water

MDPI

Article

Stocks and Sources of Soil Carbon and Nitrogen in Non-Native *Kandelia obovata* Afforestation and *Spartina alterniflora* Invasion: A Case Study on Northern Margin Mangroves in the Subtropical Coastal Wetlands of China

Qianwen Ye [1,†], Cuicui Hou [2], Qiang Wang [3], Changjun Gao [4], Kay Stefanik [5], Feng Li [6] and Bingbing Jiang [1,*,†]

[1] School of Fishery, Zhejiang Ocean University, Zhoushan 316022, China; bjiang@zjou.edu.cn
[2] College of Life Sciences, Henan Normal University, Xinxiang 453007, China; houcuicui@htu.edu.cn
[3] School of Ecological and Environmental Sciences, East China Normal University, Shanghai 200241, China; qwang@re.ecnu.edu.cn
[4] Guangdong Provincial Key Laboratory of Silviculture, Protection and Utilization, Guangdong Academy of Forestry, Guangzhou 510520, China; fling112@163.com
[5] Iowa Nutrient Research Center, College of Agriculture and Life Sciences, Iowa State University, Ames, IA 50011, USA; kcstefan@iastate.edu
[6] Key Laboratory of Agro-ecological Processes in Subtropical Region, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha 410125, China; changshalifeng@163.com
* Correspondence: j.bingbing@yahoo.com
† These authors contributed equally to this work.

Abstract: For decades in China, carbon neutrality policies have spurred the establishment of northern margin mangroves as artificial blue carbon ecosystems. However, there has been limited research on the impact of plantation and invasion on the stocks and sources of soil carbon and nitrogen in rehabilitated coastal wetlands. Non-native *Kandelia obovata* afforestation began on Ximen Island, Zhejiang, China, where *Spartina alterniflora* invasion had also occurred decades ago. Soil cores were collected from both mangrove and salt marsh habitats with depths from 0 to 50 cm and were analyzed for total carbon (TC), soil organic carbon (SOC), total nitrogen (TN), and the isotope of carbon and nitrogen in sediments. The results indicated that there were no significant differences in the TC, SOC, and C/N ratio between the *K. obovata* and the *S. alterniflora*, but there were significant differences in TN, isotope $\delta^{13}C$, and $\delta^{15}N$. The SOC content of both ecosystems in the 0–20 cm layer was significantly higher than that in the 30–50 cm layer. Our study has shown that the main sources of carbon and nitrogen for mangroves and salt marshes are different, especially under the impact of external factors, such as tidal waves and aquaculture. These findings provide insight into the ecological functioning of subtropical coastal wetlands and an understanding of the biogeochemical cycles of northern margin mangrove ecosystems.

Keywords: blue carbon; soil; biogeochemical cycle; ecosystem

Citation: Ye, Q.; Jiang, B.; Hou, C.; Wang, Q.; Gao, C.; Stefanik, K.; Li, F. Stocks and Sources of Soil Carbon and Nitrogen in Non-Native *Kandelia obovata* Afforestation and *Spartina alterniflora* Invasion: A Case Study on Northern Margin Mangroves in the Subtropic Coastal Wetlands of China. *Water* **2024**, *16*, 866. https://doi.org/10.3390/w16060866

Academic Editor: Frédéric Frappart

Received: 15 January 2024
Revised: 26 February 2024
Accepted: 11 March 2024
Published: 17 March 2024

1. Introduction

Coastal wetlands are being preserved, restored, and created globally for climate mitigation, especially following the signing of the Paris Agreement [1,2]. They are recognized for their vital ecological functions, serving as critical habitats for various species, nature's nurseries, defenses against storm surges, frontiers for protecting against coastal erosion, nutrient reservoirs, and carbon banks [3–5]. In addition, mangroves, which contain 10–15% of the organic carbon in the global ocean, are identified as blue carbon ecosystems, along with coastal vegetation ecosystems such as salt marshes and seagrass beds, despite accounting for only 0.5% of the world's ocean area [6,7]. The distribution of mangroves closely aligns with temperature requirements, and historically, the cold winters in Zhejiang Province have prevented the natural establishment of mangroves [8]. *Kandelia obovata*, identified as the most cold-tolerant among mangrove species and representing the northernmost limit of intentionally planted mangroves, was introduced to Ximen Island, Yueqing Bay, Zhejiang Province, in 1957 [9]. After decades of trials, *K. obovata* has become one of the dominant surviving species. *S. alterniflora* was introduced for shore protection in the 1990s. Consequently, the northern margin mangrove (NMM) has been experiencing both intentional afforestation and inadvertent invasion by salt marsh plants like *S. alterniflora* [10]. As a mono-system, the NMM faces challenges from nature and human activities, such as climate change, typhoons, diseases, and pollution from aquaculture [8,10,11]. The invasion of *S. alterniflora* has emerged as one of the key issues. These activities continue to be crucial for mangrove rehabilitation, yet their effects on soil carbon and nitrogen stocks were not well understood in the past [12].

Mangroves are naturally highly efficient carbon sinks and long-term pools. Soil carbon accumulation in mangrove ecosystems is a crucial component of overall coastal carbon sequestration [13,14]. The soil surface layer plays an important role in the soil carbon pool. However, its biogeochemical cycles are impacted by environmental conditions, such as climate, invasion, and nutrient limitation. The carbon content within mangrove ecosystems primarily originates from upstream river inflow, precipitation, and marine tidal influences [7,15]. The intricate root systems of mangroves play a pivotal role in sequestering carbon, effectively serving as carbon reservoirs [16]. Simultaneously, mangroves act as food sources, supplying substantial organic matter and nutrients to the surrounding biota, thereby facilitating nutrient cycling [17]. Understanding the carbon stock and sources of mangrove afforestation is key for long-term nature-based solutions, especially those targeted at climate change. Previous studies have shown that soil carbon stock decreases as latitude moves north for natural mangroves [13,16].

Like carbon, nitrogen is an indispensable key growth element within mangrove ecosystems [18]. An excess or deficiency of nitrogen, such as in eutrophic or nutrient-deficient conditions, can impede mangrove development [19]. Mangroves function as both nitrogen reservoirs and nitrogen sources, contributing to the maintenance of overall nitrogen cycling through processes like nitrogen fixation, denitrification, nitrification, anaerobic ammonium oxidation, and nitrogen mineralization [20]. Through nitrogen fixation, they can ultimately bury anthropogenic nitrogen (from sources such as aquaculture, domestic sewage, and industrial waste) in sediments for extended periods [21]. These processes are vital for sustaining mangrove productivity, ecological protection, and restoration efforts [22].

The carbon and nitrogen cycles in mangrove and salt marsh ecosystems are inextricably linked, driving the functioning and resilience of these wetlands [20]. This interplay between the two cycles is a key feature of these ecosystems and is essential to their ecological functions. Understanding these cycles is fundamental to comprehending the functioning and resilience of these critical coastal ecosystems, particularly in the context of non-native plant species and ecological changes, such as the invasion of *S. alterniflora* and afforestation with *K. obovata* in the subtropical coastal wetlands of China [13].

The objective of this study is to evaluate and compare soil carbon and nitrogen stocks and their sources in the topsoil of areas where non-native *K. obovata* afforestation and *S. alterniflora* invasion have occurred in the subtropical coastal wetlands of China. Specifically, this research aims to (1) assess disparities in soil carbon and nitrogen stocks between *K. obovata* afforestation areas and *S. alterniflora*-invaded regions; (2) identify the primary sources contributing to these stocks in each type of area. By addressing these research aims, this study endeavors to advance our understanding of how different vegetation types influence biogeochemical cycles. The outcomes hold the potential to inform mangrove conservation and rehabilitation strategies, not only in China but also in regions undergoing analogous ecological transitions [23].

2. Materials and Methods

2.1. Study Area

Yueqing Bay, located on the northern fringes of the Oujiang River estuary in southern Zhejiang, China (27°5′–28°23′ N, 120°57′–121°16′ E), is characterized by its exceptional natural surroundings, which have facilitated the development of marine aquaculture as one of the major economic sectors in the area [24] (Figure 1). As a semi-enclosed tidal bay, Yueqing Bay is significantly influenced by tidal dynamics, exhibiting a maximum tidal range of 8.34 m and an average tidal range of 4.2 m. This bay is subject to a subtropical maritime monsoon climate, featuring an average annual temperature of 17.9 °C, average annual precipitation of 1556.3 mm, and an average annual frost-free period of 258 days (http://www.yueqing.gov.cn/, accessed on 15 August 2023).

