal fungi, offer new pathways for socialized services in green agriculture (Wahab et al., 2023). Furthermore, the widespread adoption of biochar relies heavily on the establishment of agricultural carbon credit markets (Lehmann et al., 2021). The emergence of rewilding-inspired forestry reflects an important shift in socio-ecological perspectives. It demonstrates a cognitive evolution from "conquering nature" to "respecting natural processes" (Wang et al., 2025). Beyond mitigating climate change, enhancing carbon sinks generates positive social spillover effects. These include advancing food security and contributing to poverty alleviation.

Maintaining and enhancing natural carbon sinks is crucial for offsetting anthropogenic carbon emissions (Friedlingstein et al., 2023). However, current research still lacks sufficient exploration of different human intervention behaviors. The impact of human activities on carbon sequestration capacity remains highly uncertain. Variations exist in policy standards, market rules, technological levels, and low-carbon awareness. Yet, these factors have not received adequate attention in current studies on carbon sink enhancement. Such uncertainties affect human land management and decision-making processes. They directly or indirectly alter regional climates and vegetation phenology. Consequently, these changes can significantly amplify or diminish the carbon sequestration functions of ecosystems. Global forests experience a net absorption of approximately 7.6 billion tons of carbon dioxide annually (Harris et al., 2021). Nevertheless, terrestrial carbon sinks exhibit strong variability and uncertainty, driven by the CO2 fertilization effect and climate warming (Ruehr et al., 2023).

Therefore, this study draws upon disturbance ecology theory and land-use change analysis. By structuring the typical characteristics of human disturbances within land-use changes, we identify and differentiate the impacts of ecological protection versus human intervention on carbon sinks. Using the Yangtze River Delta (YRD) as a case study, this research aims to investigate the potential disturbance factors involved in anthropogenic carbon sink enhancement. Ultimately, it provides scientific insights to support carbon sink enhancement and the realization of carbon neutrality goals in global megacity regions.

2. Methodology

2.1 Conceptual Definition

In the cross-disciplinary context of disturbance ecology and modern Earth system science, disturbances and perturbations are defined as specific events. These events cause shifts in the structure of terrestrial ecosystems. They also affect material cycling pathways and the boundaries of carbon carrying capacity. Based on this perspective, we can scientifically deconstruct two primary driving forces. In this study, Ecological Land includes cropland, forest, shrub, grassland, and wetland. Constructive Land (developed land) includes impervious surfaces, barren land, water bodies, and snow/ice.

(1) Ecological protection-oriented disturbance occurs when physical land cover remains consistent over time and space. Under these conditions, the ecosystem undergoes spontaneous regulation and succession. This process is a response to gradual, exogenous changes in the global environment. When a spatial patch follows a steady trajectory as ecological land across multiple periods, its carbon sink enhancement is driven by external factors. These primarily include the CO_2 fertilization effect and spatiotemporal fluctuations in climate factors, such as temperature and precipitation.

This evolutionary model is rooted in environmental attribution theory. It assumes that the system does not cross physical boundaries or experience discontinuous "jumps" in state space. Instead, vegetation communities passively increase their Net Primary Productivity (NPP) within the framework of established spatial capacities and soil types. They achieve this by adjusting stomatal conductance, improving water-use efficiency, and optimizing the conversion rates of photosynthetic substrates.

(2) Human intervention-oriented disturbance is defined as mandatory physical interference. These actions are driven by human socio-economic objectives. Such interventions completely reset the baseline conditions, resource availability, and primary carbon density of a spatial unit. The theoretical basis for this concept is anchored in the Managed Land Proxy established by the Intergovernmental Panel on Climate Change (IPCC). It also aligns with the Land Use, Land-Use Change, and Forestry (LULUCF) accounting framework.

When land trajectories involve transitions between ecological and constructive land—such as converting bare ground into plantations through afforestation—human spatial planning directly interrupts natural succession chains. These qualitative changes in surface cover trigger a leap in carbon sequestration capacity and biomass ceilings. Consequently, all changes in carbon sinks within this pathway are scientifically attributed to exogenous human intervention.

Table 1: Definition of Land Disturbance Concepts

Concept	Definition
Ecological Land	Includes categories such as cropland, forest, shrub, grassland, and wetland.
Constructive Land	Includes categories such as impervious surfaces, barren land, water, and snow/ice.
Ecological Reserve (ER) Zong	Refers to areas that remain as ecological land over a specific period. This highlights the fundamental principles of "ecological red lines."
Human Intervention (HI) Zone	Refers to areas where land-use types transition over a specific period.
HI-I Category	Transition from ecological land to constructive land (including natural degradation resulting from the loss of protection).
HI-II Category	Transition from constructive land to ecological land (reflecting ecological management and restoration processes).
HI-III Category	Remaining as constructive land (reflecting the process of "ecological civilization" in urban construction).

