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Vertical Distribution and Stability of Soil Carbon Pools Across Ecological Zones in the Dongting Lake Basin

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Abstract

Understanding responses of soil organic carbon (SOC) fractions to variable hydrological conditions is essential to clarify carbon stabilization in subtropical lake wetlands. This study examined vertical and spatial variations of particulate organic carbon (POC), mineral-associated organic carbon (MAOC) and nutrient stoichiometry across four sites in Dongting Lake (0–200 cm depth, five layers). SOC and total nitrogen (TN) showed significant decreasing trends with depth from the surface to 60 cm ($p < 0.05$), with the highest values in the 0–40 cm layer and significantly lower values below 60 cm. In contrast, total phosphorus (TP) was vertically stable but differed greatly among sites. C/N, C/P and N/P ratios showed distinct regional disparities ($p < 0.05$). The proportions of POC/SOC and MAOC/SOC exhibited highly significant regional differences ($p < 0.05$) but no significant vertical variation or interaction effects ($p > 0.05$). The POC/MAOC ratio exceeded 1 only at Tuanzhou (1.62–2.20), indicating a vulnerable POC-dominated pool; other sites were MAOC-dominated (ratio < 1). Site-specific nutrient regulation further differentiated carbon pool characteristics: nutrients dominated carbon fraction variation at Tuanzhou and Huanghua, co-functioned with soil texture at Junshan, and reduced carbon stability under nutrient enrichment at West Dongting Lake. The texture control effect intensified with soil depth, and deep soil exhibited the strongest mineral protection capacity. We conclude that relative proportions of POC and MAOC in total SOC are region-specific, while their absolute concentrations decrease with depth. We recommend that wetland restoration prioritizes maintaining natural hydrological regimes and soil texture integrity, with future validation across multiple floodplain wetlands.

Keywords: Dongting lake wetland; soil organic carbon fractions; nutrient stoichiometry; carbon stability



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1. Introduction

Wetlands occupy only 5–8% of the global land surface but store 20–30% of terrestrial soil organic carbon (SOC) [1]. The anoxic wet conditions of wetlands can promote soil carbon accumulation, thus functioning as important carbon sinks [2,3]. The carbon pool

in wetlands can influence atmospheric CO₂ concentrations, and global climate dynamics can change with even minor fluctuations in this pool [4]. However, hydrological dynamics induce pronounced spatial heterogeneity in carbon stability, as water-level fluctuations influence vegetation communities, sediment deposition patterns, and soil redox conditions [5]. Clarifying the stabilization of SOC in wetlands is of widespread global concern [6,7].

SOC is not a homogeneous entity but rather a complex continuum comprising fractions with distinct turnover times, stabilization mechanisms, and environmental sensitivities [8]. Particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) are the two main functional pools of SOC, distinguishing these two fractionations plays a crucial role in knowing SOC accumulation and persistence [9]. POC is defined as the organic fraction > 53 µm in size, primarily composed of partially decomposed plant residues, fungal hyphae, and spores [10]. POC is characterized by relatively short turnover times, turning over within years to decades [11]. POC serves as an indicator of labile carbon availability, which positions it as a dynamic component of the active carbon pool [12]. MAOC comprises organic compounds < 53 µm that are physiochemically bound to soil minerals, including clay particles and iron/aluminum oxides [13]. With turnover times spanning decades to centuries [14], MAOC represents the stable carbon pool critical for long-term carbon sequestration [8]. The MAOC/SOC ratio serves as an indicator of bulk SOC persistence, and variations in this ratio can influence the function and stability of the bulk SOC pool [15,16].

POC exhibits greater sensitivity to environmental change, whereas MAOC accumulation is primarily constrained by mineral surface area availability and carbon input quality [13]. Climate and hydrology are widely recognized as the primary drivers of organic carbon stabilization in wetlands [17,18]. Specifically, hydrological variations regulate SOC dynamics by modifying soil oxygen supply and microbial activity, which in turn control the decomposition of plant litter, ultimately affecting the balance between SOC formation and decomposition [19]. Thus, flooding would reduce oxygen exposure, which limits POC formation in topsoil while promoting the formation of reactive Fe(III) and Al oxides, thus enhancing mineral protection of organic carbon through the “iron gate mechanism” [20,21]. Moreover, the accumulation of POC and MAOC at different depths is controlled by different environmental factors, which reflects the transformation of the carbon stabilization mechanism across soil horizons. In coastal wetland studies, surface sediments in mangrove zones were dominated by POC, in contrast, unvegetated mudflats exhibited pronounced MAOC enrichment in deeper layers (>80 cm) [22]. MAOC is often slower cycling than POC across soil horizons [23]. Thus, resolving these distinct fractions is essential for understanding how SOC responds to environmental drivers, given their likely divergent spatial patterns and sensitivities.

Dongting Lake, located in the middle reaches of the Yangtze River, is China’s second-largest freshwater lake and a representative floodplain wetland ecosystem. Obvious spatial discrepancies exist in hydrological conditions, vegetation composition and soil properties among East, South and West Dongting Lake [24]. Previous studies have investigated soil carbon dynamics in Dongting Lake [2,3]; however, several critical knowledge gaps persist regarding POC and MAOC fractions. Systematic comparisons of POC and MAOC vertical distribution patterns across different ecological zones remain absent. Existing studies have predominantly focused on total SOC or dissolved organic carbon [25], leaving the vertical partitioning of functionally distinct carbon fractions uncharacterized. Moreover, the stability characteristics of carbon pools remain poorly understood across the basin’s heterogeneous ecological zones. In this study, four typical sites covering three sub-lakes were selected, including Junshan (natural wetland) and Tuanzhou (human-disturbed wetland) in East Dongting Lake, Huanghua shoal in South Dongting Lake, and wetland

habitats in West Dongting Lake. We aimed to explore the vertical distribution and stability of soil POC and MAOC. The objectives are: (1) clarify vertical variation characteristics of POC and MAOC at different sampling sites; (2) determine dominant environmental factors affecting the two carbon fractions; (3) reveal depth-dependent and regional differences in soil carbon pool stability. The findings will advance understanding of soil carbon fraction dynamics in river–lake complex ecosystems, providing scientific foundations for wetland carbon management and nature-based climate solutions.

