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# Mangrove Transplantation to the North: Carbon Sequestration Capacity—Drivers and Strategies

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## Abstract

Mangroves play a pivotal role in carbon sequestration. To investigate the characteristics and driving factors of carbon sequestration in planted mangrove forests, we focused on planted mangrove forests in Wenzhou City, Zhejiang Province, China. Through a statistical analysis of soil physicochemical properties and plant morphological characteristics, we assessed carbon stock distribution patterns and identified key influencing factors, providing scientific support for the northward expansion of mangroves. The results demonstrated significant differences in soil properties and plant morphological characteristics among different stands ($p < 0.05$). The mean soil carbon stock of restored planted mangroves was 78.75 Mg C/ha (mature stands: 87.84 Mg C/ha; middle-aged stands: 74.09 Mg C/ha; young stands: 74.31 Mg C/ha), while the average plant carbon stock was 12.28 Mg C/ha, indicating that soil is the primary contributor to carbon sequestration in mangroves. Compared to natural mangroves, the restored planted mangroves still exhibited a lower carbon sequestration capacity. The variations in carbon sequestration levels among the planted mangrove forests were mainly attributed to differences in tree species and age composition, hydrothermal conditions, and biomass carbon quantification methods. Key drivers of soil carbon sequestration included total phosphorus content, bulk density, and clay content. Carbon storage in restored planted mangroves depends on short-term soil carbon accumulation and long-term biomass carbon accumulation. Ultimately, we recommend optimal species selection and planting design, improved soil carbon storage mechanisms, and integrated conservation monitoring systems to enhance carbon sequestration in mangrove plantations.

**Keywords:** planted mangroves; carbon sequestration characteristics; carbon stock allocation; driving factors

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## 1. Introduction

Climate change is a significant environmental concern at the global level. The term 'coastal blue carbon' is used to describe the carbon fixed by ecosystems such as mangroves, seagrass beds, and salt marsh wetlands. These ecosystems play an important role in addressing global climate change and achieving carbon neutrality [1,2]. Mangrove ecosystems

are notable examples distinguished by their efficient capacity for carbon storage. Despite their presence in less than 0.1% of the world's oceans, mangrove ecosystems are estimated to store between two and ten times the annual sequestration rates (Mg C $ha^{-1}$ $yr^{-1}$) of terrestrial forests [3]. In the absence of significant disruption, mangrove forests can function as a carbon sink for up to a century, making an invaluable contribution to the mitigation of global climate change [4].

Previous studies demonstrated the capacity of natural mangrove ecosystems to sequester carbon, with plants and soil representing the primary carbon storage media. The total carbon stock (TCS) of mangrove ecosystems globally is 956 Mg C/ha [5], with South and Southeast Asia having the largest and most diverse mangrove forests on the planet, with a TCS of 1528 Mg C/ha [6]. Mangrove plants are tropical plants that grow in warm climates and have a high photosynthetic capacity and remarkable productivity. The majority of mangrove species are salt-tolerant, with well-developed specialized root systems comprising multiple airways, including strut, aerial, and respiratory roots. Additionally, they employ a unique form of reproduction called fetal budding, which enables them to assimilate carbon in saline and tidal environments. The primary mechanism responsible for soil carbon storage is the inhibition of organic matter decomposition processes in anaerobic environments of sediments. This allows for the long-term preservation of significant quantities of plant residues [7]. Furthermore, there is a mutual interaction between biomass carbon and soil carbon. The development of mangrove ecosystems has been observed to increase soil organic carbon (SOC) content, primarily through peat production, which holds much of the carbon in anaerobic environments. Additionally, the expansion of the soil's unstable carbon pool has been demonstrated to enhance long-term carbon sequestration [8].

Mangrove carbon sinks are typically influenced by a complex array of interrelated factors. The carbon stocks of mangrove plants are closely correlated with several factors, including the structure, species, litter production, maturity, and age of the forest [9,10]. As with other forests, mangrove forests exhibit variation in size and age, which in turn affect production rates and the balance between carbon production and respiration [4]. A study conducted in Colombia indicates that mangrove basal area and height are identified as pivotal factors in elucidating the variation in carbon storage within ecosystem compartments [11]. The primary factors influencing SOC stocks encompass total organic matter inputs, sediment characteristics, hydrodynamics, and microbial activity [12]. Higher nutrient loads have been demonstrated to increase the primary productivity of vegetation, which in turn leads to greater SOC stocks [13]. Mineral trapping is acknowledged as a significant mechanism for augmenting the soil carbon pool, with its efficacy contingent upon a range of sediment characteristics [12]. The trapping efficiency is inversely correlated with sediment grain size and directly correlated with mineral-specific surface area [14]. The presence of fine clay particles in sediments facilitates the formation of organic matter aggregates, strengthening carbon-particle binding. Clay minerals provide substantial specific surface area for organic carbon adsorption onto mineral matrices. Increased clay content also creates more favorable conditions for water retention [15,16], cation exchange [17,18], and soil structural stability [19,20], all of which promote SOC storage and accumulation. Additionally, higher soil bulk density not only affects mangrove root and seedling growth but also suppresses microbial activity [21], thereby slowing organic matter mineralization rates. This reduction in carbon release consequently enhances SOC storage [22,23]. Hydrodynamics affect carbon storage by regulating soil oxygen levels and the influx of freshwater and nutrients, which in turn influences the capacity for carbon sequestration. As a consequence of sea levels rising, the soil is subjected to both faster and longer periods of inundation, which in turn promote anoxic conditions and inhibit the aerobic decomposition of organic matter [24].