Note on Classification: Image recognition is a top-down macro-technology. Remote sensing classification of land use is based on patch similarity rather than the absolute consistency of land types. Therefore, at a micro scale, constructive land may include urban greening, parks, and other areas with green vegetation cover. These areas consequently generate effective NPP and Net Ecosystem Productivity (NEP).

2.2 Methods

2.2.1 Carbon storage estimate

Carbon sinks typically refer to the processes, activities, and mechanisms that remove carbon dioxide from the atmosphere. This term specifically highlights the capacity of forest ecosystems to absorb and store CO_2. Since the release of the 2006 IPCC Guidelines, the critical role of carbon sinks in climate change mitigation has gained significant national attention in China. The Chinese government has established a system for realizing the value of ecological products. This system clearly defines the accounting boundaries for ecological carbon sinks. According to the national standard *Ecosystem assessment—Technical guidelines for terrestrial gross ecosystem product accounting* (GB/T 46869—2025), carbon sinks can be calculated using the NEP method. The calculation formula is as follows:

$$C(x,t) = \frac{M_{CO_2}}{M_C} \cdot NEP(x,t) \quad (1)$$

In this equation, *C(x,t)* represents the carbon sink volume of pixel x during period t (annual) in grams of CO_2 (g CO_2). The coefficient MCO_2/MC converts carbon to carbon dioxide, with a fixed value of 44/12. *NEP(x,t)* denotes the net ecosystem productivity, which can be derived from NPP:

$$NEP(x,t) = \alpha \cdot NPP(x,t) \tag{2}$$

Here, α is the conversion coefficient between *NEP(x,t)* and *NPP(x,t)*. For the Yangtze River Delta, we adopted a localized value of 0.978. This value is based on the *Methodology for Forest Carbon Sink Accounting in the Yangtze River Delta Eco-Green Integrated Development Demonstration Zone*.

2.2.2 Land use transition matrix

Land transition refers to land-use changes occurring within a specific pixel over a defined period. This study established a transition analysis framework using ArcGIS Pro software. First, we projected the land-use raster data into the Albers Conic Equal Area coordinate system to facilitate geometric calculations. Next, the raster data from the beginning and end of the study period were converted into vector polygons. We then used the Intersect tool to join these two vector layers. In the final vector dataset, each pixel contains the land-use types for both time points. This approach allowed us to establish a land transition matrix and statistically analyze land-use dynamics during the period.

2.2.3 Land disturbance zoning

Based on the definitions of land disturbance, we categorized ecological land and constructive land as two distinct land-use sets. We then utilized the land transition matrix framework to construct spatial zones representing the mutual conversion of these types. These zones correspond to the four categories defined in Table 1: the Ecological Reserve (ER) Zone, and Human Intervention (HI) Zones I, II, and III.

2.2.4 Moran's I

The Global Moran's I (I_g) evaluates the degree of spatial dependency across the entire study area. This index reflects whether system parameters exhibit spatial clustering characteristics. It is calculated as follows:

$$I_g = \frac{n}{S_0}\frac{\sum_i \sum_j (x_i-\bar{x})(x_j-\bar{x})}{\sum_i (x_i-\bar{x})^2} \tag{3}$$

$$S_0 = \sum_i \sum_j w_{ij} \tag{4}$$

In these formulas, x_i and x_j represent the specific variables for regions i and j, respectively. $\bar{x}$ is the mean value of the variable. w_{ij} represents the elements of the binary spatial weight matrix, which constitutes the set of all spatial weights. I_g is used to assess the spatial aggregation of attribute x, including clustered, dispersed, and random patterns. The value of I_g ranges from -1 to +1:

Dispersed mode: As I_g approaches -1, the distribution becomes more dispersed. High (or low) values are surrounded by low (or high) values, indicating significant differences between adjacent spatial units.

Clustered mode: As I_g approaches 1, the distribution becomes more clustered. High (or low) values are surrounded by similar values, indicating minimal differences between adjacent units.

Random mode: When I_g =0, variable x shows no spatial correlation and is distributed randomly.

2.3 Study Area and Data Source

The Yangtze River Delta (YRD) is one of the largest and most economically active regions in the world(Li et al., 2023). It comprises the provinces of Shanghai, Zhejiang, Jiangsu, and Anhui, covering a total area of about 358,000 km^2. Despite occupying less than 4% of China's territory, the YRD contributes to nearly one-fourth of China's economic output and exports. The region typically experiences a humid subtropical climate and features a dense river network centered around the main stem of the Yangtze River. This complex system has significantly influenced the carbon storage capacity, and urban development within the region.