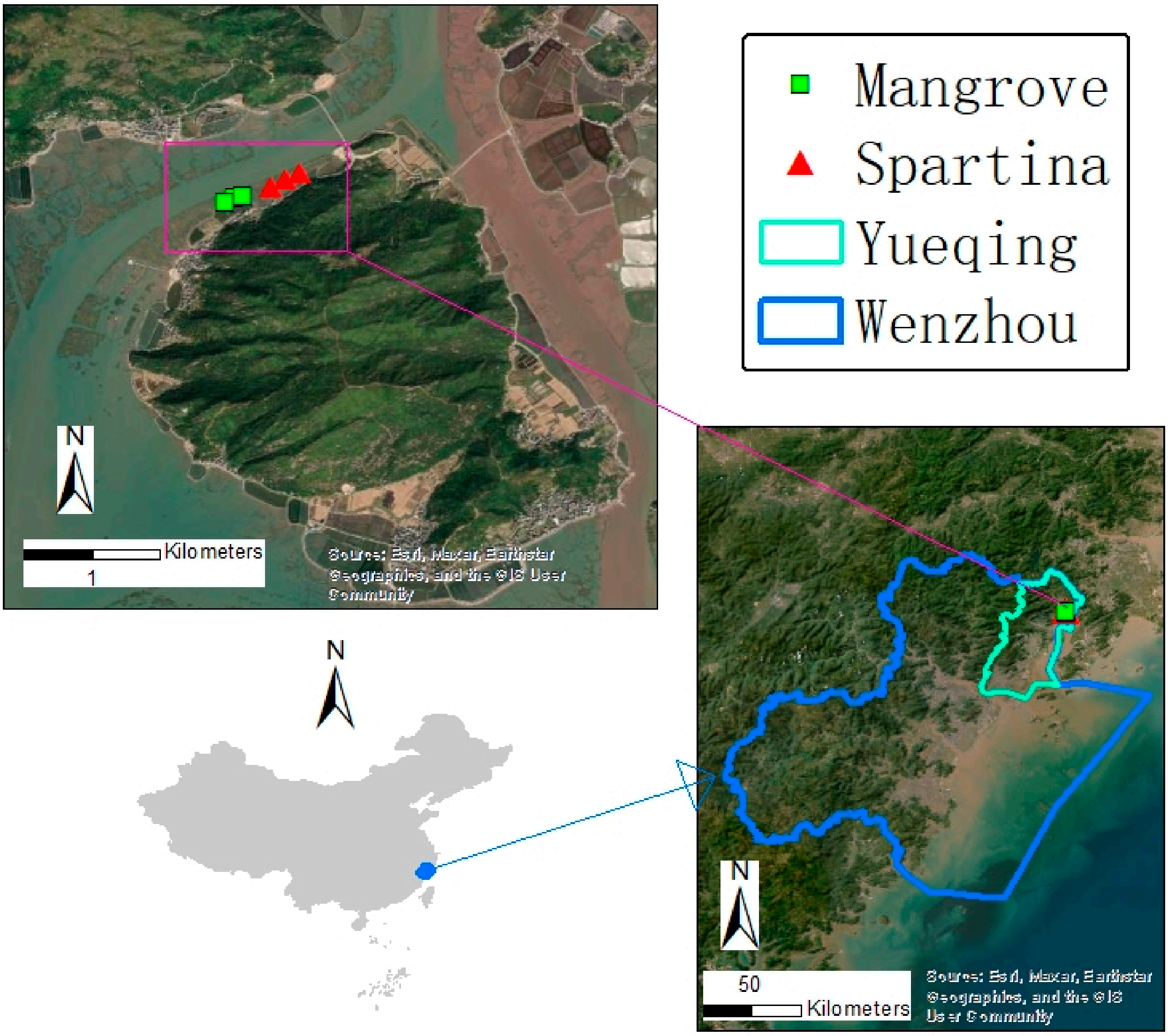

Figure 1. Ximen Island study area and sampling point in Yueqing Bay, Zhejiang Province, China (M and S represent mangrove and *Spartina alterniflora* salt marsh, respectively).

Ximen Island (28°20′ N, 121°10′ E), located in the northern region of Yueqing Bay within Yueqing City, Zhejiang Province, was designated as the first national marine special reserve in Zhejiang Province in 2005. Since 2006, it has received significant national funding aimed at the plantation and rehabilitation of mangroves. According to data from the Zhejiang Provincial Forestry Bureau, the Zhejiang Provincial Government has invested RMB 7.6668 million in the "Ximen Island Mangrove Transplantation Project," which was completed in 2013 and 2015. The mangrove species *K. obovata*, introduced from Fujian Province on five occasions, now covers approximately 5% of the coastal wetlands on the island [25]. However, since 1999, *S. alterniflora* has expanded rapidly in Yueqing Bay, dominating most of the mudflats on Ximen Island [26]. Consequently, clearing *S. alterniflora* and planting and protecting mangroves have emerged as significant conservation tasks in this area. Currently, both *K. obovata* and *S. alterniflora* coexist in the intertidal zone of Ximen Island, necessitating a comprehensive examination of their soil carbon and nitrogen dynamics.

2.2. Soil Sampling and Analysis

In May 2021, soil sampling was conducted in both the *K. obovata* mangrove area and the *S. alterniflora* salt marsh area on Ximen Island. At each sampling site, three replicate 1 m × 1 m sampling plots were established randomly with a minimum separation of 100 m between plots. Surface litter was removed from each site before collecting six soil cores, each with a depth of 50 cm and diameter of 5 cm, using Russian Sediment/Peat Borer. The cores were then sectioned into seven layers at depths of 0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm in the field. A total of 42 soil samples were collected, placed into plastic bags, refrigerated, and transported to the laboratory.

In the laboratory, the soil samples underwent freeze-drying and were cleared of impurities such as gravel and roots. Soil samples from the same layer of three cores within the community area were mixed to create a composite sample. These composite soil samples were then ground, passed through a 100-mesh sieve, and air-dried. Total carbon (TC) and total nitrogen (TN) contents were determined using the dry combustion method (Vario PYRO cube, Elementar, German). To analyze the soil organic carbon (SOC) content and stable carbon and nitrogen isotopes ($\delta^{13}C$ and $\delta^{15}N$), inorganic carbon was removed by acidification with 1 mol L^{-1} hydrochloric acid, followed by drying at 60 °C. Finally, the SOC content and stable isotopes were measured using elemental analysis coupled with stable isotope mass spectrometry (Elementar isoprime100, Germany). The isotopic compositions values of $\delta^{13}C$ and $\delta^{15}N$ were expressed as follows:

$$\delta(‰) = \left[\left(\frac{R_{sample}}{R_{standard}}\right) - 1\right] \times 1000 \tag{1}$$

where R_{sample} is the $^{13}C/^{12}C$ or $^{15}N/^{14}N$ isotope ratio of the sample, and $R_{standard}$ is the $\delta^{13}C$ characteristic value relative to the international standard material Vienna-Pee Dee Belemnite (V-PDB) for carbon and the $\delta^{15}N$ characteristic value relative to atmospheric nitrogen for nitrogen. The C/N ratio is expressed as the ratio of soil organic carbon to total nitrogen content. The calculation of organic carbon stock and nitrogen stock within each soil layer, spanning depths of 0–50 cm, was performed using the following equations:

$$SOC_{stock} = \frac{BD \times SOC_c \times D}{10} \tag{2}$$

$$TN_{stock} = \frac{BD \times TN_c \times D}{10} \tag{3}$$

where SOC_{stock} is the soil organic carbon stock (Mg C_{org} ha^{-1}), and BD is assumed based on a reference value of 0.85 g cm^{-3} from previous relevant studies [25,27]. SOC_c is the soil organic carbon content (g kg^{-1}), and D is the thickness of the soil layer (cm). TN_{stock} is the soil nitrogen stock (Mg N ha^{-1}) and TN_c is the soil total nitrogen content.