2. Materials and Methods

2.1. Study Site

The study area lies within the Dongting Lake region (28°30′–30°20′ N, 111°40′–113°10′ E), covering East, South and West Dongting Lake. Four typical sampling sites were chosen in this basin, namely Junshan natural wetland and Tuanzhou human-disturbed wetland in East Dongting Lake, Huanghua shoal in South Dongting Lake, and wetland zones in West Dongting Lake. The wetland water level undergoes dramatic seasonal variations, with regular inundations occurring from June to September and notable interannual differences. This area features a humid subtropical monsoon climate, with an annual average temperature of 16.8 °C and annual precipitation of 1382 mm.

2.2. Soil Sample Collection

Soil sampling was conducted in May 2025. Four typical wetland sites covering the East, South, and West Dongting Lake were selected, including Junshan and Tuanzhou (East Dongting Lake), Huanghua (South Dongting Lake), and the West Dongting Lake wetland. At each site, three independent sampling plots (10 m × 10 m) were established with a minimum interval of 50 m to ensure spatial independence. The geographic coordinates of each plot were recorded using a handheld GPS device.

At each plot, five soil cores were collected using a 5 cm diameter auger at five vertical soil depth intervals (0–20 cm, 20–40 cm, 40–60 cm, 80–100 cm, and 100–200 cm). The five individual cores from the same plot and identical soil depth were thoroughly homogenized to form one composite sample. In total, the sampling design yielded 4 sites × 3 plots × 5 soil depths = 60 composite soil samples for subsequent analysis.

All visible plant roots, litter fragments, and gravel were manually removed in the field. The soil samples were then transported to the laboratory for standard pre-treatment. Specifically, soils were naturally air-dried at room temperature (25–28 °C) for approximately 7–10 days until reaching a constant weight. After complete drying, the bulk soil was gently crushed and homogenized, and all air-dried samples were passed through a 2 mm mesh sieve to remove residual fine debris and aggregates. The sieved homogeneous soil materials were stored in dry and dark conditions, from which 10 g subsamples were randomly collected for subsequent sodium hexametaphosphate dispersion and soil physical fractionation experiments.

2.3. Soil Chemistry Analysis

Soil texture (clay, silt and sand) was measured by the hydrometer method. Soil pH was determined with a compound electrode (MP551, Shanghai San-Xin Instrumentation, Shanghai, China) after mixing the soil at a soil-to-water ratio of 1:2.5. The SOC content was measured using the potassium dichromate–sulfuric acid oxidation technique [26]. TN was measured using the dry-combustion method with an elemental analyzer [27]. The TP content was measured using the molybdenum–antimony anticolorimetric method [28]. The DOC was extracted with 0.5 mol L^{−1} K₂SO₄ and subsequently measured using a TOC analyzer (TOC-VWP; Shimadzu, Kyoto, Japan) [29]. The available N (AN) content was

determined by an alkaline hydrolysis and diffusion method [30]. The Olsen P content was extracted with $0.5 \text{ mol L}^{-1} \text{ NaHCO}_3$ and measured by the molybdenum–antimony–ascorbic acid colorimetric method [30].

Bulk soil organic carbon (SOC) was physically separated into particulate organic matter (POM, $>53 \mu\text{m}$) and mineral-associated organic matter (MAOM, $<53 \mu\text{m}$) fractions via size fractionation. Briefly, 10 g of air-dried soil was weighed into a 50 mL plastic bottle, and 50 mL sodium hexametaphosphate solution (5 g L^{-1} , soil: solution mass ratio = 1:5) was added. The mixture was fully homogenized and dispersed on a reciprocating shaker for 16 h. The dispersed soil suspension was poured through a $53 \mu\text{m}$ sieve and rinsed continuously with deionized water until the filtrate became clear without fine particles. The retained material ($>53 \mu\text{m}$, POM fraction) was transferred into a pre-weighed aluminum tray and oven-dried at 60°C to a constant weight. The mass proportion of this dried fraction relative to the total bulk soil mass was calculated as the mass fraction of POM. The fraction passing through the sieve ($<53 \mu\text{m}$) was defined as the MAOM fraction. After fraction isolation, the organic carbon concentrations within the separated POM and MAOM fractions were quantified by the potassium dichromate wet oxidation method, which yielded POC and MAOC, respectively.

2.4. Statistical Analysis

All statistical analyses were performed using SPSS Statistics 21.0 (IBM SPSS Inc., Chicago, IL, USA) and R version 4.2.2. Two-way analysis of variance (ANOVA) was employed to test the main effects of region (East, South, West Dongting Lake) and soil depth (five layers), as well as their interaction effect, on SOC, TN, TP, C:N:P stoichiometry, POC, MAOC, POC/MAOC, POC/SOC, and MAOC/SOC. Prior to ANOVA, Shapiro–Wilk test and Levene’s test were used to verify normality and homoscedasticity of raw data; the data satisfied the prerequisite assumptions for ANOVA. Tukey’s HSD post hoc test was adopted for pairwise multiple comparisons at the significance level $\alpha = 0.05$. Pearson correlation coefficients were calculated to assess the linear relationships of POC and MAOC with SOC, as well as with other environmental variables (TN, TP, AN, Olsen P, clay, silt, sand, pH, C/N, C/P, N/P). Spearman correlation matrices were used to construct network visualizations (using the “igraph” package in R) to explore multivariate associations. All figures were generated using OriginPro 2021.

3. Results

3.1. Soil C, N, and P Contents and Their Stoichiometries

Soil physicochemical properties and stoichiometric ratios showed distinct spatial and vertical patterns across the four sites (Junshan (JS), Tuanzhou (TZ), Huanghua (HH), and West Dongting Lake (W)). SOC and TN exhibited significant decreasing trends with soil depth ($p < 0.001$), with the highest values observed in the 0–40 cm layer (SOC: 13.5 g/kg , TN: 1.37 g/kg), while the lowest occurred in the 80–200 cm layer (SOC: 4.53 g/kg , TN: 0.58 g/kg) (Figure 1), indicating that surface soils are the primary reservoir of organic carbon and nitrogen in these wetlands. Significant regional differences were also detected for both SOC and TN ($p < 0.001$), although no significant region–depth interaction was found. JS had relatively high SOC and TN contents in the surface and subsurface layers, while W maintained significantly higher SOC and TN in deep soils compared with the other sites. In contrast, TP showed no significant vertical variation ($p > 0.05$) but displayed a significant regional effect ($p < 0.05$) and a significant region–depth interaction ($p < 0.01$). Notably, TZ had the highest TP content in the 100–200 cm layer, significantly exceeding the other sites. For stoichiometric ratios, C/N, C/P, and N/P all showed significant regional differences ($p < 0.05$ or $p < 0.001$) but no significant vertical variation or interaction effects.