The natural dynamics of mangrove carbon stocks are controlled by geomorphic and biophysical environmental changes associated with topography, rainfall, freshwater inflow, tidal amplitude, and cyclone disturbances. Additionally, long-term land-use changes exert a significant influence on carbon loss and gain [25–28]. To illustrate, aquaculture shrimp farms that encroach upon mangrove forests exhibit diminished ecosystem carbon stocks, exhibiting a 50% reduction in comparison to undisturbed mangrove forests [29]. The artificial planting of mangroves has the potential to maximize the sequestration of soil organic carbon, thereby effectively preventing further carbon loss due to land-use change [30,31]. Planting mangroves can affect key parameters governing soil processes (such as pH, redox potential, and total organic carbon content), which regulate redox reactions and organic matter decomposition, thereby influencing the cycling of iron, carbon, and phosphorus [32]. The implementation of mangrove planting practices has been demonstrated to enhance the provision of essential soil ecosystem services, including the regulation of nutrients and the storage of carbon.

Natural mangrove forests are concentrated in tropical and subtropical coastal areas, primarily between latitudes 25° N and 25° S, and are highly susceptible to temperature fluctuations. Concurrently, mangrove forests are the sole tree species that can adaptively flourish in high-salt environments. These adaptive mechanisms give rise to mangrove forests exhibiting specialized growth patterns that are markedly distinct from those observed in other tropical or subtropical forests. Despite the importance of mangrove forests as natural solutions, there is still a paucity of research on the carbon storage capacity of artificially introduced mangrove forests and the factors affecting them, particularly concerning the practice of northward migration of mangrove forests. Mangrove forests in China are primarily concentrated in the southeastern coastal region, with the northernmost extent of their natural distribution occurring in Fuding City, Fujian Province. In light of the significant ecological roles played by mangrove forests in safeguarding coastlines, mitigating wave impacts, and sustaining biodiversity, Zhejiang Province launched a project to introduce and cultivate mangrove forests in Yueqing Bay during the late 1950 s. This initiative was undertaken in response to the degradation of coastal mudflats. To date, mangroves have been successfully introduced and cultivated in Longgang City, Cangnan City, and Pingyang County in Wenzhou.

This study employed a case study approach to investigate the carbon sequestration characteristics and carbon stock allocation patterns in northward-migrating mangrove forests in Wenzhou City, Zhejiang Province, China. To this end, 27 sample plots were selected from three mangrove-monitoring transects. The study objectives were threefold: (1) to examine the carbon sequestration drivers in northward-migrating mangrove forests; (2) to assess the short- and long-term carbon accumulation in these forests; and (3) to identify the carbon sequestration characteristics and patterns in northward-migrating mangrove forests. Ultimately, recommendations are provided for the northward migration of planted mangrove forests. The findings of this study will provide managers with direct evidence of carbon sequestration in northward-migrating mangrove forests, thereby supporting the development of effective policies for the northward migration of mangrove forests and the management of coastal blue carbon ecosystems in the future.

## 2. Materials and Methods

### *2.1. Study Area and Sampling*

The study area is situated within the Mangrove Provincial Wetland Park in Longgang City, Wenzhou City, Zhejiang Province, China (27°32′42″~27°35′21″ N, 120°38′53″~120°30′50″ E). The study area is situated within the subtropical monsoon climate zone, with a multi-year average temperature range of 17.3 to 19.4 °C, and a maximum extreme temperature of

41.3 °C and a minimum of −4.5 °C. The majority of precipitation occurs between May and September, with an average annual precipitation of approximately 1100 to 2200 mm. The study area is situated at the confluence of the Aojiang River, where the tide is influenced by the shallow sea. The tides are mixed semi-diurnal tides, with a maximum tide difference of 6.41 m and an average tide difference of 4.25 m. The Longgang Mangrove Provincial Wetland Park initiated the planting of mangrove forests in 2007. Currently, the mangrove forests cover an area of approximately 11.8 hectares and consist of a single species of vegetation, namely *Kandelia obovata.*

The sampling period is from July to September 2022. Three mangrove monitoring sites were established in Longgang Mangrove Provincial Wetland Park: MF1, MF2, and MF1 (Figure 1). The *Kandelia obovata* trees at the MF1 site were 1–3 years old (Young forests), while those at MF2 were 10–20 years old (Old-growth forests), and those at MF3 were 4–9 years old (Middle-aged forests). A monitoring station was established in each high-tide (tidal flat elevation > 3 m), mid-tide (1–3 m), and low-tide (<1 m) zone within each monitoring site. Furthermore, a bare beach monitoring section (BM1) was established (Figure 1). In consideration of the principles of safety and accessibility, three 10 m × 10 m mangrove vegetation fixed sample plots were established at each monitoring station, resulting in a total of 27 sample plots. Markers were placed at the corners of each sample plot to indicate the section and sample plot number, and the types, quantities, stem height, and trunk diameter of the plants in each sample plot were recorded. In the fixed mangrove vegetation sample plots and the bare beach monitoring section, the surface litter on the soil was removed, and soil columns approximately 100 cm long were collected using a 60-mm-diameter half-round chisel. The soil columns were divided into 8 layers, 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, 50–70 cm, 70–90 cm, and 90–100 cm, to collect a total of 224 samples.