2.3. Data Analysis

Statistical analysis began with the evaluation of normality for soil parameter data from mangrove and *S. alterniflora* habitats, utilizing the Shapiro–Wilk test. For data adhering to a normal distribution, Student's *t*-test for independent samples was applied to identify differences between groups. Conversely, for data not following a normal distribution, the Mann–Whitney U test was utilized. Pearson correlation coefficients were calculated to explore the relationships among soil SOC, TIC, TN, and C/N ratio. A significance level of $p < 0.05$ was adopted to determine statistically significant differences. All statistical analyses were conducted using IBM SPSS Statistics (version 27.0.1.0).

3. Results

3.1. Vertical Distribution Characteristics of Soil TC, SOC, and TN

The mean TC and SOC contents in the soil samples were 13.26 ± 0.39 g Kg^{-1} and 6.60 ± 0.15 g Kg^{-1}, respectively. The TC contents ranged from 8.7 g Kg^{-1} to 21.7 g Kg^{-1} in mangrove soils and ranged from 9.6 g Kg^{-1} to 16.2 g Kg^{-1} in *S. alterniflora* soils. Vertically, the TC content of mangrove soil exhibited an upward trend from the profile base to the surface and was higher than those in *S. alterniflora* soils at the depths of 0–10 cm and 15–20 cm (Figure 2A). However, no significant difference was observed in TC content between mangrove soil (13.36 ± 0.73 g Kg^{-1}) and *S. alterniflora* soil (13.15 ± 0.30 g Kg^{-1}). The contents of SOC in mangrove and *S. alterniflora* soils were 5.3 g Kg^{-1}–9.3 g Kg^{-1} (6.40 ± 0.21 g Kg^{-1}) and 5.7 g Kg^{-1}–8.7 g Kg^{-1} (6.80 ± 0.20 g Kg^{-1}), respectively. The SOC content of *S. alterniflora* soil decreased with depth and was higher in the surface layer than in mangrove soils (Figure 2C).

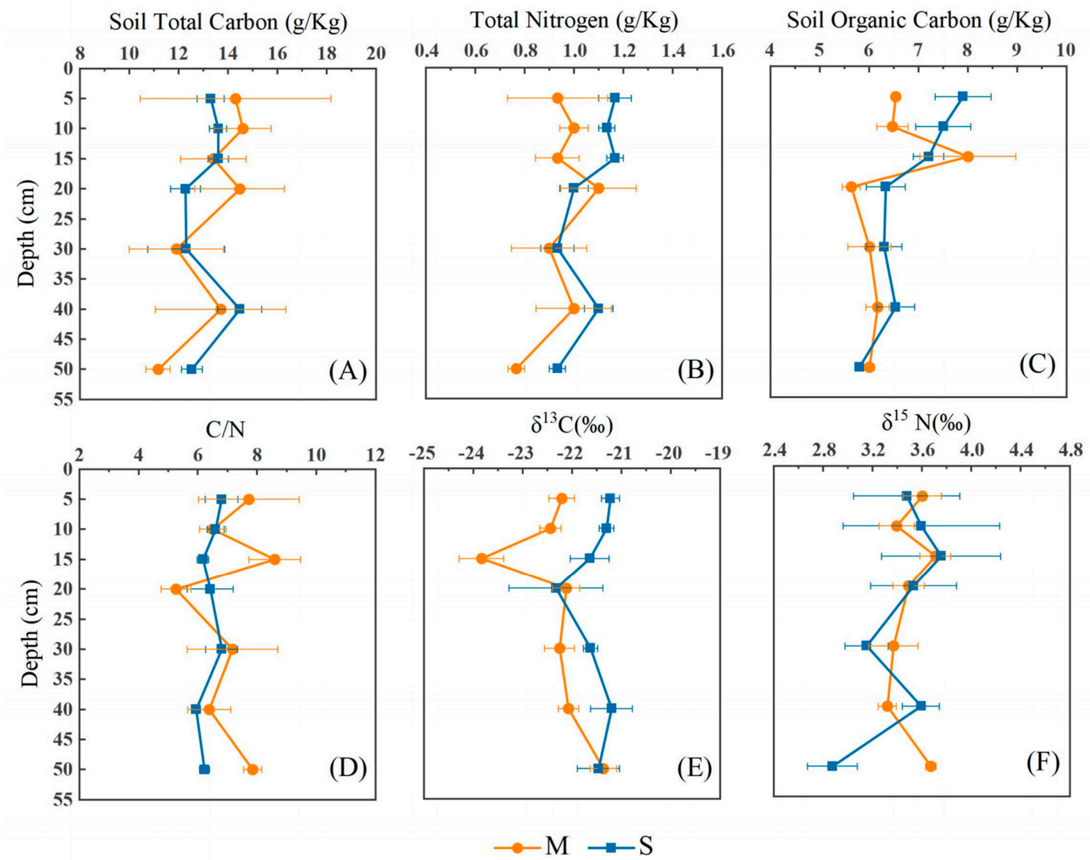

Figure 2. Vertical distribution of (**A**) TC content, (**B**) TN content, (**C**) SOC content, (**D**) C/N ratio, (**E**) $\delta^{13}C$ value, and (**F**) $\delta^{15}N$ value in different soil depth profiles of mangrove (M) and *Spartina alterniflora* (S).

The average TN content in the soil samples was 1.00 ± 0.03 g Kg^{-1}. The TN contents in mangrove and *S. alterniflora* soils were 0.6 g Kg^{-1}–1.4 g Kg^{-1} (0.95 ± 0.05 g Kg^{-1}) and 0.8 g Kg^{-1}–1.3 g Kg^{-1} (1.06 ± 0.03 g Kg^{-1}), respectively. TN content showed a decreasing trend with soil depth, with mangrove soil exhibiting higher TN content than *S. alterniflora* soil only at the 15–20 cm layer (Figure 2B).

3.2. Vertical Distribution Characteristics of Soil $\delta^{13}C$, $\delta^{15}N$, and C/N Ratio

The $\delta^{13}C$ values of the collected soil samples ranged from −24.38‰ to −20.53‰, with a mean of −21.93 ± 0.14‰ (Table 1). And the $\delta^{13}C$ values of mangroves and *S. alterniflora* soils ranged from −24.38‰ to −21.02‰ and −24.09‰ to −20.53‰, respectively. In vertical distribution, the $\delta^{13}C$ values all showed a decrease followed by an increase with the increase in soil depth. Except for the 15–20 cm and 40–50 cm depths, the $\delta^{13}C$ values of *S. alterniflora* were higher than those of mangroves (Figure 2E). The $\delta^{15}N$ values of mangrove soil and *S. alterniflora* soil ranged from 3.11‰ to 3.93‰ and 2.52‰ to 4.85‰, respectively, while showing an initial increase from the profile base to the 10–15 cm depth, followed by a decrease towards the surface layer (Figure 2F).

The average C/N ratio of the collected soil samples was 6.75 ± 0.21 (Table 1). The C/N ratios of mangrove and *S. alterniflora* soils were 4.29–10.83 (7.07 ± 0.39) and 5.27–7.91 (6.42 ± 0.16), respectively. The C/N ratio of mangrove soil showed significant fluctuations from 30 cm to 10 cm, peaking at 15 cm depth. However, the C/N ratio in *S. alterniflora* soils slightly decreased with increasing soil depth (Figure 2D). No significant difference was found in the C/N ratio between the soils of the two vegetation soils.

Table 1. Normality test of soil composition variables: carbon, nitrogen, and isotopic ratios in coastal wetlands on Ximen Island, Zhejiang, China.

Variable	Mean	Standard Error	n	Skewness	Kurtosis	Shapiro–Wilk Test of Normality	
						Statistic W Value	*p*
Total Carbon (%)	1.33	0.04	42	1.04	2.20	0.931	0.014 *
Soil Organic Carbon (%)	0.66	0.01	42	1.21	0.98	0.884	0.000 **
Total Nitrogen (%)	0.10	0.00	42	0.00	−0.47	0.972	0.377
C/N	6.75	0.21	42	0.97	1.59	0.934	0.018 *
$\delta^{13}C$ (‰)	−21.93	0.14	42	−1.05	1.36	0.917	0.005 **
$\delta^{15}N$ (‰)	3.47	0.07	42	0.73	1.53	0.954	0.092

Note: * $p < 0.05$ ** $p < 0.01$.