TZ consistently had the highest C/N ratio across all depths, indicating less decomposed organic matter dominated by plant debris. In deep layers, JS and W showed significantly higher N/P ratios than TZ and HH, suggesting a relative enrichment of nitrogen compared with phosphorus at these sites.

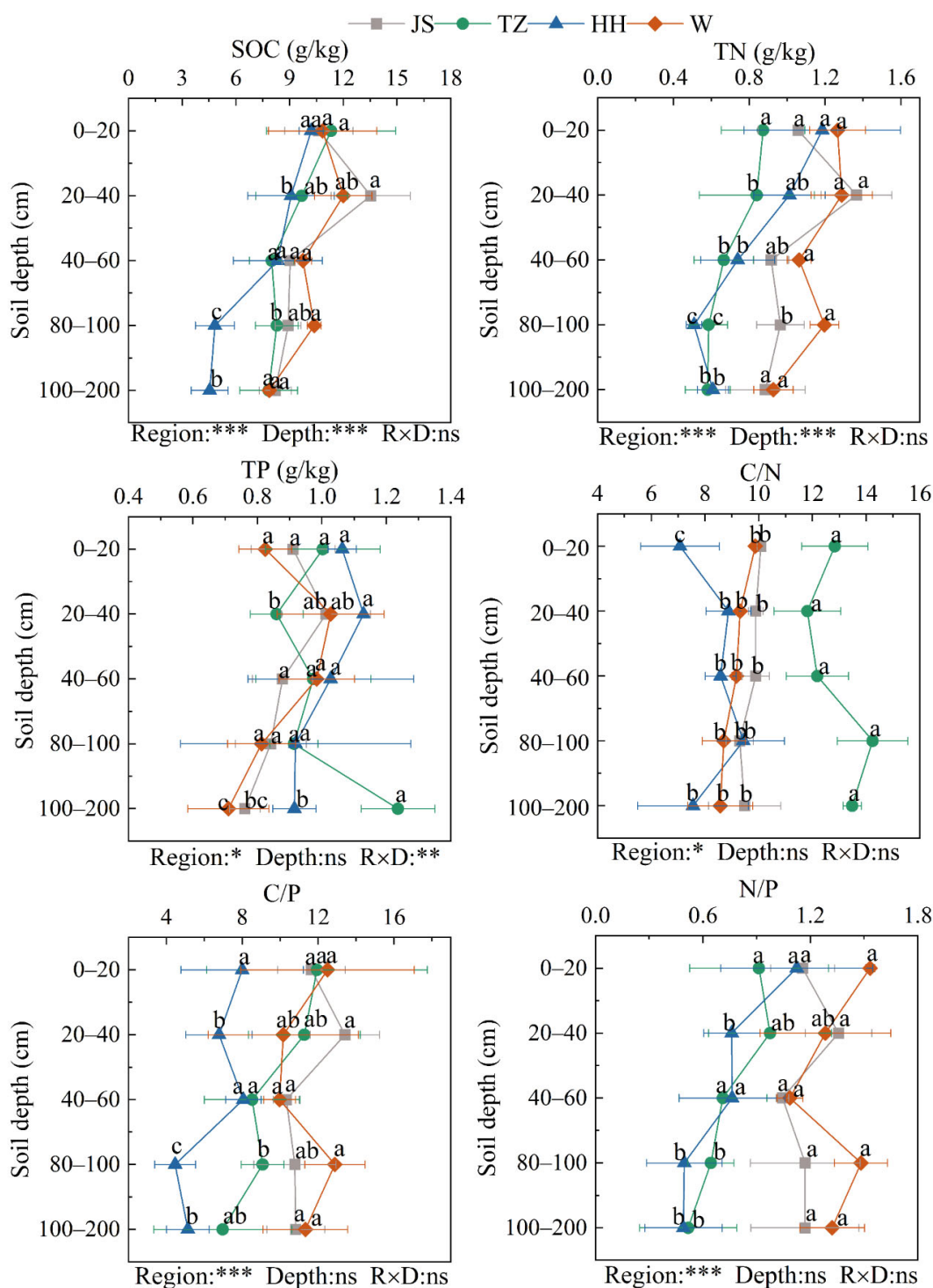


Figure 1. Vertical distribution of soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), and their stoichiometric ratios (C/N, C/P, N/P) at four sites in Dongting Lake: Junshan (JS), Tuanzhou (TZ), Huanghua (HH), and West Dongting Lake (WD). Different letters denote significant differences among sites at the same depth (Tukey's HSD, $p < 0.05$). Two-way ANOVA was used to test the effects of region (R), depth (D), and their interaction (R×D). Significance levels are indicated as: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; ns, not significant.

3.2. Soil Particulate and Mineral-Associated Organic Content and Distribution

Soil organic carbon fractions (POC and MAOC) and their ratio exhibited distinct spatial and vertical patterns across the four study sites (Figure 2). POC concentrations decreased significantly with soil depth ($p < 0.001$) and showed highly significant regional differences ($p < 0.001$), with no significant interaction effect. TZ consistently had the highest POC content across all depths (range 4.77–5.97 g/kg), while HH showed the lowest values (range 0.66–2.34 g/kg), indicating that POC accumulation is strongly site-dependent. MAOC concentrations also decreased significantly with depth ($p < 0.05$) and differed significantly among regions ($p < 0.001$). JS and W maintained higher MAOC contents throughout the profile (range 5.53–7.66 g/kg), whereas TZ and HH had relatively lower MAOC (range 2.63–6.56 g/kg), suggesting stronger mineral-associated carbon stabilization at JS and W. The POC/MAOC ratio showed highly significant regional differences ($p < 0.001$) but no significant vertical variation. Notably, TZ exhibited significantly higher POC/MAOC ratios (all > 1) than the other three sites (all < 1) at every soil depth, indicating that particulate organic carbon dominated the carbon pool at TZ, while mineral-associated organic carbon prevailed at the other sites.