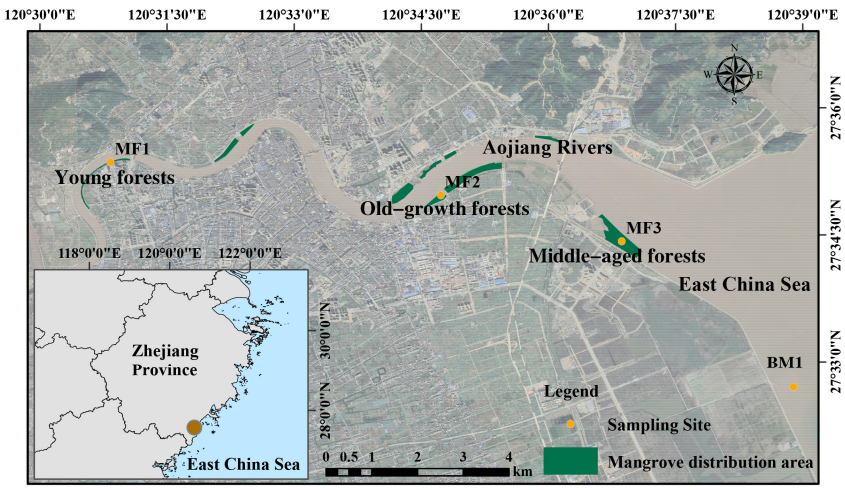



**Figure 1.** Distribution of mangrove sampling and monitoring sites.

### 2.2. Measurement of Soil Properties

The determination of soil physicochemical properties was undertaken using the methods mentioned by Lu (1999) as a reference [33]. Undisturbed soil samples were used to determine the bulk density (BD) by the ring knife method. Soil particle size distributions of sand (SA, 0.02–2 mm), silt (SI, 0.002–0.02 mm), and clay (CL, <0.002 mm) were assayed by the Mastersizer 2000 instrument (Malvern Panalytical, Malvern, UK) [34]. SOC was obtained with the potassium dichromate (Chongqing Changyuan Chemical Group Co., Ltd., Chongqing, China)and external heating method [35]. TN and TP were analyzed by the Kjeldahl method and Mo-Sb colorimetric approach, respectively [36,37].

### 2.3. Analysis of Carbon Stock

The total mangrove carbon stock (TCS) is the sum of the plant carbon stock (PCS) and the soil carbon stock (SCS). The formula is as follows:

$$TCS = SCS + PCS \quad (1)$$

where TCS is the total mangrove carbon stock (Mg C/ha), SCS is the soil carbon stock (Mg C/ha), and PCS is the plant carbon stock (Mg C/ha).

The SCS is quantified by multiplying the soil BD, SOC, and soil thickness [38]. The formula is as follows:

$$CSS = \sum_{i=1}^{m} SD_i \times BD_i \times SOC_i \quad (2)$$

where $SD_i$ is the soil depth (m), $BD_i$ is soil bulk density ($g/cm^3$), $SOC_i$ is soil organic carbon content (%), and m is the number of soil sampling layers.

The PCS is quantified by multiplying the mangrove biomass per unit area by a carbon density factor.

$$CSMF = BIO \times f \quad (3)$$

where BIO is the mangrove biomass per unit area (g), which encompasses trunk biomass, root and branch base biomass, and leaf biomass following Equations (4) and (5), and f is the carbon density coefficient, which is assumed to be 0.5.

The biomass of the mangrove plants was determined using the allometric growth model equation (Equation (4)) [39], while the mangrove biomass per unit area was determined based on the sample area (Equation (5)).

$$BIO_i = 3.614D_i^{1.446} \quad (4)$$

$$BIO = (3.614\sum_{i=1}^{n} D_i^{1.446})/A \quad (5)$$

where $BIO_i$ is the biomass of the ith mangrove plant, including trunk biomass, root system and branch base biomass and leaf biomass (g), $D_i$ is the trunk diameter, which is the diameter of one-tenth of the length of the trunk near the ground position of the trunk of each plant (mm), BIO is the biomass of mangrove plant per unit area (Mg/ha), n is the number of mangrove plants in the sampling area, and A is the area of the plot area ($m^2$).

### 2.4. Statistical Analysis

Data were statistically analyzed using SPSS 22.0 software. Figures were generated using ArcGIS 10.5 and Origin 2021 software. The Kruskal–Wallis H-test and Kruskal–Wallis one-way ANOVA multiple comparisons were employed to assess the variability of mangrove soil physicochemical properties, plant morphology, and other parameters, with a significance level of $p < 0.05$ for the detection of differences. The relationship between environmental variables and SOC content and soil carbon density (SCD) was investigated using the redundancy analysis (RDA) function of Canoco 5.0 software.

## 3. Results

### 3.1. Physical and Chemical Characteristics of Mangrove Soil

Following the physical and chemical characterization of the mangrove soil (Table 1), it was determined that the mean value of soil bulk density was 1.14 $g/cm^3$, with a low standard deviation and coefficient of variation, indicating that the soil BD was relatively stable within the study area. The mean value of SOC content was 0.73%, while the mean value of SCD was 7.93 Mg C/ha. The mean values of TN and TP were 0.49 g/kg and 0.63 g/kg, with standard deviations of 0.23 g/kg and 0.17 g/kg, respectively. Notably, the coefficient of variation of TN was higher than that of TP. In particular, the mean value of

the C/N ratio was 21.59, indicating a relative enrichment of carbon in the soil. As a typical area susceptible to tidal influences, the soil texture was predominantly silt, with a mean value of 67.19%, while the content of sand and clay was relatively low.

**Table 1.** Statistics of soil and plant characteristic parameters of mangrove forests.

| Parameters | Mean | SD | SE | CV | 95% Confidence Interval |
|---|---|---|---|---|---|
| Soil parameters | | | | | |
| BD ($g/cm^3$) | 1.14 | 0.20 | 0.02 | 0.17 | (1.10, 1.18) |
| SOC (%) | 0.73 | 0.24 | 0.03 | 0.33 | (0.67, 0.79) |
| SCD (Mg C/ha) | 7.93 | 1.95 | 0.22 | 0.25 | (7.38, 8.48) |
| TN (g/kg) | 0.49 | 0.23 | 0.04 | 0.46 | (0.26, 0.72) |
| TP (g/kg) | 0.63 | 0.17 | 0.03 | 0.27 | (0.53, 0.73) |
| SA (%) | 2.02 | 0.88 | 0.20 | 0.44 | (1.59, 2.45) |
| SI (%) | 67.19 | 4.37 | 0.98 | 0.07 | (64.90, 69.48) |
| CL (%) | 30.79 | 4.85 | 1.08 | 0.16 | (28.48, 31.10) |
| SCS (Mg C/ha) | 78.75 | 10.76 | 2.07 | 0.14 | (74.25, 83.25) |
| Plant parameters | | | | | |
| H (cm) | 140.73 | 120.45 | 24.59 | 0.86 | (84.66, 196.8) |
| D (mm) | 47.52 | 22.94 | 4.68 | 0.48 | (37.27, 57.77) |
| DMF (plant/$m^2$) | 3.50 | 3.60 | 1.27 | 1.03 | (0.20, 6.80) |
| BIO (Mg/ha) | 26.82 | 27.32 | 5.58 | 1.02 | (15.48, 38.16) |
| PCS (Mg C/ha) | 12.28 | 13.25 | 2.07 | 1.08 | (6.97, 17.59) |

BD, SOC, SCD, TN, TP, SA, SI, CL, and SCS indicate bulk density, soil organic carbon content, soil carbon density, total nitrogen, total phosphorus, sand content, silt content, clay content, and soil carbon stock. H, D, DMF, BIO, and PCS indicate plant height, trunk diameter, plant density, biomass per unit area, and plant carbon stock.