3.3. Differences between Ecotypes and Soil Layers

Among the soil composition variables analyzed, only TN content and $\delta^{15}N$ were normal distribution, whereas TC, SOC content, C/N ratio, and $\delta^{13}C$ values exhibited non-normal distribution (Table 1). In terms of vegetation types, the SOC content in salt marsh soil (0.68 ± 0.02%) was higher than in mangrove soil (0.64 ± 0.02%) ($p < 0.05$), and the TN content in salt marsh soil (0.11 ± 0.003%) was also significantly greater than in mangrove soil (0.09 ± 0.005%) ($p < 0.05$) (Figure 3A, B). The difference in the $\delta^{13}C$ value between mangrove soil (−22.33 ± 0.18‰) and salt marsh soil (−21.54 ± 0.17‰) was very significant ($p < 0.01$) (Figure 3C). However, the $\delta^{15}N$ value did not significantly differ between mangrove soil (3.51 ± 0.05‰) and salt marsh soil (3.43 ± 0.14‰) (Figure 3D).

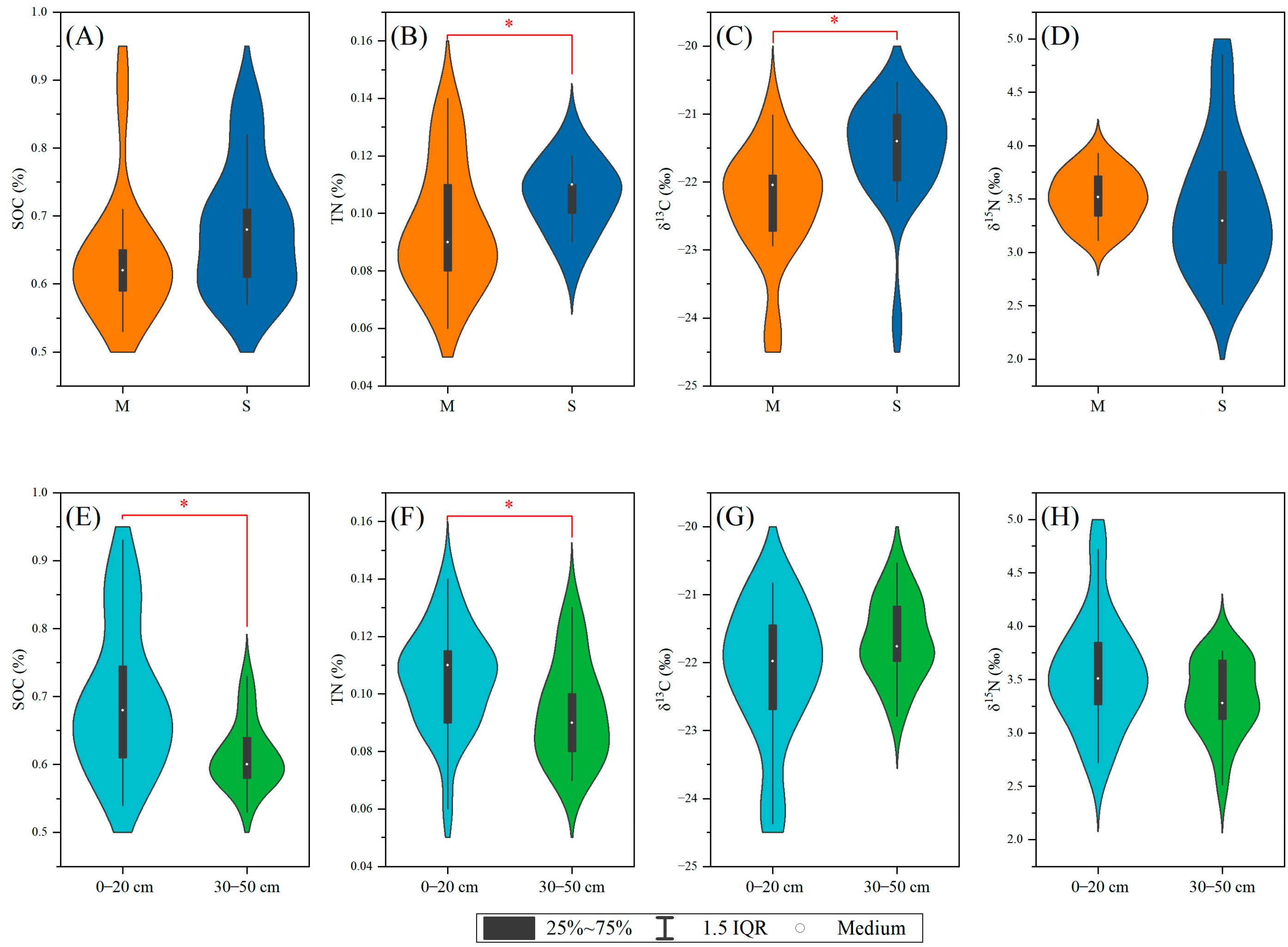

Figure 3. Violin plot with included boxplot of (A) SOC content, (B) TN content, (C) $\delta^{13}C$ value, and (D) $\delta^{15}N$ value in mangrove (M); (E)SOC content, (F) TN content, (G) $\delta^{13}C$ value, and (H) $\delta^{15}N$ value *Spartina alterniflora* (S) soils, as well as soil surface layer and soil subsurface layer. an asterisk (*) denotes a statistically significant difference, with a p-value less than 0.05.

Analyzing the soil profile stratification, the difference in the SOC content between the soil surface layer (0–20 cm) (0.69 ± 0.02%) and soil subsurface layer (30–50 cm) (0.61 ± 0.01%) was very significant ($p < 0.01$) (Figure 3E), with higher values in the surface layer. Similarly, TN content was also significantly higher in the soil surface layer (0.11 ± 0.004%) compared to the soil subsurface layer (0.09 ± 0.004%) ($p < 0.05$) (Figure 3F). Nevertheless, there were no significant differences between the $\delta^{13}C$ values (−22.13 ± 0.21‰) and $\delta^{15}N$ values (3.57 ± 0.11‰) of the soil surface layer and the $\delta^{13}C$ values (−21.66 ± 0.14‰) and $\delta^{15}N$ values (3.33 ± 0.08‰) of the soil subsurface layer (Figure 3G, H).

In the 0–50 cm soil layer, the SOC stock of *S. alterniflora* (28.14 ± 0.35 Mg C_{org} ha^{-1}) was higher than that of mangrove soils (26.76 ± 0.82 Mg C_{org} ha^{-1}) (Figure 4), although this difference was not statistically significant. Similarly, no significant difference was found in TN stock between two vegetation types, with mangrove soils having a TN_{stock} of 3.95 ± 0.02 Mg N ha^{-1} compared to 4.42 Mg N ha^{-1} in *S. alterniflora* soils.

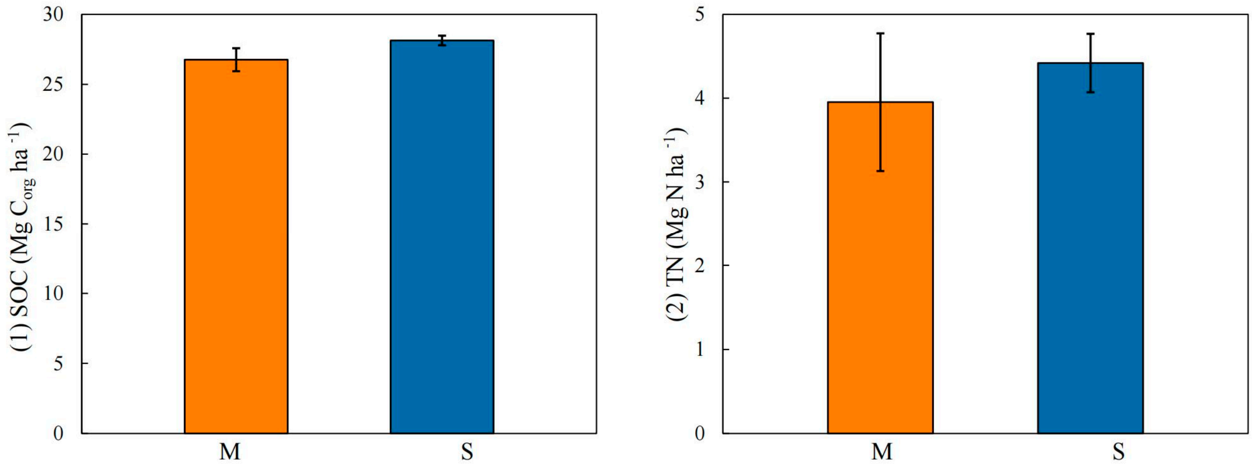

Figure 4. Organic carbon and nitrogen stocks of mangrove (M) and *Spartina alterniflora* (S) in 0–50 cm soil.