NPP data were derived from the MODIS satellite dataset MOD17A3HGF.061. We retrieved the annual composite products of this dataset via Google Earth Engine (GEE). This product provides annual information on both GPP and NPP at a spatial resolution of 500 meters. The temporal coverage of the data spans from January 1, 2001, to January 1, 2025.

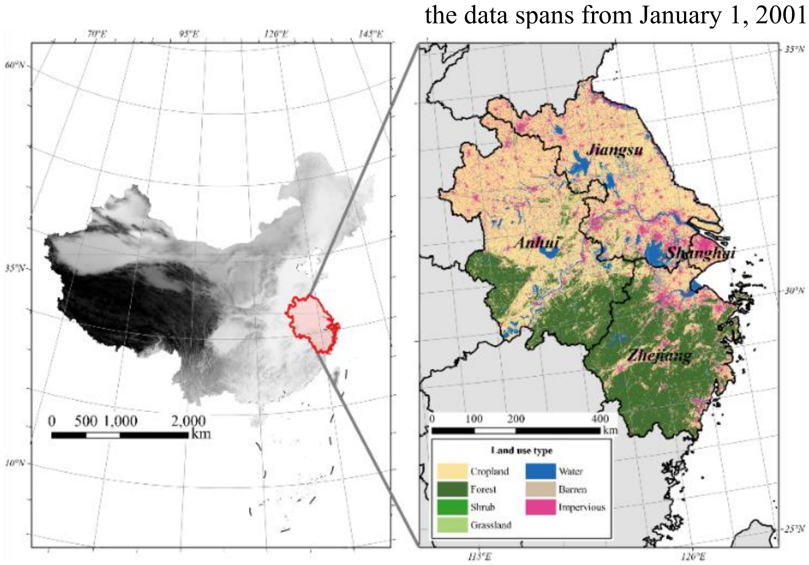

Figure 1: Yangtze River Delta regional map

Land-use classification data were sourced from the annual China Land Cover Dataset (CLCD) published by Yang and Huang(Yang & Huang, 2021). The latest version (V1.0.5) provides annual land-use maps at a 30m × 30m resolution for the period from 2001 to 2025. This dataset categorizes land use into several types. These include cropland, forest, shrub, grassland, wetland, impervious surfaces, barren land, water bodies, and snow/ice.

To ensure consistency in data granularity, all raster images were clipped to the spatial extent of the Yangtze River Delta. Subsequently, the data were resampled to a uniform resolution of 100m × 100m.

3. Results

3.1 Spatiotemporal Evolution Trends Analysis

From a temporal perspective (Figures 2 and 3), both the total volume and intensity of carbon sinks in the Yangtze River Delta (YRD) exhibited periodic fluctuations and gradual growth. Specifically, the total carbon sink volume increased from 588.0 Mt Mt CO_2 in 2001 to 637.0 Mt CO_2 in 2025, representing a growth of 8.33%. Within this period, carbon sinks from ecological land rose from 525.0 Mt Mt CO_2 to 572.0 Mt Mt CO_2, an increase of 8.95%. Notably, carbon sinks from constructive land grew from 30.7 Mt Mt CO_2 to 64.40 Mt Mt CO_2, reflecting a significant increase of 110%.

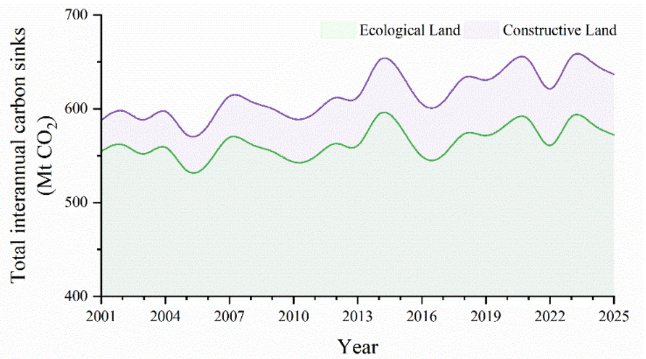

Figure 2: Trend of total carbon sink changes in the YRD from 2001 to 2025

The evolutionary trend of carbon sink intensity aligns with the findings of Fang et al. (2025). Similarly, vegetation NPP in the YRD followed a pattern of fluctuating growth. Brief peaks were observed in specific years, such as 2007, 2015, and 2021. Overall, carbon sink intensity rose from 1.91 kg CO_2/m^2 in 2001 to 2.07 kg CO_2/m^2 in 2025, an 8.38% increase. For ecological land, the intensity increased from 1.96 kg CO_2/m^2 to 2.14 kg CO_2/m^2 (+9.18%). Meanwhile, the intensity for constructive land grew from 1.49 kg CO_2/m^2 to 1.67 kg CO_2/m^2 (+12.1%). Interestingly, the growth rate of carbon sink density for constructive land was much lower than its total growth rate (110%). This discrepancy is primarily attributed to the scale effect resulting from continuous expansion of constructive land over the past two decades.