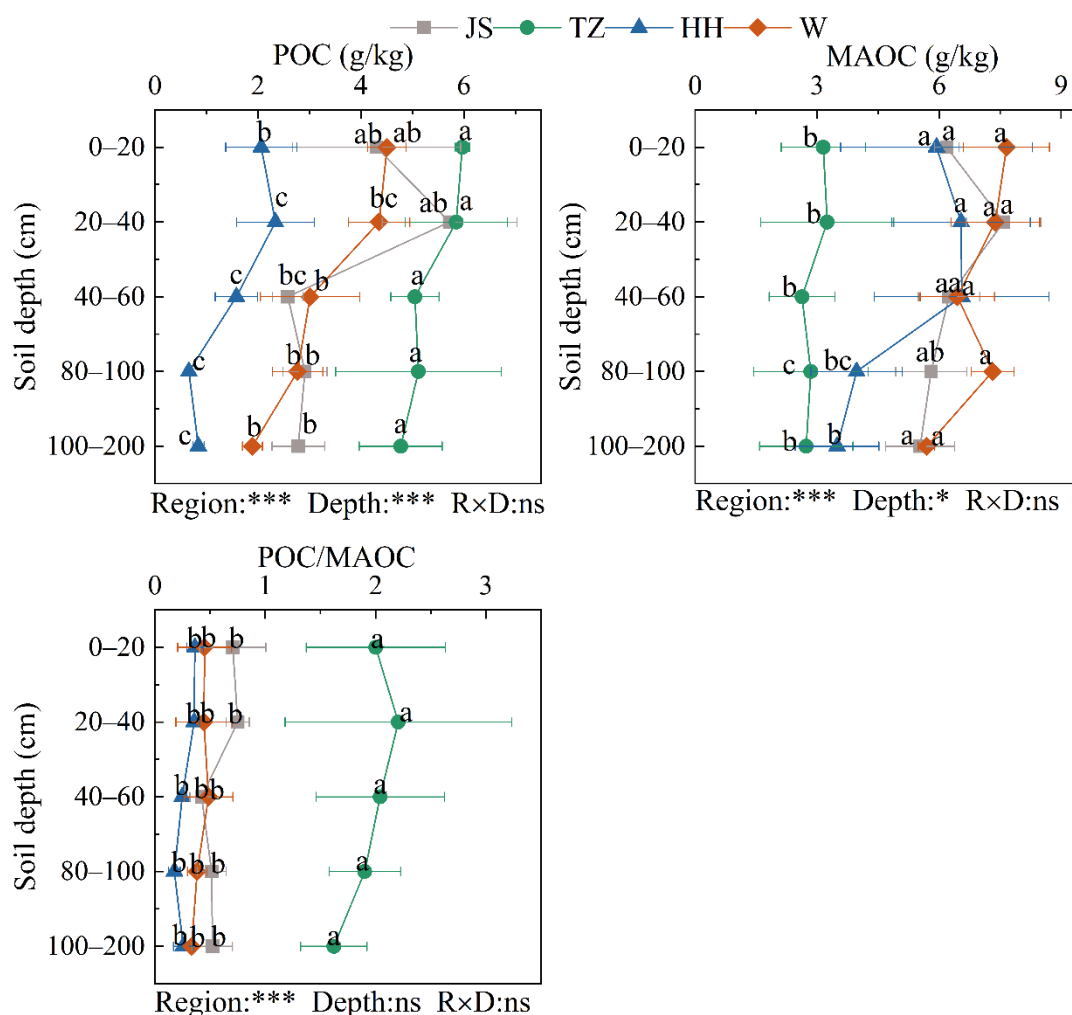


Figure 2. Vertical distribution of particulate organic carbon (POC), mineral-associated organic carbon (MAOC), and POC/MAOC ratio at four sites in Dongting Lake: Junshan (JS), Tuanzhou (TZ), Huanghua (HH), and West Dongting Lake (WD). Different letters denote significant differences among sites at the same depth (Tukey's HSD, $p < 0.05$). Two-way ANOVA was used to test the effects of region (R), depth (D), and their interaction (R·D). Significance levels are indicated as: * $p < 0.05$, *** $p < 0.001$; ns, not significant.

3.3. Spatial Differentiation in the Relative Contribution of POC and MAOC to Bulk SOC

The proportions of particulate organic carbon (POC/SOC) and mineral-associated organic carbon (MAOC/SOC) in total soil organic carbon showed highly significant regional differences ($p < 0.001$) but no significant vertical variation or interaction effects (Figure 3). Across all soil depths, TZ exhibited significantly higher POC/SOC ratios ($p < 0.05$), accounting for 58.7–63.6% of total SOC, while MAOC/SOC ratios were correspondingly low (32.3–38.3%). In contrast, JS, HH and W showed significantly lower POC/SOC (14.2–42.0%) but higher MAOC/SOC ratios (56.3–81.6%). These results indicate that the organic carbon pool at TZ was dominated by unstable particulate fractions, whereas mineral-associated organic carbon prevailed at the other three sites.

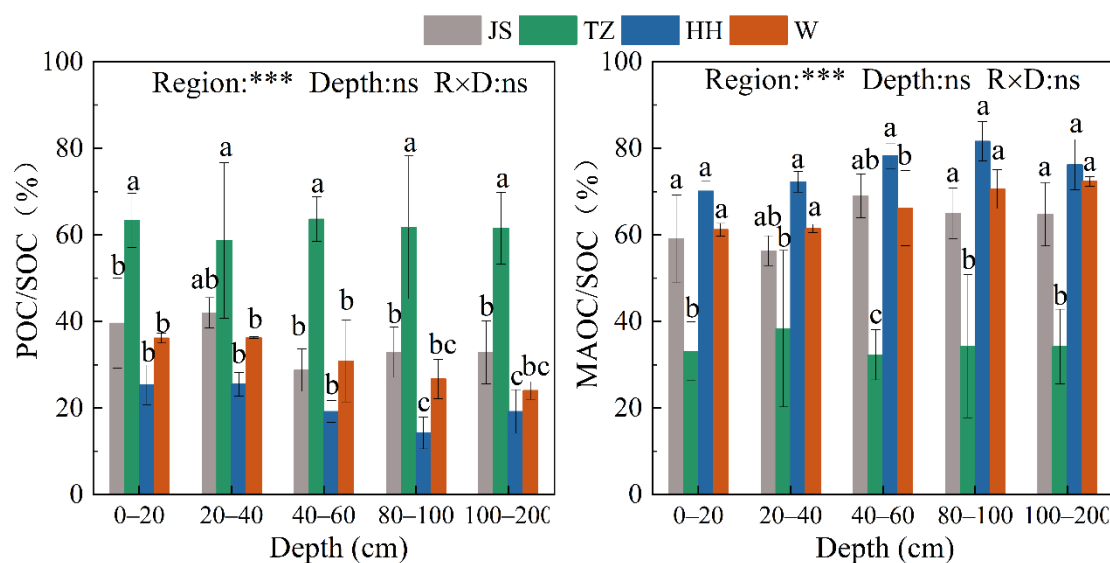


Figure 3. Proportions of particulate organic carbon (POC/SOC, %) and mineral-associated organic carbon (MAOC/SOC, %) across different soil depths at four study sites in Dongting Lake. Different letters denote significant differences among sites at the same depth (Tukey's HSD, $p < 0.05$). Two-way ANOVA was used to test the effects of region (R), depth (D), and their interaction (R·D). Significance levels are indicated as: *** $p < 0.001$; ns, not significant.