4. Discussion

4.1. Stocks and Sources of Soil Carbon in Non-Native K. obovata Afforestation and S. alterniflora Invasion

Previous studies have indicated that the carbon pools in mangrove ecosystems increase with age, peaking in mature mangroves [16]. Compared with other subtropical mangrove species, such as *Avicennia marina* and *Aegiceras corniculatum*, *K. obovata* exhibits relatively weaker carbon fixation capabilities (Table 2) [28]. Nonetheless, some studies show that the impacts of *S. alterniflora* invasion and mangrove restoration on soil carbon stocks are different (Table 2) [29,30]. Gu et al. [30] suggested that both *S. alterniflora* invasion and mangrove restoration contribute to increased soil carbon stocks, whereas Feng et al. [29] reported no significant changes in soil organic carbon stocks as a result of these interventions.

Table 2. Stocks and sources of soil carbon and nitrogen in subtropic coastal wetlands of China.

Subtropic Coastal Wetlands		Latitude	Dominate Species	Soil Depth	Soil Organic Carbon	Soil Total Nitrogen	C/N	$\delta^{13}C$	$\delta^{15}N$	References
				cm	Mg C ha^{-1}	Mg N ha^{-1}		‰	‰	
Native + Invasive species	Mangrove	23°53′ N	*Kandelia obovate, Avicennia marina,* and *Aegiceras corniculatum*	0– 30	65.6	5.6	5.62~20.04	−28.42~ −21.74	3.95~7.59	[31]
		24°24′ N	*K. obovata*	0–60	39.7	4.5				[29]
		23°53′ N	*S. alterniflora*	0–30	52.1	5.4	6.82~14.62	−23.02~ −18.15	4.51~7.54	[31]
		24°24′ N	*S. alterniflora*	0–60	39.5	4.9				[29]
	Mudflat	23°53′ N		0–30	33.3	4.1	7.17~26.25	−25.70~ −23.21	3.53~5.72	[31]
	Mudflat	24°24′ N		0–60	41	4.45				[29]
Non-native + Invasive species	Northern Margin Mangrove	28°20′ N	*K. obovata*	0–100	65.53		6.7	−22.30		[27]
		28°20′ N	*K. obovata*	0–50	26.76	3.95	4.29~10.83	−24.38~ −21.02	3.11~3.93	This study
		28°21′ N	*S. alterniflora*	0–100	71.72					[27]
		28°20′ N	*S. alterniflora*	0–50	28.14	4.42	5.27~7.91	−24.09~ −20.53	2.52~4.85	This study
	Mudflat	28°20′ N		0–100	69.52			−21.6~ −22.5		[27]
Invasive species	Salt marsh	31°30′ N	*Phragmites australis*	0–20		1.6	19.7			[32]
		32°48′ N	*Phragmites australis*	0–30	16.84			−24.97	2.37	[33]

	31°30′ N	*S. alterniflora*	0–20		1.78	18.6			[32]
	32°48′ N	*S.alterniflora*	0–30	37.83			−18.41	3.93	[33]
Mudflat	32°48′ N		0–30	4.49			−21.11	0.48	[33]

In this study, the SOC stocks between mangrove and *S. alterniflora* soils did not significantly differ, aligning with results observed in Zhangjiakou but diverging from those in the Jiulong River estuary, Fujian Province [34,35]. Moreover, the SOC content in both vegetation types was found to be lower than that reported for Qi'ao Island, Guangdong Province [36]. Similarly, the soil organic carbon stocks in mangroves from this study were lower than those in natural mangroves in Zhangjiangkou, Fujian, and SOC stocks in S. *alterniflora* were also lower compared to those reported in other regional studies (Table 2). This discrepancy could be attributed to variations in latitude, geographical location, and climate conditions [37]. The mangroves in the study area, being recently restored, are sparse and immature, leading to reduced soil carbon accumulation. Additionally, tidal erosion may contribute to the loss of surface litter, further affecting carbon stock levels.

In this investigation, salt marsh soils exhibited significantly higher $\delta^{13}C$ values compared to mangrove soils, consistent with findings reported by Xia et al. (Figure 5) [20]. Wetland soil organic matter (SOM) primarily originates from two sources: allochthonous inputs, such as river and ocean contributions, and autochthonous production. Allochthonous sources, enriched with nutrients from riverine inputs, are typically more substantial contributors to wetland soil SOC than autochthonous origins [31]. The differentiation between terrestrial and aquatic plant sediment sources has been effectively achieved through the analysis of stable carbon isotopes ($\delta^{13}C$) and C/N ratios [38]. C3 plants (like mangroves) have $\delta^{13}C$ values ranging from −34‰ to −23‰, C4 plants (like *S. alterniflora*) range from −17‰ to −9‰, and marine phytoplankton range from −17‰ to −23‰ [39–41]. Terrestrial plants predominantly consist of high-nitrogen compounds like lignin and cellulose, leading to C/N ratios above 12, in contrast to marine phytoplankton, which typically possess C/N ratios below 10 [42,43].

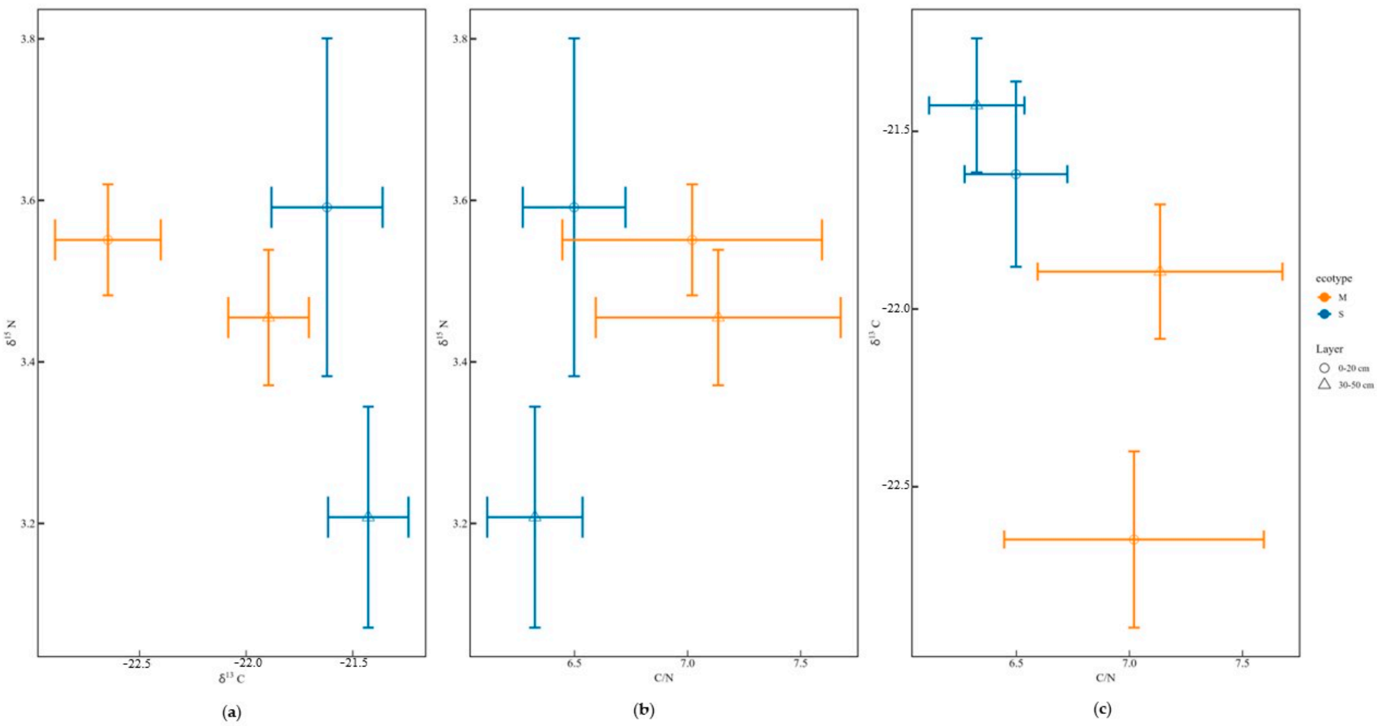

Figure 5. Biplot of (**a**) $\delta^{13}C$ and $\delta^{15}N$, (**b**) $\delta^{15}N$ and C/N, and (**c**) $\delta^{13}C$ and C/N in different soil depth profiles of mangrove (M) and *Spartina alterniflora* (S).