The spatial distribution of soil properties in young (MF1), old-growth (MF2), and middle-aged (MF3) mangrove forests was analyzed (Figure 2), and significant differences were observed in soil BD, SOC content, SCD, TN, TP and C/N ratio in mangrove forests of different stands ($p < 0.05$). The BD of middle-aged forests was found to be significantly higher than that of young forests ($p < 0.05$), with mean values of 1.17 $g/cm^3$ and 1.04 $g/cm^3$, respectively. The BD of old-growth forests was also observed to be higher than that of young forests; however, this did not reach a significant level. The SOC content was found to be significantly higher ($p < 0.05$) in old-growth forests than in middle-aged forests, with mean values of 0.81% and 0.64%, respectively. The SOC content was found to be higher in both the old-growth and middle-aged forests than in the young forests; however, this did not reach a statistically significant level. The mean value of SCD was 8.78 Mg C/ha in the old forest, which was significantly higher than the values observed in the young forest (7.43 Mg C/ha) and the middle-aged forest (7.41 Mg C/ha) ($p < 0.05$). The distribution of TN, TP, and C/N ratio exhibited a discernible temporal pattern across the various stages of mangrove development. The mean value of TN content in the middle-aged forest was 0.73 g/kg, which was 2.46 times higher than that of the young forest and 1.60 times higher than that of the old-growth forest, respectively. Furthermore, this value was significantly higher than that of the young forest and the old-growth forest ($p < 0.05$). The mean value of TP content in the old-growth forest was 0.78 g/kg, which was significantly higher than that in the middle-aged and young forests ($p < 0.05$). Furthermore, the soil C/N ratios of the young and old-growth forests were significantly higher ($p < 0.05$) than those of the middle-aged forests, being 3.26 and 2.67 times higher, respectively.

The vertical distribution of soil properties in young (MF1), old-growth (MF2), and middle-aged (MF3) mangrove forests were analyzed (Figure 3). The soil BD and SCD of each layer in the sample plots of mangrove forests of different stands exhibited similar vertical distribution patterns, which increased with depth. The bottom layer BD and SCD were approximately 1.5 times that of the surface layer. The SOC content of the old-growth forest

exhibited a decrease with depth, with the SOC content of the bottom layer representing 62% of that of the surface layer. In contrast, no significant decrease was observed in the young and middle-aged forests ($p > 0.05$). The TN and TP contents of the soil exhibited a decline with increasing depth, with the majority of these elements concentrated in the 0–50 cm layer. In contrast, the soil C/N ratios in middle-aged and old-growth forests demonstrated stability throughout the depth profile ($p > 0.05$), whereas the mean soil C/N ratio in young forests exhibited an increase from 17.74 in the surface layer to 57.84 in the bottom layer.

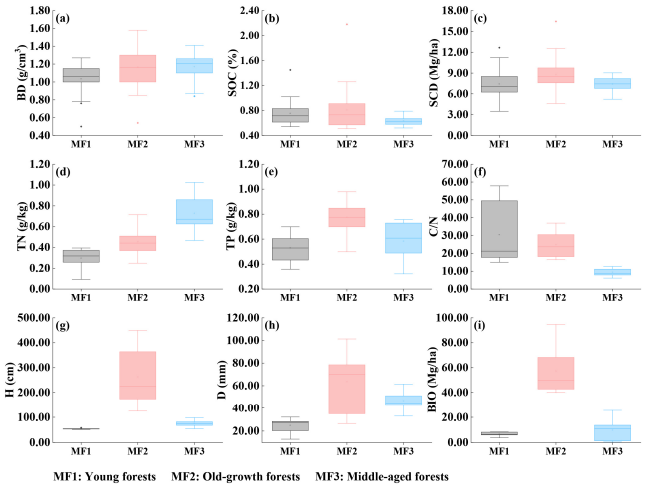



**Figure 2.** Spatial distribution characteristics of mangrove soil and plant properties. (**a**) Bulk density; (**b**) organic carbon content; (**c**) soil carbon density; (**d**) total nitrogen; (**e**) total phosphorus; (**f**) C/N ratio; (**g**) plant height; (**h**) trunk diameter; and (**i**) biomass per unit area.

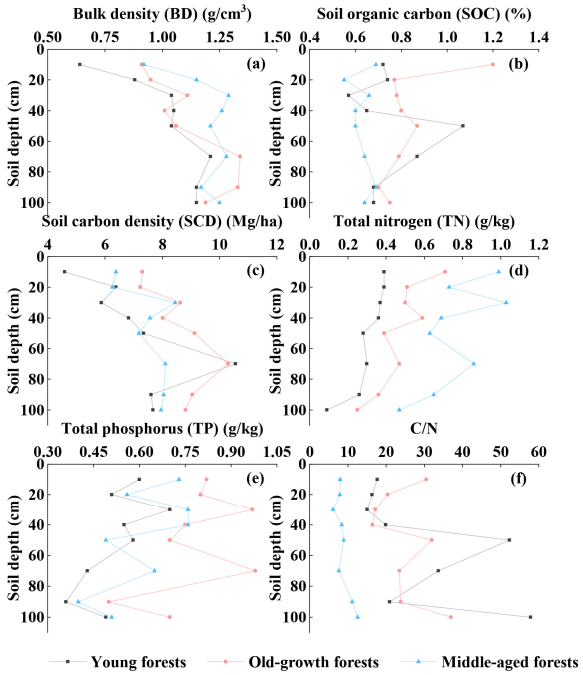



**Figure 3.** Vertical distribution characteristics of mangrove soil properties. (**a**) Bulk density; (**b**) organic carbon content; (**c**) soil carbon density; (**d**) total nitrogen; (**e**) total phosphorus; and (**f**) C/N ratio.The values of soil property indicators at varying depths are the means of all sample plots at the corresponding depth.