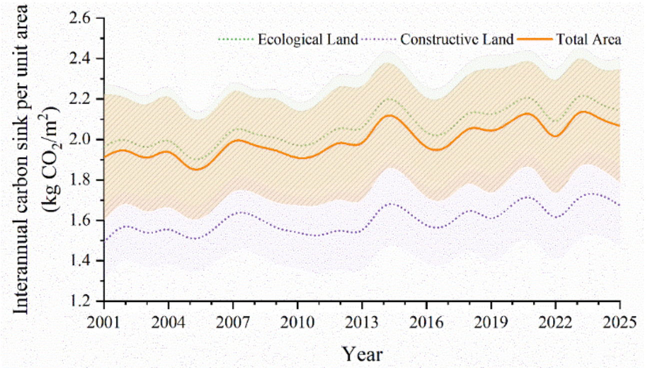

Figure 3: Trend of carbon sink intensity changes in the YRD from 2001 to 2025. (The shadow represents 0.5 times the standard deviation)

Spatial trends (Figure 4) reveal significant heterogeneity in carbon sink intensity across the YRD. The spatial autocorrelation index (*Z-score*) is well above 2.58 ($p < 0.01$), indicating strong spatial clustering. High-latitude regions, including parts of Anhui and Jiangsu Provinces, showed a marked increase in carbon sink intensity. In contrast, intensity decreased in low-latitude areas. These include most of Zhejiang Province and southern portions of Anhui, Jiangsu, and Shanghai.

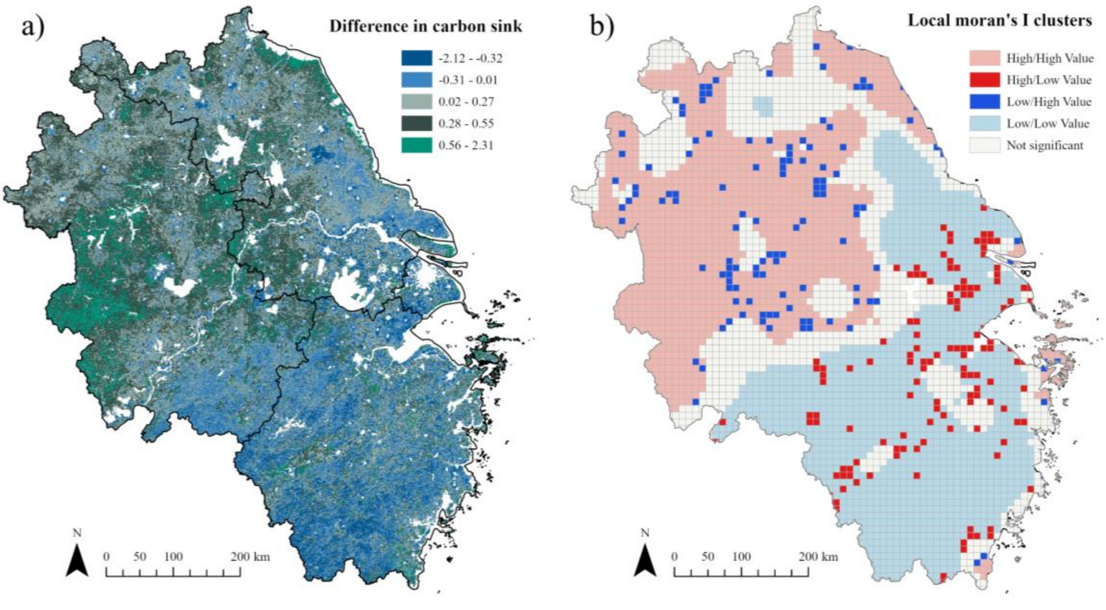

Figure 4: Carbon sink intensity change from 2001 to 2025 (a) and spatial heterogeneity (b)

Spatial zonal statistics further confirm these dynamics between 2001 and 2025. Anhui and Jiangsu Provinces recorded the highest increments, reaching 34.76 Mt CO_2 and 15.85 Mt CO_2, respectively. As a highly developed megacity with high population density, Shanghai still achieved a carbon sink increase of 0.15 Mt CO_2. Conversely, Zhejiang Province experienced a decrease of 1.41 Mt CO_2, despite possessing the region's most abundant forest resources. This decline may be due to two primary factors. First, the negative impact of urbanization on carbon sinks is more pronounced in areas with extensive forest cover. Second, vegetation in dense forest regions may be more sensitive to climate disturbances. For instance, phenomena such as flash droughts can lead to a significant reduction in carbon sequestration capacity.