In contrast to Hu et al.'s findings on plant tissue $\delta^{13}C$ and C/N ratios on Ximen Island, our results indicate that mangrove soils feature a higher $\delta^{13}C$ value (−22.33 ± 0.18‰) and a lower C/N ratio (7.07 ± 0.39), whereas S. *alterniflora* soils present a lower $\delta^{13}C$ value (−21.54 ± 0.17‰) and C/N ratio (6.42 ± 0.16). This pattern suggests a reduced contribution of plant tissues to the soil carbon pool, implying a significant influence of marine phytoplankton on soil organic matter composition [27,44]. Additionally, the $\delta^{13}C$ value in the mangrove soil surface layer (0–20 cm) was found to be lower than in the subsurface layer, indicating the substantial role of mangrove litter decomposition in contributing to the SOC of the surface layer [27]. Tidal dynamics on Ximen Island facilitate the influx of external carbon sources, supporting evidence from studies along the Zhejiang coast of the East China Sea that muddy surface sediments primarily derive from marine organic matter [45]. Furthermore, human activities, such as aquaculture, may also contribute to the carbon sources in vegetation soils. Further research is warranted to explore the impact of such activities on the carbon sources of mangrove and S. *alterniflora* soils on Ximen Island.

4.2. Stocks and Sources of Soil Nitrogen in Non-Native K. obovata Afforestation and S. alterniflora Invasion

In both vegetation types, a positive correlation was observed between soil TN and TIC contents (r = 0.73, $p < 0.01$), whereas no significant correlation was found with SOC content (Figure 6), suggesting that mangroves and S. *alterniflora* may share similar soil nutrient sources. The invasion of S. *alterniflora* has been shown to significantly enhance the TN content in the soil of sparse mangrove wetlands, aligning with findings from previous research [34,46]. This increase can be attributed to S. *alterniflora*'s capacity to utilize ammonium and nitrate nitrogen forms less accessible to other wetland species and its ability to alter the nitrogen-fixing microbial community, thus exhibiting a higher nitrogen fixation rate compared to native plants [47–49]. Nitrogen, a critical limiting nutrient for S. *alterniflora*, finds an abundant source in the extensive aquaculture practices on Ximen Island, facilitating its growth [50,51].

The $\delta^{15}N$ values in the surface layers of both mangrove and S. *alterniflora* soils were found to be higher than those in the subsurface layers (Figure 5), a finding that corroborates the study by Wang et al. but contrasts with Xia et al. [20,31]. This discrepancy may result from more intense microbial decomposition activity in the surface layer, whereas subsurface $\delta^{15}N$ enrichment is mitigated by temperature and tidal influences. As an indicator of soil organic matter quality, the $\delta^{15}N$ value increases with the progression of organic matter decomposition and humification [32]. Although the $\delta^{15}N$ value in S. *alterniflora* soils was slightly lower than in mangrove soils, the significantly higher TN content suggests a greater contribution of external inputs to soil organic matter.

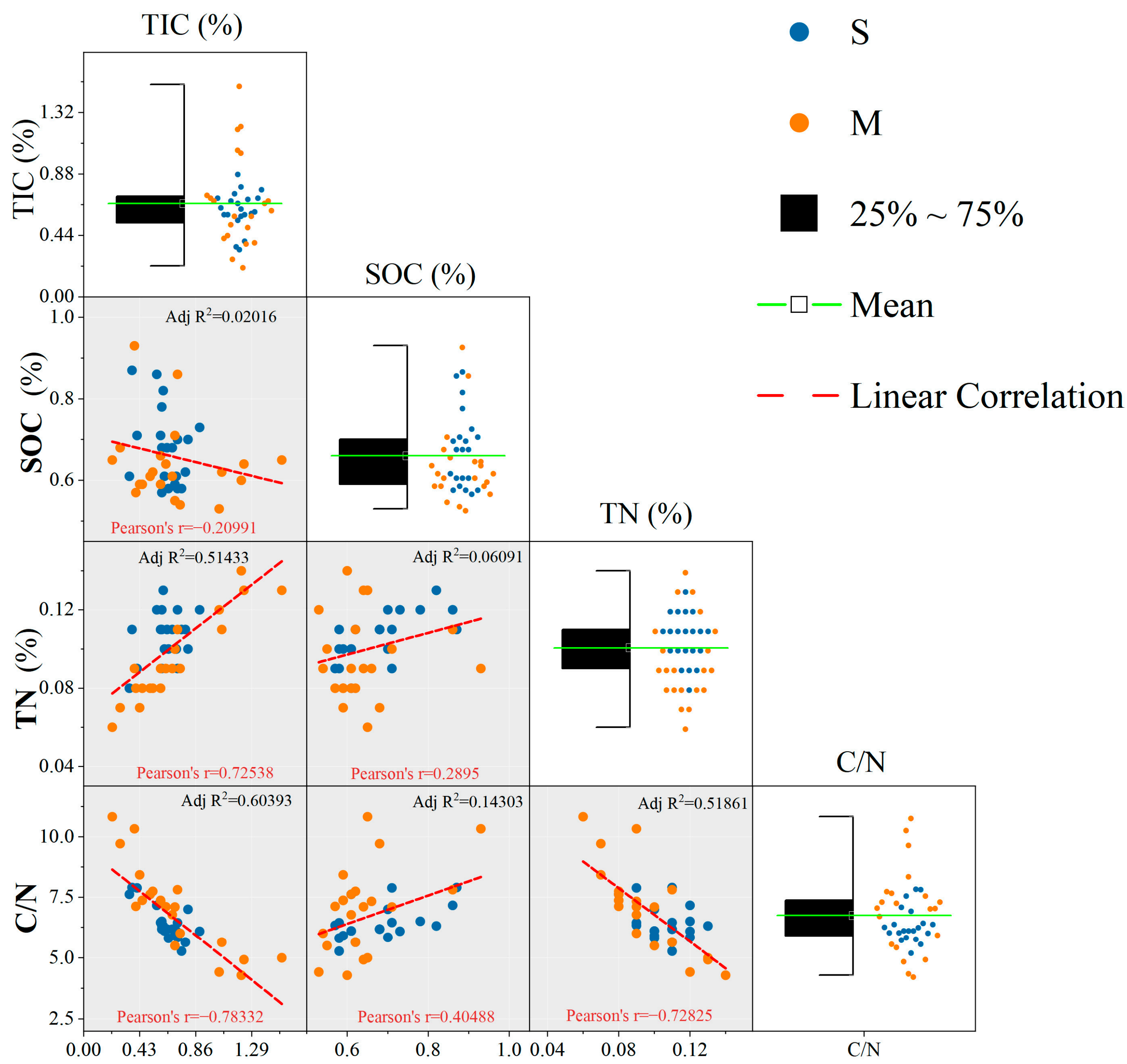

Figure 6. Correlation between SOC, TIC, TN, and C/N in mangrove (M) and *Spartina alterniflora* (S) soils.