3.4. Correlations of SOC with POC and MAOC Across Sites and Soil Depths

The relationships between SOC and its two fractions (POC and MAOC) differed significantly across study sites and soil depths (Figure 4). At the site level, POC was strongly correlated with SOC ($p < 0.001$) at all sites, with the highest slope observed at Tuanzhou (TZ, slope = 0.92) and the lowest at Junshan (JS, slope = 0.62), indicating that POC accumulation was most responsive to SOC increases at TZ. Conversely, MAOC showed the strongest correlation with SOC at Huanghua (HH, slope = 0.98, $p < 0.001$) and the weakest at TZ (slope = 0.81, $p < 0.001$), suggesting that MAOC was the dominant contributor to SOC at HH, JS, and WD, but less so at TZ. At the depth level, POC was significantly correlated with SOC in most layers ($p < 0.05$), except for the 40–60 cm layer (slope = -0.02 , $p > 0.05$). MAOC, however, showed significant positive correlations with SOC across all deeper layers ($p < 0.05$ or $p < 0.01$), with a weak and non-significant correlation in the surface layer (0–20 cm, slope = 0.28, $p > 0.05$). These patterns indicate that SOC was mainly driven by POC in surface soils (0–20 cm), while MAOC dominated the SOC pool in deeper layers (below 40 cm), reflecting a shift from plant-derived carbon input in surface soils to mineral-associated carbon stabilization at depth.

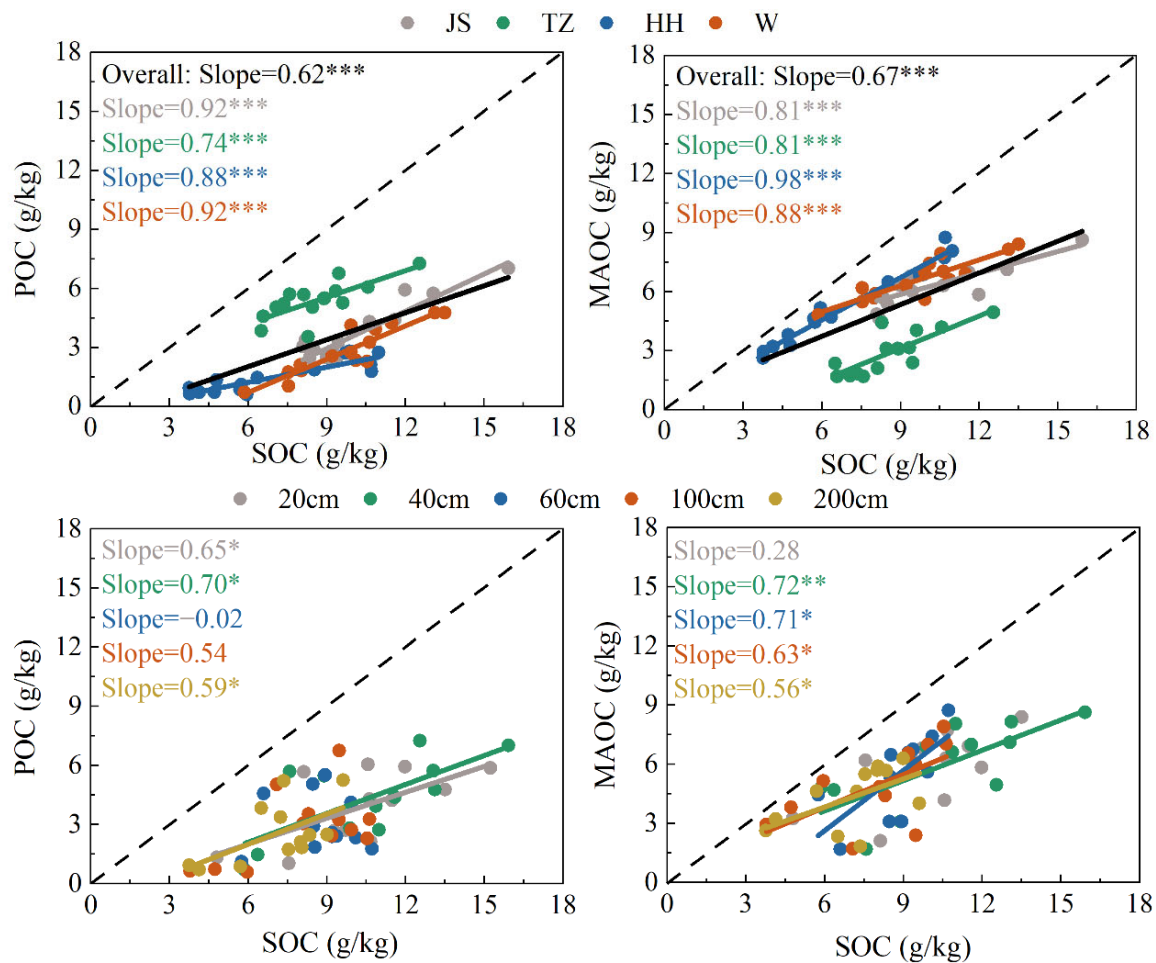


Figure 4. Relationships between soil organic carbon (SOC) and its fractions (POC and MAOC) across four study sites (**upper row**) and different soil depths (**lower row**). The black dashed lines represent the 1:1 relationship. Colored solid lines are regression fitting lines for each site or soil layer; regression slopes and corresponding coefficients of determination (R^2) are labeled for each model. Asterisks indicating significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns: no significant effect).