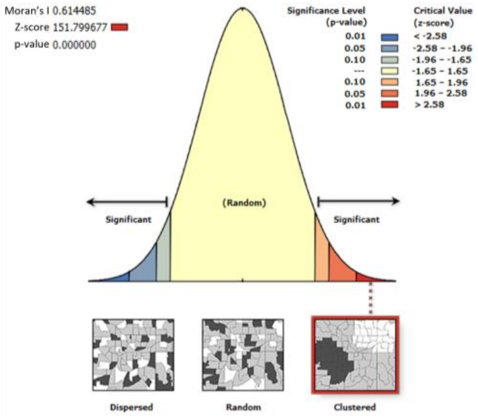

Figure 5: Global Moran's I of carbon sink intensity change

Table 2: Carbon sink changes in provinces of the YRD from 2001 to 2025

Provinces	Carbon sinks in 2001(Mt CO_2)	Carbon sinks in 2025) (Mt CO_2)	Volume variation (Mt CO2)	Intensity variation ($kgCO_2/m^2$)
Shanghai	9.79	9.94	0.15	0.0285
Jiangsu	138.80	154.65	15.85	0.1790
Zhejiang	236.30	234.89	-1.41	-0.0146
Anhui	202.76	237.52	34.76	0.2620

3.2 Land Use Transition Matrix Analysis

Land-use transition analysis reveals that the YRD achieved significant results in returning farmland to forests and water bodies between 2001 and 2025. According to Tables 3 and 4, cropland area decreased by a total of 2.672 million hectares. Approximately 8.8% of this reduction was due to conversion into water bodies, while 14% was converted into forest land. These transitions contributed carbon sink increments of 0.04 Mt CO_2 and 1.44 Mt CO_2, respectively. During the urbanization process, impervious surfaces increased by a cumulative 94%. Transitions from cropland accounted for 92% of this total expansion. Despite this large-scale conversion, the total carbon sink decreased by only 1.09 Mt CO_2. This suggests that ecological space protection measures in the YRD have yielded positive outcomes during urban transformation.

Table 3: Land use transition matrix from 2001 to 2025(ha)

2001	2025							
	Water	Barren	Forest	Shrub	Cropland	Grassland	Impervious	Total
Water	1771004	286	2357	2	432496	112	167970	2374227
Barren	553	39	2	0	364	3	611	1572
Forest	3761	19	10175842	370	586084	1390	68597	10836063
Shrub	0	0	666	219	87	216	1	1189
Cropland	235072	119	384019	3	17010619	812	2052479	19683123
Grassland	311	30	3392	8	9391	2759	2241	18132
Impervious	41172	37	163	0	25372	35	2372459	2439238
total	2051873	530	10566441	602	18064413	5327	4664358	35353544

Table 4: Carbon sink transition matrix from 2001 to 2025($\times 10^4$ t CO_2)

2001	2025							
	Water	Barren	Forest	Shrub	Cropland	Grassland	Impervious	Total
Water	101.1	-0.1	0.4	0.0	106.4	0.0	13.7	221.7
Barren	0.1	0.0	0.0	0.0	0.1	0.0	0.2	0.4
Forest	-0.1	0.0	272.3	0.0	123.5	0.2	-5.7	390.2
Shrub	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1
Cropland	3.8	-0.1	144.0	0.0	3864.8	0.2	-109.4	3903.4
Grassland	0.1	0.0	1.8	0.0	4.4	1.3	0.8	8.3
Impervious	5.4	0.0	0.1	0.0	7.3	0.0	397.6	410.4
Total	110.5	-0.2	418.6	0.0	4106.5	1.7	297.4	4934.5

Notably, while forest land maintained an area share of approximately 30% to 31% during the study period, its carbon sink increment only represented about 8.3% of the total increase. This is primarily attributed to the lack of significant improvement in forest carbon sink density. Between 2001 and 2025, forest carbon sink density increased by only about 0.027 kg CO_2/m^2. In contrast, cropland contributed a total of 41.06 Mt CO_2, accounting for 83% of the total growth. This indicates that in the YRD, the potential for carbon sink development is mainly concentrated in the high-quality protection and development of croplands.

3.3 Land Disturbance Analysis

Based on land-use evolution patterns and the fundamental mechanisms of carbon sink intensification, this study defines four types of disturbance zones (Figure 6).