5. Conclusions

This study on the soil carbon and nitrogen stocks and sources within the subtropical coastal wetlands of Yueqing Bay, China, especially in areas affected by the afforestation of non-native *K. obovata* and the invasion of S. *alterniflora*, provides essential insights into the biogeochemical processes shaping these ecosystems. Our findings reveal notable similarities in soil carbon and nitrogen stocks between *K. obovata* and S. *alterniflora* habitats, indicating that the ecological impacts of these two vegetation types on soil biogeochemical properties are comparable. The observed vertical distribution patterns of TC, SOC, TN, $\delta^{13}C$, and $\delta^{15}N$ within the soil profiles highlight complex biogeochemical interactions, modulated by both natural processes and human activities. Merging biogeochemical research with an evaluation of ecosystem services could elucidate the economic and societal advantages of wetland conservation and restoration efforts. This integrative approach offers a persuasive rationale for policy endorsement, aimed at rejuvenating and expanding natural blue carbon ecosystems.

Author Contributions: Conceptualization, B.J. and K.S.; methodology, K.S., C.G., C.H., F.L., and B.J.; software, B.J.; validation, B.J., Q.Y., and Q.W.; form analysis, B.J.; investigation, B.J.; resources, B.J.; data curation, B.J. and Q.Y.; writing—original draft preparation, B.J. and Q.Y. ;writing—review and editing, B.J. and Q.Y.; visualization, B.J.; supervision, B.J.; project administration, B.J.; funding acquisition, B.J. and Q.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research and the APC was funded by a project supported by the Young Scientists Fund of the National Natural Science Foundation of China, grant number 32202935, and Zhejiang Province College Students' Science and Technology Innovation Activity Plan (Xinmiao Project), grant number 2023R411006.

Data Availability Statement: Data related to this study are available from the authors upon reasonable request.

Acknowledgments: Thanks to Wen Ding, Ziying Zhao, Ruohan Zhao, Jing Yang, Siqi Liu, Yuxuan Zou, Leying Cai, Congcong Lv, Xin Zhou, Zeyu Zhou, Xueli Li, Kai Zhang, and many other students and Bonian Shui and many other teachers from Zhejiang Ocean University who provided valuable support and assistance.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Macreadie, P.I.; Costa, M.D.; Atwood, T.B.; Friess, D.A.; Kelleway, J.J.; Kennedy, H.; Lovelock, C.E.; Serrano, O.; Duarte, C.M. Blue carbon as a natural climate solution. *Nat. Rev. Earth Environ.* **2021**, *2*, 826–839.
2. Wilson, A.M.W.; Forsyth, C. Restoring near-shore marine ecosystems to enhance climate security for island ocean states: Aligning international processes and local practices. *Mar. Policy* **2018**, *93*, 284–294.
3. Mitsch, W.J.; Gosselink, J.G. *Wetlands*; John Wiley & Sons: Hoboken, NJ, USA, 2015.
4. Barbier, E.B.; Hacker, S.D.; Kennedy, C.; Koch, E.W.; Stier, A.C.; Silliman, B.R. The value of estuarine and coastal ecosystem services. *Ecol. Monogr.* **2011**, *81*, 169–193.
5. Nagelkerken, I.; Blaber, S.; Bouillon, S.; Green, P.; Haywood, M.; Kirton, L.; Meynecke, J.-O.; Pawlik, J.; Penrose, H.; Sasekumar, A. The habitat function of mangroves for terrestrial and marine fauna: A review. *Aquat. Bot.* **2008**, *89*, 155–185.
6. Macreadie, P.I.; Anton, A.; Raven, J.A.; Beaumont, N.; Connolly, R.M.; Friess, D.A.; Kelleway, J.J.; Kennedy, H.; Kuwae, T.; Lavery, P.S. The future of Blue Carbon science. *Nat. Commun.* **2019**, *10*, 3998.
7. Alongi, D.M. Carbon cycling and storage in mangrove forests. *Annu. Rev. Mar. Sci.* **2014**, *6*, 195–219.
8. Chen, L.; Wang, W.; Li, Q.Q.; Zhang, Y.; Yang, S.; Osland, M.J.; Huang, J.; Peng, C. Mangrove species' responses to winter air temperature extremes in China. *Ecosphere* **2017**, *8*, e01865.
9. Lu, W.-X.; Zhang, B.-H.; Zhang, Y.-Y.; Yang, S.-C. Differentiation of cold tolerance in an artificial population of a mangrove species, *Kandelia obovata*, is associated with geographic origins. *Front. Plant Sci.* **2022**, *12*, 695746.
10. Chen, L.; Wang, W.; Zhang, Y.; Lin, G. Recent progresses in mangrove conservation, restoration and research in China. *J. Plant Ecol.* **2009**, *2*, 45–54.
11. Wang, Y.-S.; Gu, J.-D. Ecological responses, adaptation and mechanisms of mangrove wetland ecosystem to global climate change and anthropogenic activities. *Int. Biodeterior. Biodegrad.* **2021**, *162*, 105248.
12. Zhou, T.; Liu, S.; Feng, Z.; Liu, G.; Gan, Q.; Peng, S. Use of exotic plants to control *Spartina alterniflora* invasion and promote mangrove restoration. *Sci. Rep.* **2015**, *5*, 12980.
13. Atwood, T.B.; Connolly, R.M.; Almahasheer, H.; Carnell, P.E.; Duarte, C.M.; Ewers Lewis, C.J.; Irigoien, X.; Kelleway, J.J.; Lavery, P.S.; Macreadie, P.I. Global patterns in mangrove soil carbon stocks and losses. *Nat. Clim. Change* **2017**, *7*, 523–528.
14. Donato, D.C.; Kauffman, J.B.; Murdiyarso, D.; Kurnianto, S.; Stidham, M.; Kanninen, M. Mangroves among the most carbon-rich forests in the tropics. *Nat. Geosci.* **2011**, *4*, 293–297.
15. Sasmito, S.D.; Kuzyakov, Y.; Lubis, A.A.; Murdiyarso, D.; Hutley, L.B.; Bachri, S.; Friess, D.A.; Martius, C.; Borchard, N. Organic carbon burial and sources in soils of coastal mudflat and mangrove ecosystems. *Catena* **2020**, *187*, 104414.
16. Alongi, D.M. Carbon sequestration in mangrove forests. *Carbon Manag.* **2012**, *3*, 313–322.
17. Sarker, S.; Masud-Ul-Alam, M.; Hossain, M.S.; Rahman Chowdhury, S.; Sharifuzzaman, S. A review of bioturbation and sediment organic geochemistry in mangroves. *Geol. J.* **2021**, *56*, 2439–2450.
18. Alongi, D.M. Cycling and global fluxes of nitrogen in mangroves. *Glob. Environ. Res.* **2013**, *17*, 173–182.