3.5. Factors Influencing Soil POC and MAOC

Correlation networks revealed distinct controls of environmental factors on POC, MAOC, and POC/MAOC across study sites and soil depths. At the site level (Figures 5 and 6), POC and MAOC were both significantly correlated with SOC, TN and related stoichiometric indices at all four sites, demonstrating that soil nutrients universally regulated carbon fraction accumulation across the Dongting Lake wetland. Significant correlations between POC/MAOC ratio and soil texture only occurred at JS, with a positive response to sand and a negative response to clay and silt, indicating that texture control on carbon stability was site-specific. No obvious influencing factors were detected for the POC/MAOC ratio at TZ and HH, suggesting that other unmeasured factors (e.g., hydrological disturbance, agricultural management) may dominate carbon partitioning at these two sites. By contrast, the POC/MAOC ratio at W was positively linked to SOC, TN, DOC, and AN, implying that the elevated nutrient availability at this site was associated with reduced carbon stability.

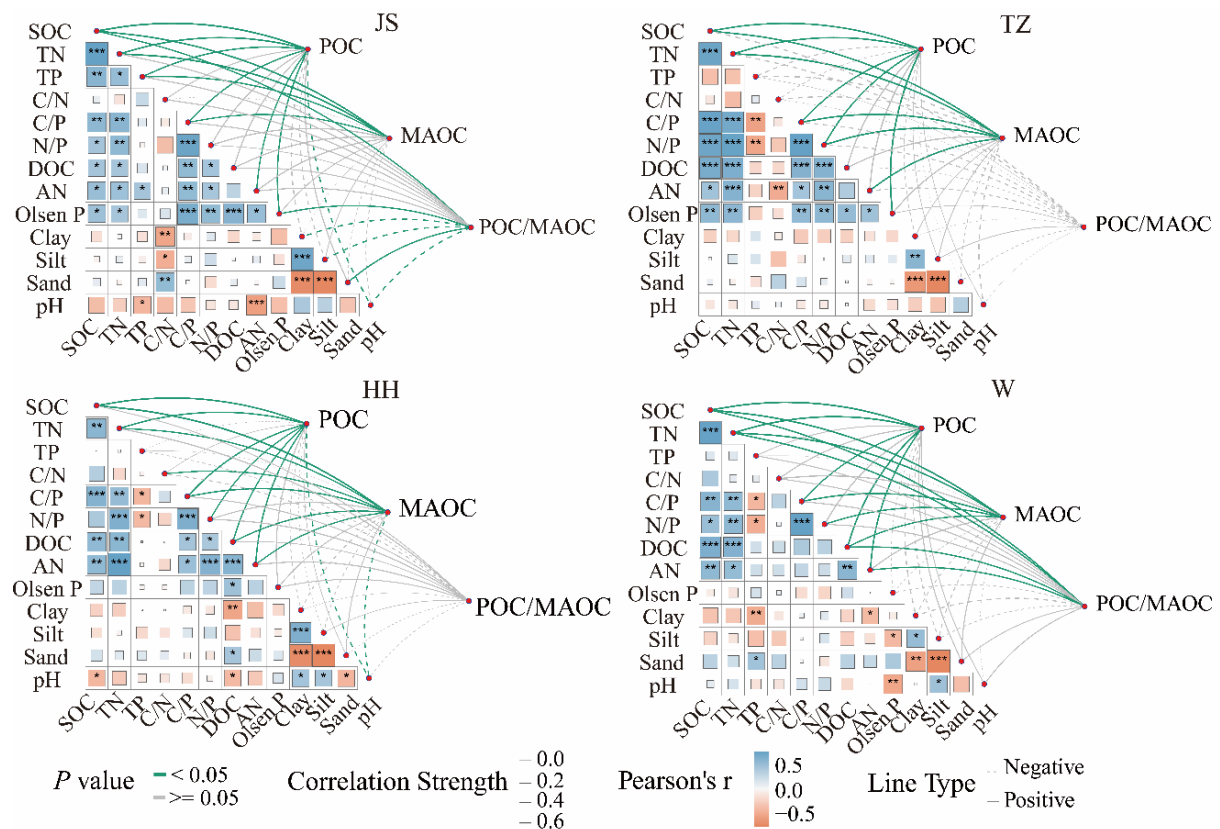


Figure 5. Spearman's correlation network among soil properties, stoichiometry, POC, and MAOC in Dongting Lake wetlands. Edge width and color indicate correlation strength (thicker = stronger) and type (red positive, blue negative), respectively. The square matrix shows pairwise correlations among environmental factors using a color gradient (darker = stronger). Only significant correlations ($p < 0.05$) are shown. Asterisks indicating significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns: no significant effect).

At the depth level, texture exerted growing regulatory effects along soil profiles. The POC/MAOC ratio was positively correlated with sand and negatively correlated with clay, reaching the maximum correlation strength at 40–60 cm. This indicates that mid-depth soils (40–60 cm) represent a transition zone where texture control on the balance between labile and stable carbon is most pronounced. MAOC had a weak association with clay in topsoil, while its positive correlation with clay gradually strengthened downward and peaked in the 100–200 cm layer. This depth-increasing trend represents the strongest mineral protection capacity in deep soil, consistent with the higher MAOC/SOC ratios observed below 80 cm. The progressive strengthening of clay–MAOC coupling with depth suggests that deep soils are the primary reservoir of stable, mineral-protected carbon in these lake wetlands.