1) Impact on Total Carbon Sink

In terms of total carbon sink amount (Figure 7), the YRD recorded an increase of 49.3 Mt CO_2 between 2001 and 2025. The ER Zone was the primary driver of this growth. It contributed a carbon sink increment of 45.1 Mt CO_2, representing 90.7% of the total increase. Combined with Table 4, it is evident that cropland carbon sinks are the most prominent component.

Human intervention zones contributed the remaining 9.3% of the carbon sink increment. Within these zones, HI-I intervention (ecological to constructive land) was the only human factor leading to a reduction in carbon sinks. This reflects the structural impact of land development during the reform and opening-up process in the YRD over the past 25 years. However, from a technical perspective, human activities achieved positive growth through specific management practices. These include supplementary planting and greening (HI-II) and forest silviculture (HI-III). HI-II contributed 1.0 Mt CO_2 (approx. 1.7%), while HI-III contributed 4.7 Mt CO_2 (approx. 7.6%).

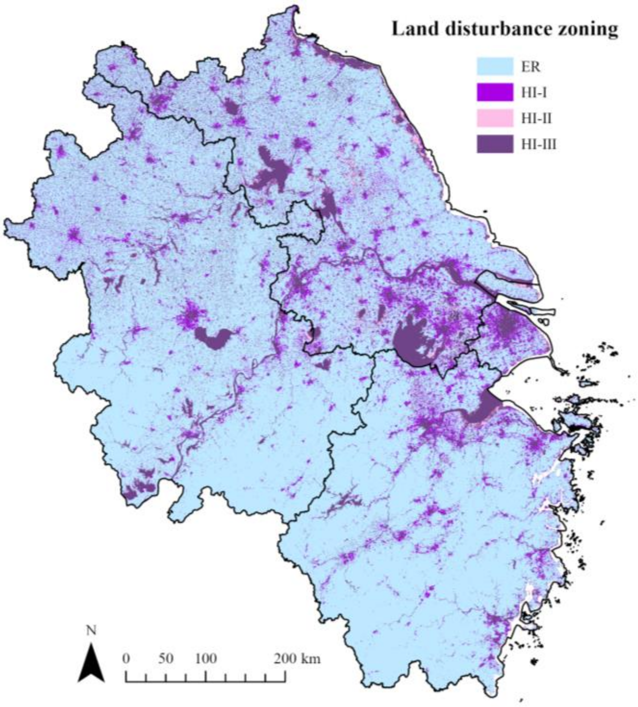

Figure 6: Land disturbance zoning in the YRD from 2001 to 2025

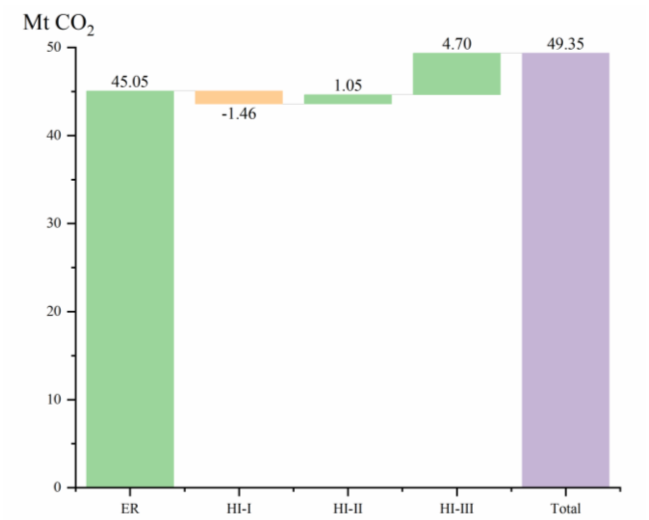

Figure 7: Total carbon sink changes under different land disturbances from 2001 to 2025

2) Interannual Variations in Carbon Sink Intensity

The influence of various disturbances on carbon sink intensification exhibited periodic fluctuations and consistent overall trends (Figure 8). Generally, the carbon sink intensity in HI-I zones was lower than that in the ER Zone. This directly illustrates the weakening of land carbon sequestration capacity under the urbanization trends of the YRD.