### *3.2. Morphological Characteristics of Mangrove Plants*

The mean values of mangrove plant height and trunk diameter were 140.73 cm and 4.75 mm, respectively, with standard deviations of 120.45 cm and 2.29 mm, respectively

(Table 1). These results demonstrate a considerable degree of variability in plant morphology. The coefficients of variation for plant density and biomass per unit area were 1.03 and 1.02, respectively, indicating a lack of uniformity in the distribution of plants across the mangrove sample plots.

Significant differences were observed in plant height, trunk diameter, and biomass per unit area of mangrove forests across different stands ($p < 0.05$) (Figure 2). The plant height and biomass per unit area were found to be significantly higher ($p < 0.05$) in old-growth forests than in young and middle-aged forests. The plant height of the old-growth forest was 4.87 and 3.48 times higher than that of the young and middle-aged forests, respectively, while the biomass per unit area was 8.75 and 5.80 times higher than that of the young and middle-aged forests, respectively. The mean trunk diameter was significantly greater in the middle-aged and old-growth forests, with a mean value of 46.61 mm and 63.64 mm, respectively, compared to the young forest, with a mean value of 37.86 mm ($p < 0.05$).

### *3.3. Allocation Pattern of Mangrove Carbon Stock*

The TCS in mangroves is composed of PCS and SCS. The PCS encompasses the carbon stored in the trunk, root system, and branch bases, as well as the leaves. The SCS is dependent upon the SOC content of the soil surface layer, extending up to a depth of 1 m. The mean value of SCS was found to be 78.75 Mg C/ha, with a coefficient of variation of 0.14 (Table 1), which suggests that the SCS in the study area is relatively stable. The mean PCS value was found to be 12.28 Mg C/ha, with a standard deviation of 13.25 and a coefficient of variation of 1.08. These results indicate the presence of regional variability in the PCS among the sample sites. The ratio of soil to plant carbon stocks was approximately 6:1. In general, soil carbon sequestration was the primary contributor to mangrove carbon sequestration.

The distribution of PCSs across different forest stands is visualized in Figure 4. The SCS was found to be 87.84 Mg C/ha in old-growth forests, which was higher than the 74.31 Mg C/ha and 74.09 Mg C/ha recorded in young and middle-aged forests, respectively. However, the observed difference was not deemed to be significant ($p > 0.05$). Significant differences were observed in the TCS and PCS between the different forest stands ($p < 0.05$). The mean PCS value in old-growth forests was 28.64 Mg C/ha, which was significantly higher than that in young and middle-aged forests ($p < 0.05$). Furthermore, it was 8.75 times higher than that in young forests and 5.80 times higher than that in middle-aged forests, respectively. The mean value of the TCS in the old-growth forest was 116.48 Mg C/ha, which was significantly higher than that of the young and middle-aged forests ($p < 0.05$).

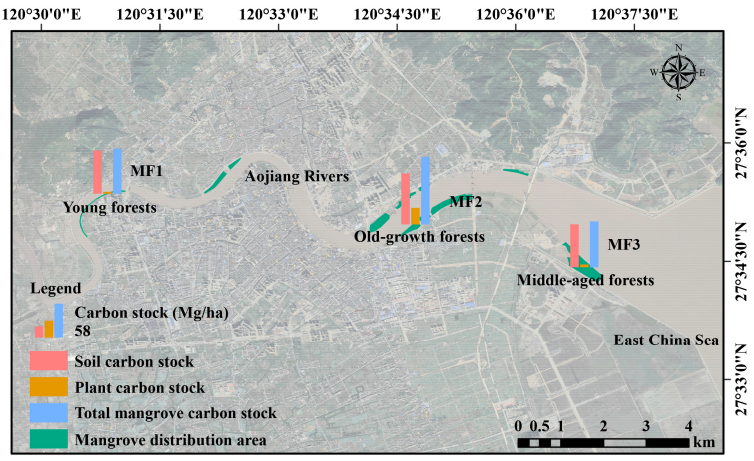



**Figure 4.** Spatial distribution characteristics of mangrove carbon stocks. The values of total mangrove carbon stock, soil carbon stock, and plant carbon stock are the mean of all sample plots.

### 3.4. Relationship Between Mangrove Soil Carbon Sequestration and Environmental Factors

Redundancy analysis (RDA) was employed to elucidate the associations between soil carbon sequestration and environmental factors, with the results being presented in Figure 5. The environmental factors collectively explained 65% of the variation in the response variables. The first axis of the redundancy analysis (Axis-1) dominated the data variation (eigenvalue 0.6385, explanatory power 63.85%, pseudo-canonical correlation coefficient 0.99). Three significant factors ($p < 0.05$) were identified, with their contribution rates ranked as follows: BD (40.3%) > TP (33.5%) > CL (20.7%).

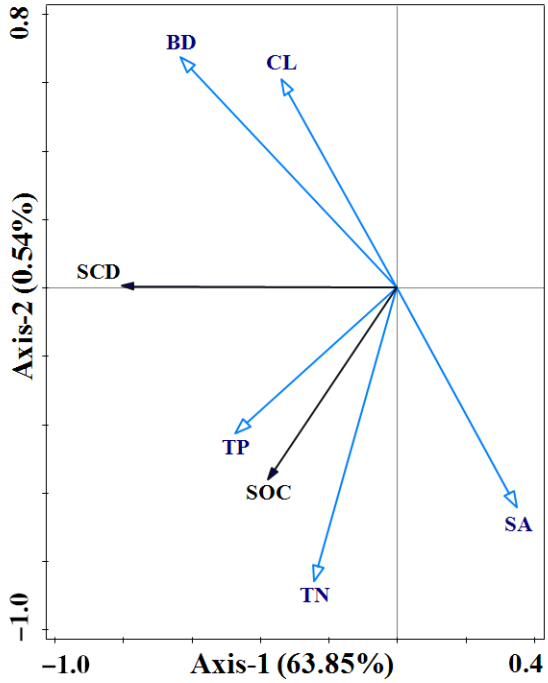



**Figure 5.** RDA sequencing of correlations between mangrove soil organic carbon content, soil carbon density, and environmental factors. CL, BD, SCD, TP, SOC, TN, and SA indicate clay content, bulk density, soil carbon density, total phosphorus, soil organic carbon, total nitrogen, and sand content.