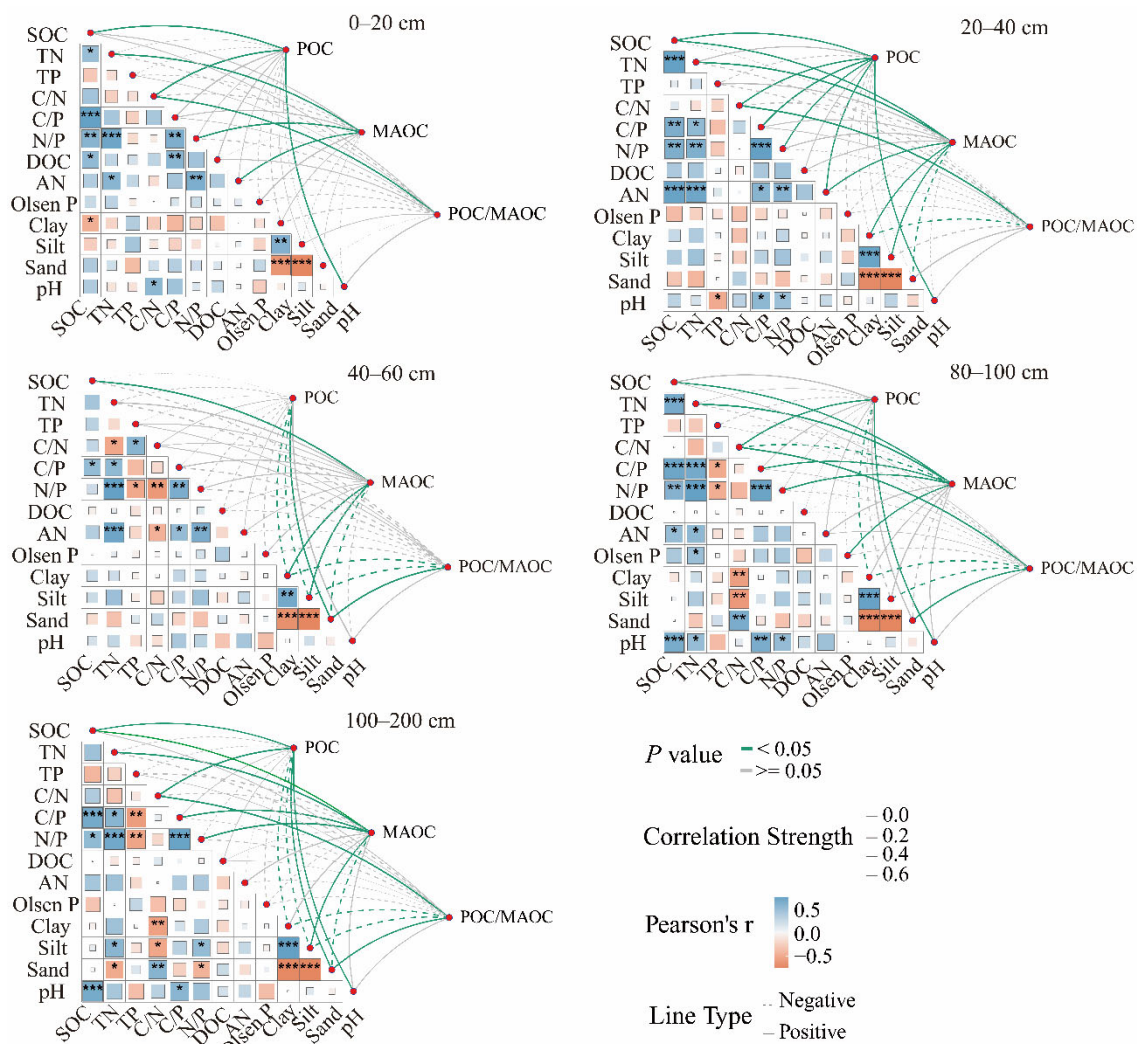


Figure 6. Spearman's correlation network among soil properties, stoichiometry, POC, and MAOC across soil depth. Edge width and color indicate correlation strength (thicker = stronger) and type (red positive, blue negative), respectively. The square matrix shows pairwise correlations among environmental factors using a color gradient (darker = stronger). Only significant correlations ($p < 0.05$) are shown. Asterisks indicating significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns: no significant effect).

4. Discussion

4.1. Vertical Distribution and Driving Mechanisms of Soil Carbon Pools Across Ecological Zones in Dongting Lake

Soil physicochemical properties, nutrient stoichiometry and organic carbon fractions presented obvious spatial and vertical heterogeneity among four typical wetland sites in Dongting Lake. SOC and TN displayed pronounced surface enrichment characteristics and declined markedly with soil depth (Figure 1). The consistent vertical decreasing trend was closely attributed to concentrated distribution of plant roots and surface litter input, which supplied abundant organic substances predominantly in the topsoil [3,31]. Similar depth patterns have been widely reported in Coastal Wetlands [32], indicating that surface carbon accumulation driven by vegetation input is a common feature of wetland ecosystems. No significant interaction between region and depth was observed, suggesting similar vertical variation patterns for carbon and nitrogen across different habitats. Junshan possessed higher SOC and TN contents in shallow layers, while West Dongting Lake retained more carbon and nitrogen in deep soil, reflecting divergent organic matter preservation capacities

among ecological zones [25]. Different from carbon and nitrogen, TP remained relatively stable along soil profiles and lacked distinct vertical variation, whereas remarkable regional discrepancy and interactive effect between site and depth were identified (Figure 1). The maximum TP value occurred in the deep soil horizon of the Tuanzhou site. Located at the river estuary, this site receives unique sediment inputs [33], which formed a texture with elevated deep-layer clay fractions (Table S1). The abundant fine clay particles effectively adsorb phosphorus, leading to prominent TP accumulation in deep soil [34,35]. Soil C/N, C/P and N/P ratios had negligible vertical changes but strong site divergence. The consistently high C/N ratio at Tuanzhou reflected the low decomposition degree of indigenous organic matter, with fresh plant debris serving as the main composition [28]. Varied N/P ratios indicated inconsistent nutrient limitation status among wetlands [33].

Both POC and MAOC declined gradually down the soil profile (Figure 2). The declining trend of POC with soil depth in South and West Dongting reflected depletion of labile plant-derived organic components down the profile, owing to the gradual reduction of root litter input and enhanced decomposition limitation in deep layers [3,36]. With continuous organic decomposition and mineral transformation in deeper horizons, labile particulate carbon transformed into a stable, mineral-bound form, making MAOC predominant in the subsoil [12]. This depth-driven shift from POC to MAOC is consistent with the mineral protection theory, which posits that persistent carbon is primarily associated with soil minerals rather than remaining as particulate residues [37]. Linear regression further verified the vertical functional differentiation of carbon fractions (Figure 4). POC dominated SOC variation in the surface layer, while MAOC became the major contributor to SOC dynamics in deep soil. This pattern suggests that surface carbon pools are more responsive to plant-derived inputs and environmental perturbations, while deep carbon pools are stabilized through mineral association, conferring greater long-term persistence [38]. Across the entire study area, correlation analysis confirmed that soil carbon, nitrogen, and stoichiometric characteristics acted as universal driving factors controlling the accumulation of POC and MAOC (Figures 5 and 6). This finding indicates that nutrient availability and stoichiometric balance play a fundamental role in regulating the partitioning between labile and stable carbon fractions, regardless of site-specific hydrological or textural differences [39].