19. Sanders, C.J.; Eyre, B.D.; Santos, I.R.; Machado, W.; Luiz-Silva, W.; Smoak, J.M.; Breithaupt, J.L.; Ketterer, M.E.; Sanders, L.; Marotta, H. Elevated rates of organic carbon, nitrogen, and phosphorus accumulation in a highly impacted mangrove wetland. *Geophys. Res. Lett.* **2014**, *41*, 2475–2480.
20. Xia, S.; Song, Z.; Singh, B.P.; Guo, L.; Bolan, N.; Wang, W.; Lin, G.; Fang, Y.; Wen, X.; Wang, J. Contrasting patterns and controls of soil carbon and nitrogen isotope compositions in coastal wetlands of China. *Plant Soil* **2023**, *489*, 483–505.
21. Ray, R.; Majumder, N.; Das, S.; Chowdhury, C.; Jana, T.K. Biogeochemical cycle of nitrogen in a tropical mangrove ecosystem, east coast of India. *Mar. Chem.* **2014**, *167*, 33–43.
22. Ellison, A.M. Mangrove restoration: Do we know enough? *Restor. Ecol.* **2000**, *8*, 219–229.
23. Junk, W.J.; An, S.; Finlayson, C.; Gopal, B.; Květ, J.; Mitchell, S.A.; Mitsch, W.J.; Robarts, R.D. Current state of knowledge regarding the world's wetlands and their future under global climate change: A synthesis. *Aquat. Sci.* **2013**, *75*, 151–167.
24. Wang, C.; Cui, L.; Wang, D. Distribution and pollution assessment of heavy metals in surface sediments of aquaculture area in Yueqing bay. *Trans. Chin. Soc. Agric. Eng.* **2015**, *31*, 204–210.
25. Thura, K.; Serrano, O.; Gu, J.L.; Fang, Y.Y.; Htwe, H.Z.; Zhu, Y.J.; Huang, R.Q.; Agusti, S.; Duarte, C.M.; Wang, H.L.; et al. Mangrove restoration built soil organic carbon stocks over six decades: A chronosequence study. *J. Soils Sediments* **2023**, *23*, 1193–1203. https://doi.org/10.1007/s11368-022-03418-2.
26. Wang, A.; Chen, J.; Jing, C.; Ye, G.; Wu, J.; Huang, Z.; Zhou, C. Monitoring the invasion of *Spartina alterniflora* from 1993 to 2014 with Landsat TM and SPOT 6 satellite data in Yueqing Bay, China. *PLoS ONE* **2015**, *10*, e0135538.
27. Hu, J.; Loh, P.S.; Pradit, S.; Le, T.P.Q.; Oeurng, C.; Mohamed, C.A.R.; Lee, C.W.; Lu, X.; Anshari, G.Z.; Kandasamy, S. Assessing the effect of age and geomorphic setting on organic carbon accumulation in high-latitude human-planted mangroves. *Forests* **2022**, *13*, 105.
28. Chen, S.; Chen, B.; Chen, G.; Ji, J.; Yu, W.; Liao, J.; Chen, G. Higher soil organic carbon sequestration potential at a rehabilitated mangrove comprised of Aegiceras corniculatum compared to *Kandelia obovata*. *Sci. Total Environ.* **2021**, *752*, 142279.
29. Feng, J.X.; Zhou, J.; Wang, L.M.; Cui, X.W.; Ning, C.X.; Wu, H.; Zhu, X.S.; Lin, G.H. Effects of short-term invasion of *Spartina alterniflora* and the subsequent restoration of native mangroves on the soil organic carbon, nitrogen, and phosphorus stock. *Chemosphere* **2017**, *184*, 774–783.
30. Gu, J.; Wu, J. Blue carbon effects of mangrove restoration in subtropics where *Spartina alterniflora* invaded. *Ecol. Eng.* **2023**, *186*, 106822.
31. Wang, F.; Zhang, N.; Yang, S.; Li, Y.; Yang, L.; Cao, W. Source and stability of soil organic carbon jointly regulate soil carbon pool, but source alteration is more effective in mangrove ecosystem following Spartina alterniflora invasion. *Catena* **2024**, *235*, 107681.
32. Gao, Y.; Peng, R.-H.; Ouyang, Z.-T.; Shao, C.-L.; Chen, J.-Q.; Zhang, T.-T.; Guo, H.-Q.; Tang, J.-W.; Zhao, F.; Zhuang, P.; et al. Enhanced Lateral Exchange of Carbon and Nitrogen in a Coastal Wetland with Invasive *Spartina alterniflora*. *J. Geophys. Res. Biogeosci.* **2020**, *125*, e2019JG005459.
33. Yang, W.; An, S.; Zhao, H.; Xu, L.; Qiao, Y.; Cheng, X. Impacts of *Spartina alterniflora* invasion on soil organic carbon and nitrogen pools sizes, stability, and turnover in a coastal salt marsh of eastern China. *Ecol. Eng.* **2016**, *86*, 174–182.
34. Wang, Q.; Kang, Q.; Zhao, B.; Li, H.; Lu, H.; Liu, J.; Yan, C. Effect of land-use and land-cover change on mangrove soil carbon fraction and metal pollution risk in Zhangjiang Estuary, China. *Sci. Total Environ.* **2022**, *807*, 150973.
35. Yu, X.; Yang, J.; Liu, L.; Tian, Y.; Yu, Z. Effects of *Spartina alterniflora* invasion on biogenic elements in a subtropical coastal mangrove wetland. *Environ. Sci. Pollut. Res. Int.* **2015**, 22, 3107–3115.
36. Feng, J.; Wang, S.; Wang, S.; Ying, R.; Yin, F.; Jiang, L.; Li, Z. Effects of invasive *Spartina alterniflora* loisel. and subsequent ecological replacement by *Sonneratia apetala* Buch. -Ham. on soil organic carbon fractions and stock. *Forests* **2019**, *10*, 171.
37. Meng, W.; Feagin, R.A.; Hu, B.; He, M.; Li, H. The spatial distribution of blue carbon in the coastal wetlands of China. *Estuar. Coast. Shelf Sci.* **2019**, *222*, 13–20.
38. Meyers, P.A. Organic geochemical proxies of paleoceanographic, paleolimnologic, and paleoclimatic processes. *Org. Geochem.* **1997**, *27*, 213–250.
39. Bouillon, S.; Connolly, R.; Lee, S. Organic matter exchange and cycling in mangrove ecosystems: Recent insights from stable isotope studies. *J. Sea Res.* **2008**, *59*, 44–58.
40. Rani, V.; Nandan, S.B.; Schwing, P.T. Carbon source characterisation and historical carbon burial in three mangrove ecosystems on the South West coast of India. *Catena* **2021**, *197*, 12.
41. Chmura, G.; Aharon, P. Stable carbon isotope signatures of sedimentary carbon in coastal wetlands as indicators of salinity regime. *J. Coast. Res.* **1995**, *11*, 124–135.
42. Lamb, A.L.; Wilson, G.P.; Leng, M.J. A review of coastal palaeoclimate and relative sea-level reconstructions using $\delta^{13}C$ and C/N ratios in organic material. *Earth-Sci. Rev.* **2006**, *75*, 29–57.
43. Martiny, A.; Vrugt, J.A.; Primeau, F.W.; Lomas, M.W. Regional variation in the particulate organic carbon to nitrogen ratio in the surface ocean. *Glob. Biogeochem. Cycles* **2013**, *27*, 723–731.
44. Tue, N.T.; Nguyen, P.T.; Quan, D.M.; Dung, L.V.; Quy, T.D.; Nhuan, M.T.; Thai, N.D. Sedimentary composition and organic carbon sources in mangrove forests along the coast of northeast Vietnam. *Reg. Stud. Mar. Sci.* **2018**, *17*, 87–94.
45. Xu, G.; Liu, J.; Hu, G.; Jonell, T.N.; Chen, L.L. Distribution and source of organic matter in surface sediment from the muddy deposit along the Zhejiang coast, East China Sea. *Mar. Pollut. Bull.* **2017**, *123*, 395–399.

46. Wang, D.B.; Huang, W.; Liang, R.W.; Li, F.S. Effects of *Spartina alterniflora* Invasion on Soil Quality in Coastal Wetland of Beibu Gulf of South China. *PLoS ONE* **2016**, *11*, 17.
47. Li, B.; Liao, C.-H.; Zhang, X.-D.; Chen, H.-L.; Wang, Q.; Chen, Z.-Y.; Gan, X.-J.; Wu, J.-H.; Zhao, B.; Ma, Z.-J.; et al. *Spartina alterniflora* invasions in the Yangtze River estuary, China: An overview of current status and ecosystem effects. *Ecol. Eng.* **2009**, *35*, 511–520.
48. Huang, J.X.; Xu, X.; Wang, M.; Nie, M.; Qiu, S.Y.; Wang, Q.; Quan, Z.X.; Xiao, M.; Li, B. Responses of soil nitrogen fixation to *Spartina alterniflora* invasion and nitrogen addition in a Chinese salt marsh. *Sci. Rep.* **2016**, *6*, 8.
49. Morris, J.T. The nitrogen uptake kinetics of Spartina alterniflora in culture. *Ecology* **1980**, *61*, 1114–1121.
50. Joesting, H.M.; Blaylock, R.; Biber, P.; Ray, A. The use of marine aquaculture solid waste for nursery production of the salt marsh plants *Spartina alterniflora* and *Juncus roemerianus*. *Aquac. Rep.* **2016**, *3*, 108–114.
51. Craft, C.; Reader, J.; Sacco, J.N.; Broome, S.W. Twenty-five years of ecosystem development of constructed *Spartina alterniflora* (Loisel) marshes. *Ecol. Appl.* **1999**, *9*, 1405–1419.