## 4. Discussion

### 4.1. Comparison of Carbon Sequestration Characteristics of Planted and Natural Mangroves

This study revealed that soil carbon stocks (SCS) in mangroves ranged from 70.69 to 107.22 Mg C/ha, with a mean of 78.75 Mg C/ha, while plant carbon stocks (PCS) varied between 0.26 and 47.33 Mg C/ha, averaging 12.28 Mg C/ha. Although these are not equivalent systems, comparative analysis with similar study areas reveals that these values are significantly lower than those reported in other regions of China. For instance, mangroves in Hainan Province exhibit substantially higher SCS (159.14 Mg C/ha) and PCS (192.00 Mg C/ha) [40], while those in Yingluo Bay (Guangdong Province) record SCS and PCS values of 238.02 Mg C/ha and 85.99 Mg C/ha, respectively [41]. Similarly, in Beihai City (Guangxi), mean SCS and PCS reach 185.10 Mg C/ha and 20.98 Mg C/ha [24]. On a global scale, the carbon stocks in this study area represent only 12% of those observed in high-carbon mangrove ecosystems such as South Sulawesi (Indonesia) and Pongara National Park (Gabon) [42,43]. Furthermore, the SCS and PCS in this region account for just 24.85% and 11.54%, respectively, of the levels documented in the Mekong Delta (Vietnam) [44].

The carbon storage capacity of the transplanted rehabilitated planted mangrove forests in the study area remains lower than that of other regions. Firstly, considerable variation was observed in carbon storage among different tree species and age groups [25,45–47]. The tree species in the study area were dominated by Kandelia obovate, and were rela-

tively homogeneous and generally younger, with limited capacity for carbon sequestration. In contrast, mangrove species are prevalent in Hainan Province, Beihai City of Guangxi Zhuang Autonomous Region, Zhanjiang City of Guangdong Province, the Mekong Delta of Vietnam, etc. These include Avicennia marina, Aegiceras corniculatum, Rhizophora stylosa, Bruguiera gymnorrhiza, and others. The diversity of mangrove species not only increases the biomass of mangrove forests but also enhances the carbon storage capacity of both above-ground vegetation and below-ground soil. Additionally, these regions encompass areas of naturally developing mature mangrove forests with extended histories and considerable potential for carbon storage. For instance, Bruguiera sexangula in a mature mangrove forest in Qinglan Bay, Hainan Province, can attain ages exceeding 100 years [10], whereas the majority of Kandelia obovata old-growth forests within the study area are between 10 and 20 years old. Secondly, climatic factors play a significant role in this disparity: the study area is situated in the mid-latitudes, where the mean annual temperature is approximately 10 °C lower and annual precipitation is ~1000 mm less than in tropical mangrove habitats. Additionally, light intensity and sunlight duration are 30% and 20% lower, respectively, compared to tropical regions. These conditions enhance photosynthetic efficiency in tropical mangroves, facilitating greater organic carbon accumulation in surface soils [24,48]. In contrast, the suboptimal hydrothermal conditions (lower temperature and precipitation) in the study area constrain both mangrove photosynthesis and soil carbon sequestration potential. Finally, it should be noted that the biomass determination method, the value of the carbon density coefficient, and the depth of the soil carbon stock calculation may also differ in different regions [1,49]. In the case of Hainan, China, for instance, a more precise methodology for determining biomass and a more logical value for the carbon density coefficient have been employed in long-term research and practice [40,50,51]. Biomass encompasses both the above-ground and below-ground components of an organism, as well as litter. As the mangrove forests under examination have been planted, the determination of biomass and the calculation of carbon density are based on the findings of studies conducted on natural mangrove forests. Concerning the SCS calculation depth, it should be noted that although the study employs a calculation depth of 1 m of SCS, consistent with the current guidelines for assessing carbon stock in blue carbon ecosystems, in actual practice, different calculation depths are utilized, including 0.3 m, 0.6 m, 2 m, 3 m and 3.5 m [24,43,52–54]. The SCS will be significantly increased when a deeper calculation depth is adopted.

In natural mangrove ecosystems, SCSs typically constitute a significant portion of the ecosystem, often exceeding 50% [55]. The soil type and fertility of different areas will result in variations in SCSs, consequently influencing the ratio of soil to plant carbon stocks [29,56,57]. In this study, the ratio of soil to plant carbon stocks in planted mangrove forests was approximately 6:1, indicating that both planted and natural mangrove forests exhibit a comparable pattern of carbon stock allocation and that soil carbon plays a pivotal role in carbon storage. In comparison to natural mangrove forests, transplanted rehabilitated planted mangroves may require a longer period to achieve an equivalent level of carbon storage capacity [30]. Natural mangroves typically exhibit a longer growth history and more stable ecosystem dynamics, resulting in a relatively slower but more sustained rate of carbon accumulation. While transplanted rehabilitated planted mangrove forests may achieve a faster rate of carbon accumulation through scientific planting and management methods at the initial stage, this may be limited by a variety of factors at a later stage. These include species selection, climate change, ecosystem stability, and human activities. It remains to be seen whether transplanted rehabilitated planted mangrove forests can be made to approach the carbon storage capacity of naturally growing mangroves.