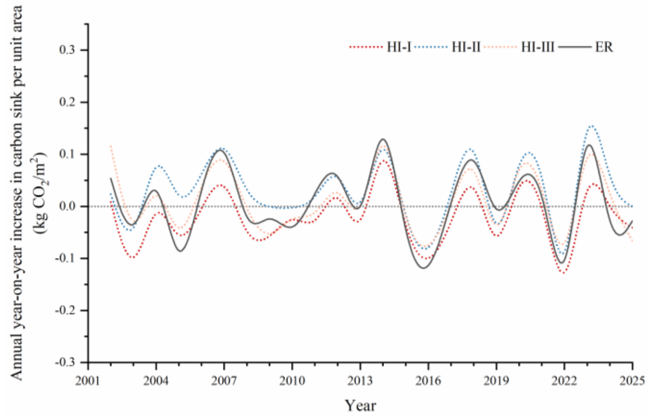

Figure 8: Carbon sink intensity changes under different land disturbances from 2001 to 2025

In contrast, HI-II and HI-III interventions maintained intensity levels similar to the ER Zone. Notably, since 2018, the carbon sink intensity increment in HI-II zones has surpassed that of the ER Zone. This suggests that humans have exceeded natural carbon sequestration capacities through active forest management, ecological compensation, and ecological restoration.

3) Spatial Heterogeneity and Climate Sensitivity

Ecological protection and human intervention disturbances show significant spatial heterogeneity across provinces and cities (Figure 9). Regarding the ER Zone, existing research suggests that intensified climate change alters vegetation phenology. This can lead to earlier or extended growing seasons and the strengthening or weakening of transpiration.

In the YRD, this phenomenon follows a latitudinal gradient. In higher-latitude regions, such as Shanghai, Anhui, and Jiangsu, carbon sinks within the ER Zone showed an increasing trend. Conversely, in the lower-latitude Zhejiang Province, the ER Zone strongly inhibited carbon sink growth. Between 2001 and 2025, this resulted in a decrease of 1.03 Mt CO_2 For human intervention zones, trends were more consistent. Both HI-II and HI-III enhanced carbon sinks. Except in Anhui, HI-I interventions reduced carbon sinks across the region. This indicates that ecological spaces, such as croplands and forests, have been effectively protected during urbanization. Consequently, human activity in the YRD has transitioned from being a "sink demand-side" to a "sink supply-side."

The localized negative impacts of ecological protection on carbon sinks are intensifying. Of the total reduction of 2.95 Mt CO_2 across all provinces (2001–2025), the ER Zone accounted for 1.03 Mt CO_2 (35%), while HI-I zones contributed 65%. While the negative impact of HI-I zones is a predictable outcome of urbanization, the decline within the ER Zone is alarming. This reflects complex, systemic shifts in vegetation phenology driven by climate change. Such unpredictable and uncontrollable characteristics cause strong fluctuations in carbon sequestration capacity. Ultimately, this may affect the progress toward regional carbon peak and carbon neutrality goals.

Previous studies identified carbon sink reductions in the southern YRD but primarily attributed them to urbanization and industrialization (Fang et al., 2025; Shen et al., 2025). However, a detailed analysis of Zhejiang's ER Zone reveals that areas remaining as forest land experienced the highest reduction (nearly 99%). This loss exceeded 5 Mt CO_2, representing approximately 2.2% of Zhejiang's total carbon sink in 2025. Therefore, environmental factors such as temperature, light, and humidity likely interfered with vegetation photosynthesis, thereby inhibiting carbon sink growth (He et al., 2020; Sun et al.).

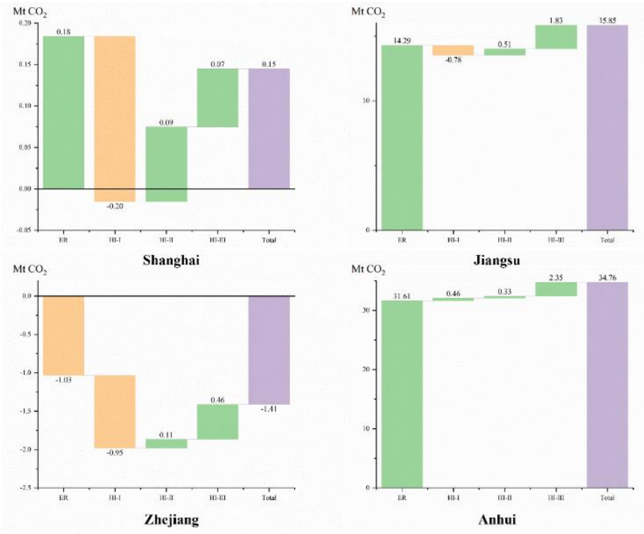

Figure 9: Carbon sink changes in provinces under different land disturbances from 2001 to 2025

4. Discussion

4.1 Periodic Growth and Cropland Conservation as Key Drivers

Between 2001 and 2025, the total volume and intensity of ecological carbon sinks in the Yangtze River Delta (YRD) exhibited a pattern of periodic fluctuating growth. The total carbon sink volume increased by 8.33%. Spatially, this growth demonstrated significant latitudinal heterogeneity, characterized by a "northward increase and southward decrease" pattern.