4.2. Stability Characteristics and Influencing Factors of Soil Carbon Pools at Different Ecological Locations

Soil carbon pool stability differed substantially among four wetland sites, as reflected by divergent POC/MAOC values and component proportion structure. Consistent with previous studies, the POC/MAOC ratio served as a reliable indicator of carbon pool stability [40]. A lower POC/MAOC ratio implies that a greater proportion of SOC is stabilized via mineral association, indicating higher resistance to decomposition and longer carbon persistence. Conversely, a higher ratio suggests that SOC is more vulnerable to environmental changes [41]. In our study, significant spatial differences in carbon pool stability were observed among natural wetland, human-disturbed wetland and lacustrine shoal habitats. Only Tuanzhou presented POC/MAOC ratios greater than 1, accompanied by an extremely high POC/SOC proportion and a low MAOC/SOC proportion (Figure 3), demonstrating that labile particulate organic carbon dominated its carbon pool with relatively low stability. This ratio range is comparable to values reported for drained or agriculturally impacted wetlands [42], where POC/MAOC >1 indicated reduced carbon persistence. By contrast, Junshan (JS), Huanghua (HH), and West Dongting Lake (WD) showed POC/MAOC ratios consistently below 1, with MAOC/SOC exceeding 60%, suggesting a stronger carbon preservation capacity (Figure 2). These values fall within the typical range for undisturbed natural wetlands.

The exceptionally high POC/MAOC ratio (>1) and POC-dominated carbon pool at Tuanzhou are closely linked to its short flooding duration and well-aerated conditions. As a typical estuarine beach with flooding for only 60–90 days per year [25], Tuanzhou experiences prolonged oxic conditions that stimulate aerobic microbial activity, leading to rapid but incomplete decomposition of *Carex* litter and root debris [43,44]. This process favors the accumulation of POC derived from partially decomposed plant residues, while restricting the formation of MAOC due to reduced iron oxide activation and limited mineral adsorption capacity under oxidation [43]. In contrast, the longer flooding periods (>90 days) at Junshan (JS) and West Dongting Lake (W) create anaerobic environments that suppress POC decomposition and promote the formation of stable MAOC via enhanced mineral–organic complexation [3,25], resulting in POC/MAOC ratios <1 at these sites. The consistently high C/N ratio at TZ further indicates low decomposition intensity of indigenous organic matter, where fresh plant debris dominates the carbon pool and reinforces POC predominance [28]. Regression slopes further supported the site-specific carbon composition discrepancy. SOC variation at Tuanzhou was mostly driven by POC, while MAOC contributed the most to SOC changes at other sites (Figure 4).

Environmental factors exerted differentiated regulation effects on carbon stability. Soil nutrients were fundamental factors affecting POC and MAOC accumulation at all sites [45,46]. Generally, enriched soil carbon, nitrogen and stoichiometric conditions significantly promoted the accumulation of organic carbon fractions by sustaining vegetation productivity and providing sufficient organic substrates [46]. Consistent with the view that labile fractions are more responsive to nutrient availability [39], POC was more sensitive to nutrient variation due to its plant-derived and labile properties [13]. Site-specific nutrient regulation further differentiated carbon pool characteristics: nutrients dominated carbon fraction variation at Tuanzhou and Huanghua, co-functioned with soil texture at Junshan, and reduced carbon stability under nutrient enrichment at West Dongting Lake (Figure 5). This finding suggests that nutrient inputs, while promoting overall carbon accumulation, may simultaneously shift the carbon pool toward more-labile forms in certain contexts. Soil texture dominated the differentiation of carbon pool stability [47]. High clay and silt contents facilitated organic mineral combination and promoted stable MAOC formation, while sandy soil tended to retain undecomposed POC [15]. In our study, the positive correlation between POC/MAOC and sand and the negative correlation with clay quantitatively confirms this textural control. The texture control effect intensified with soil depth, and deep soil exhibited the strongest mineral protection capacity (Figure 6). Thus, the disturbed wetland (TZ) accumulated large amounts of active organic carbon but faced a higher mineralization risk, implying that its carbon sink is less durable under continued land use or climate pressure [11]. Natural wetlands maintained a stable carbon sequestration capacity, suggesting that their preservation is critical for long-term carbon storage in the Dongting Lake region.

We acknowledge that this study was conducted exclusively in the Dongting Lake Basin. While the basin exhibits substantial internal heterogeneity (three ecological zones), the observed relationships between POC/MAOC and environmental drivers may be region-specific. Future research should extend this analytical framework to other river–lake complexes (e.g., Poyang Lake, the Amazon floodplain) to test the generalizability of our conclusions.

5. Conclusions

This study systematically investigated spatial and vertical patterns of soil organic carbon fractions (POC, MAOC) and nutrient stoichiometry (C:N:P) across four representative sites in the Dongting Lake wetland, a typical river–lake floodplain ecosystem in subtropical

China. We found significant vertical stratification: SOC and TN decreased with depth, with surface enrichment in the 0–40 cm layer. In contrast, TP showed no vertical trend but varied markedly among sites. C/N, C/P, and N/P ratios exhibited significant regional disparities but no vertical variation, implying that nutrient limitation regimes are site-specific. Carbon fractions showed clear functional differentiation with depth: POC dominated surface carbon dynamics, while MAOC governed deeper layers through mineral protection. Notably, the POC/MAOC ratio proved to be a sensitive indicator of carbon stability, exceeding 1 only at the human-disturbed Tuanzhou site, indicating a vulnerable, POC-dominated pool, while the other three sites exhibited ratios below 1, reflecting MAOC-dominated, stable pools. Environmental controls on carbon fractions were context-dependent. Nutrients universally promoted POC and MAOC accumulation, but their effects on stability varied by site: nutrients co-functioned with texture at Junshan, dominated fraction variation at Tuanzhou and Huanghua, and reduced stability under nutrient enrichment at West Dongting Lake. Soil texture emerged as the dominant stability regulator, with control intensifying with depth—deep soils exhibited the strongest mineral protection, reinforcing MAOC persistence. We conclude that carbon stability in lake wetlands is primarily determined by site-specific factors (hydrology, texture, nutrients) rather than depth alone. The POC/MAOC ratio offers a practical indicator for assessing wetland carbon persistence. Maintaining natural hydrological regimes and soil texture integrity is critical for long-term carbon sequestration. Future validation across multiple floodplain wetlands is needed to confirm the generalizability of these findings.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/land15071170/s1>: Figure S1: Spatial distribution of sampling sites in the Dongting Lake basin.; Table S1: Soil particle size distribution (clay, silt, and sand percentages) across soil depths at the four sampling sites in the Dongting Lake wetland.

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