### 4.2. Drivers of Mangrove Carbon Sequestration

The results of the redundancy analysis indicated a significant positive correlation between the TP content of mangrove soil and the SOC content and SCD. This is consistent with the research results of red mangrove forests in Beihai City, Guangxi and the state of Sergipe, Brazil [24,58]. The main reason is that the sufficient supply of phosphorus provides strong support for the growth of mangrove plants, resulting in an increase in plant biomass and an enhancement in the production of litter. The decomposition of plant residues will increase the content of soil organic carbon (SOC). Furthermore, phosphorus is an essential component of microbial cell structure and enzyme activity, and plays a positive role in the decomposition of organic matter [59]. By participating in the decomposition of organic matter, phosphorus provides a rich source of precursor substances for the accumulation of soil organic carbon. Soil BD is a structural indicator of soil, reflecting the degree of compactness and porosity of the soil [60]. This study found that a significant positive correlation was observed between soil BD and clay content and SCD. An increase in soil BD typically signifies a reduction in the interstitial space between soil particles, resulting in a more compacted soil structure [61]. In this instance, the immobilization of soil carbon is facilitated within the interstitial spaces between soil particles, resulting in augmented SCD. Soil BD exerts a significant influence on the solute movement and water-holding capacity of the soil [62], which in turn affects the rate of organic matter mineralization and the ultimate SOC content. This study also found that the patterns of SOC content and SCD exhibited differences in their vertical distributions (Figure 3b,c). The vertical distribution patterns of SCD were observed to be similar across different monitoring sites, which is likely attributable to changes in soil BD. Additionally, clay particles typically exhibit a range of sizes below 2 μm, coupled with a substantial specific surface area and a high adsorption capacity [51]. Soils with finer particle sizes act as organic matter aggregates, effectively binding carbon to the particles. This particle binding results in the sequestration of organic matter and the limitation of the enzymatic reactions that catalyze organic matter decomposition, oxidation, and carbon dioxide release from the soil. These processes lead to an increase in soil carbon storage [12].

However, the excessive addition of phosphorus may contribute to the emission of greenhouse gases from mangrove soils and result in a depletion of the TOC, which could ultimately lead to a loss of carbon stocks [63]. The formation and stabilization of soil aggregates are adversely impacted when soil BD is elevated. Additionally, compacted soil impedes root growth, expansion, and microbial activity, which in turn influences the input, decomposition, and transformation of organic carbon [64–67]. The aforementioned phenomena illustrate that the relationship between soil's physical and chemical properties and SOC is not a straightforward, linear correlation [68]. Furthermore, it is important to acknowledge that the accumulation of organic carbon in mangrove forests is regulated by a complex interplay of environmental factors. While sediment properties are significant factors influencing the carbon accumulation capacity of mangrove forests in Wenzhou City, the hydrodynamic characteristics of mangrove forests dominated by estuaries are also of paramount importance and can play a pivotal role in driving carbon accumulation. Hydrological conditions result in a periodic inundation and exposure of soils to seawater. In such circumstances, soils exhibit lower redox potentials and higher salinities, which inhibit excessive microbial decomposition and the release of organic carbon [69]. This, in turn, slows the rate of decomposition and favors the accumulation and preservation of organic carbon. However, mangrove planting areas are susceptible to tidal influences and inputs from various rivers. Increases in water body exchange and sediment fluxes can facilitate horizontal carbon transport, which ultimately reduces carbon accumulation [70,71]. It is thus imperative to consider the interactions of multiple environmental factors comprehensively when study-

ing the drivers of carbon sequestration in mangrove forests to effectively manage carbon sinks in mangrove forests.

### 4.3. Difference Between Short-Term and Long-Term Carbon Accumulation in Planted Mangrove Forests

The mean SCS value was determined to be 74.31 Mg C/ha in forests planted for 1–3 years, 74.09 Mg C/ha in forests planted for 4–9 years, and 87.84 Mg C/ha in forests planted for more than 10 years. No statistically significant difference was observed ($p > 0.05$). Additionally, this study determined the mean SCS value in the bare beach to be 57.35 Mg/h. The artificial planting of mangrove forests resulted in a 30% increase in the SCS during the first three years, a result that is consistent with the findings of 684 studies on the artificial planting of mangrove forests worldwide [30]. Concurrently, a field study conducted in a reforestation project in southeastern China also demonstrated that the increase in the SCS in planted mangrove forests was particularly pronounced during the initial growth period (0–5 years) [55], thereby further substantiating the rapid accumulation of soil carbon in planted mangroves in the short term. In the long term, there is no significant change in the SCS in planted mangrove forests. The study of transplanted rehabilitated planted mangrove forests in Ximen Island, Wenzhou City, Zhejiang Province, also demonstrated that SCS exhibited exponential growth during the initial phase of mangrove planting, reaching an asymptotic trend after 15 years of mangrove planting [72]. In contrast to the rapid increase in short-term SCSs, long-term SCSs demonstrated a slower growth rate or even stabilization.

The mean value of biomass per unit area was determined to be 6.55 Mg/ha in forests planted for 1–3 years, 9.87 Mg/ha in forests planted for 4–9 years, and 57.28 Mg/ha in forests planted for more than 10 years. The PCS increased from 3.27 Mg C/ha in the young forest to 28.64 Mg C/ha in the old-growth forest. The mean value of PCS in the old-growth forest was significantly higher than that in the young and middle-aged forests ($p < 0.05$), indicating that with the passage of time, the mangrove plants continued to grow and the PCS continued to increase. In general, the carbon stock of planted mangrove forests is primarily dependent on the rapid accumulation of soil carbon in the short term. However, in the long term, it is mainly reliant on the accumulation of biogenic carbon, which gradually reaches a state of stability.

In the process of long-term ecosystem development, there is an interaction between plant and soil carbon, which serves to maintain the carbon balance of the planted mangrove ecosystem. On the one hand, soil nutrients and water content influence plant growth and biomass accumulation. As an illustration, regions exhibiting elevated soil nitrogen and phosphorus levels also demonstrate enhanced mangrove biodiversity and soil carbon reserves, which in turn facilitate the accumulation of plant carbon [24,58]. On the other hand, an increase in biomass will provide the soil with a greater quantity of litter and root secretions, which provide a rich source of nutrients for microorganisms and accelerate their activities, thus promoting the accumulation of soil carbon.