Anhui and Jiangsu Provinces, located at higher latitudes, recorded the most significant gains. This success is attributed to their robust ecological foundations and active afforestation projects. Specifically, Anhui's total carbon sink grew by 34.76 Mt CO_2, leading the entire region. In contrast, Zhejiang Province, situated at lower latitudes, experienced a decrease of 1.41 Mt CO_2 despite possessing the most abundant forest resources. This phenomenon reflects marked differences in ecological carrying capacity and carbon sink contributions across geographical zones. It also reveals how land-use changes reshape the spatial patterns of carbon sinks during regional economic integration. Furthermore, cropland contributed 41.06 Mt CO_2, accounting for 83.2% of the total increment. Consequently, future carbon sink development in the YRD must prioritize cropland nurturing and the active guidance of stakeholders, such as farmers.

4.2 Intensifying Local Negative Impacts in Ecological Reserve Zones

At a macro scale, ecological protection serves as the core driver of regional carbon sink intensification. It contributed 90.7% of the carbon sink growth in the YRD. However, its negative impact on specific local areas is intensifying due to global climate change.

The results show that within the local reduction of 2.95 Mt CO_2 across the YRD, the share from Ecological Reserve (ER) Zones was significant. In Zhejiang Province, the carbon sink in the ER Zone decreased by 1.03 Mt CO_2, representing the majority of the province's total loss. This decline is primarily attributed to systematic changes in vegetation phenology triggered by global warming. Extreme weather events, such as high temperatures and droughts, inhibit photosynthesis or intensify transpiration. These factors lead to severe fluctuations in the carbon sequestration capacity of ecosystems.

According to the Zhejiang Province Climate Change Adaptation Action Plan, average temperatures in the province will continue to rise. The frequency of extreme heat and heavy rainfall is also expected to increase. These trends will further amplify the potential complexity of carbon sink dynamics during ecological protection. Consequently, carbon sinks in protection zones are no longer merely passive growth factors driven by the CO_2 fertilization effect. Instead, unpredictable and uncontrollable negative feedback mechanisms are becoming critical variables. These variables will significantly influence the progress toward regional carbon peak and carbon neutrality goals.

4.3 Limitations

This study established a carbon sink accounting method based on NEP. Nevertheless, limitations remain in addressing climate change responses and micro-scale phenological differences.

The YRD spans multiple climate zones. As a result, vegetation succession and soil carbon turnover rates vary significantly across different provinces and cities. The conversion coefficient between NEP and NPP depends heavily on local precipitation, temperature, and soil moisture conditions. Future research should incorporate remote sensing platforms with higher spatial resolution. Additionally, studies should integrate field monitoring methods, such as flux observation towers and laboratory soil sampling analysis. Fine-scale calibration of model parameters across different regions and seasons will be essential. These improvements will enhance the accuracy of carbon sink accounting in response to extreme climate events and their associated ecological feedbacks.

5. Conclusions

This study provided a spatiotemporal dynamic analysis of ecological carbon sink evolution in the Yangtze River Delta (YRD) from 2001 to 2025. Results indicate that carbon sink distribution in the YRD exhibits significant heterogeneity. Specifically, it follows a pattern of being "rich in the south and scarce in the north" and "high in the west and low in the east." Furthermore, temporal trends show distinct periodic fluctuations.

The study identified clear differences in disturbances between ecological protection and human intervention. Out of the cumulative growth of 49.3 Mt CO_2, ecological protection contributed 91% of the carbon sink increment. Within this category, cropland management—dominated by agricultural activities—contributed over 83%. Additionally, the carbon density increment of forest land relative to cropland reached 14% to 35%. This suggests that the further development of forest carbon sink products by farmers offers substantial potential for carbon sequestration.

Carbon sinks in Ecological Reserve (ER) Zones possess characteristics such as nonlinearity. They are also difficult to predict or control. Consequently, traditional carbon sink accounting and evaluation systems require urgent reform. Regional quantification methods for carbon sinks and emissions should deeply integrate localized climate effects. Concurrently, to address negative feedbacks in local carbon sinks within ER Zones, this study advocates for embedding dynamic climate sensitivity models into the quantification process.

By identifying spatiotemporal heterogeneity and human intervention boundaries in carbon accounting, we can better evaluate the true efficacy of active management measures. These include ecological restoration and ecological compensation. Ultimately, this research provides a rigorous theoretical and methodological foundation. It supports the establishment of a unified, standardized carbon accounting system and facilitates the qualitative improvement of ecosystem carbon sequestration functions.

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