### 4.4. Suggestions for the Management and Protection of Transplanted Rehabilitated Planted Mangrove Forests and Implications for the Northward Migration of Mangrove Forests in China

Mangrove forests play a vital role in marine ecosystems, serving as a vital purifier of coastal water quality, a carbon sink, a wind and wave barrier, and a protective embankment [7,73]. In response to the decline in mangrove forests, numerous countries have implemented mangrove afforestation programs over the past few decades. In light of the growing concerns about climate change, the sequestration of carbon has also been identified as a key objective of mangrove conservation and afforestation [73,74]. In China, for instance, approximately 7200 hectares of new mangrove forests have been established

over the past two decades, making it one of the few countries in the world to have experienced a net increase in mangrove area over the past 20 years. However, the management of transplanted rehabilitated planted mangrove forests still presents several challenges, including interference from human activities, environmental pollution, sea level rise, and the invasion of exotic species. The mangrove forests that flourish in estuaries and bays are susceptible to contamination from a range of wastewater and marine waste sources [59]. The accumulation of pollutants, sedimentation, and the presence of unmanaged marine debris have a detrimental impact on the sustainability of mangrove habitats and ecosystems. The population structure of transplanted rehabilitated planted mangrove forests is typically homogeneous, exhibiting low biodiversity and fragility. The proliferation of exotic species, such as Spartina alterniflora, has emerged as a significant threat to the growth of mangrove forests. This expansion hurts the source and stability of SOC in mangrove ecosystems, leading to a decline in SCSs [75,76]. Therefore, the treatment and disposal of pollutants in estuaries and bays should be strengthened to protect the mangrove habitat environment, as it is suitable for the location. Other actions to be carried out include determining the appropriate planting density, carrying out plant configuration, enriching the mangrove plant community configuration, and forming a composite community; strengthening the prevention and control of foreign pests, further removing S. alterniflora that threatens the growth of dominant species, and preventing and controlling harm caused by organisms such as barnacles to restore plants.

Among the many challenges, the northward migration of mangrove forests is undoubtedly one of the greatest. Based on the MaxEnt model and 22 bioclimatic variables [77], identified suitable areas for restoration in China, the northernmost of which is located in Zhejiang Province. Kandelia obovata, a cold-tolerant species of subtropical native mangrove forest, is projected to migrate northward from 26.8° N to the estuary of the Yangtze River (31.9° N) by 2100 when its optimal habitat is anticipated to be available. While climate change presents potential opportunities for the northward expansion of mangroves, it simultaneously introduces significant challenges. According to the IPCC's Sixth Assessment Report (Climate Change 2021: The Physical Science Basis), the frequency and intensity of extreme cold events have declined since the 1950 s. However, projections indicate an increased likelihood of compound extreme events in future climate scenarios. From a long-term adaptation perspective, the viability of northward-transplanted mangrove plantations may demonstrate a "phased dynamic" survival pattern. In the short term, assuming stable warming trends, these forests could potentially develop enhanced resilience as they mature (e.g., beyond 10 years of establishment). Nevertheless, the increasing frequency of extreme climate events may ultimately constrain species survival, representing a critical bottleneck for successful migration. Secondly, migration must be balanced with the need to maintain the overall ecosystem structure and ensure its sustainable development [78,79]. From an ecosystem structure perspective, there is a notable decline in mangrove species richness with increasing latitude. Alterations in mangrove community composition are significantly correlated with winter temperatures, and the number of thermophilic species exhibits a gradual decline with increasing latitude [80]. As the mangrove forests migrate northward, some organisms that were originally adapted to warmer conditions in the southern regions will expand their ranges. Conversely, some northern endemics will face new competitive pressures. Such alterations in species interactions rearrange the food chain and food web structure of the ecosystem, which, in turn, influences the stability of the entire ecosystem. From an ecosystem function perspective, the northward migration of mangrove forests may impact the performance of their ecological service functions, including wind protection, wave dissipation, water purification, carbon sequestration, and oxygen release. These potential changes could have uncertain implications for global climate change mitigation

efforts. Furthermore, the northward migration of mangrove forests may exert a linkage effect on neighboring terrestrial and marine ecosystems. Consequently, the northward migration of mangrove forests is not only a localized ecological phenomenon but also a significant issue that concerns the balance of ecosystems and sustainable development. Future research should focus on the environmental adaptability (especially the threshold for low-temperature tolerance) of the target species at different forest age stages, as well as the dynamic coupling between climate change and the feasibility of northward migration. It should be adapted to local conditions, and suitable planting sites should be chosen, predominantly utilizing local plants, supplemented by the introduction of alien species. Efforts should be made to strengthen the cultivation of target species for mangrove restoration and to cultivate new species that are resistant to low temperatures and extreme climates; mangrove protection, management, monitoring, and evaluation should be enhanced, along with the improvement of background investigation and management mechanisms to elevate the standard of mangrove management. Monitoring and evaluation methods for mangroves should be improved to provide a vital reference for achieving goals related to mangrove carbon sequestration, sink enhancement, and carbon sink trading.

## 5. Conclusions

Mangroves play a critical role in carbon sequestration. In Wenzhou, Zhejiang Province, the average soil carbon stock (0–100 cm depth) of transplanted rehabilitated planted mangroves is 78.75 Mg/ha, while the average plant carbon stock is 12.28 Mg/ha. Research indicates that variations in carbon sequestration capacity among planted mangroves are primarily attributed to tree species and age differences, hydrothermal conditions, and biomass carbon quantification methods. Key drivers of soil carbon storage include total phosphorus content, bulk density, and clay content. Soils constitute the dominant carbon sink in mangrove ecosystems, particularly for short-term carbon accumulation. To address current challenges in mangrove afforestation, this study proposes carbon sequestration enhancement strategies, focusing on optimal species composition for mixed plantations, enhancing carbon fixation in soils, and strengthening the conservation management, monitoring, and assessment of planted mangroves.

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