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Analysis of Organic Carbon Content and Sources in Sediments from the Outer Reef Slope of Yongle Atoll, Xisha Islands

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Abstract

Organic carbon burial is an important component of the carbon cycle; however, studies on organic carbon in coral reef sediments have been scarce to date, affecting the accurate assessment of carbon cycling in coral reefs. This study analyzed modern surface sediments from the outer reef slope of Yongle Atoll in the Xisha Islands of the South China Sea, examining total organic carbon (TOC) content, total nitrogen (TN) content, organic carbon isotope ($ 13C)values, aswellassedimentgrainsize, chlorophyllcontent, andotherparameters.Theecologicalconditionc
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g−1, withanaverageof1.23±0.31mg·g−1; TNcontentrangesfrom0.12 0.28mg·
g−1, withanaverageof0.20±0.05mg·g−1.2)TheC/Nratiorangesfrom6.16 7.59, withanaverageof6.75±$0.34;
$ 13Cvaluesrangefrom−17.49 −15.85‰, withanaverageof−16.61±0.49‰, indicatingthatorganiccarboninthe
a−1), theorganiccarbonburialfluxontheouterreefslopeofYongleAtollisestimatedtobebetween1.12 2.61g·
m − 2 · a − 1, withanaverageof1.93±$0.49 g · m-2 · a-1. This study provides new information for assessing the contribution of South China Sea coral reefs to the carbon cycle.

Full Text

Content and Source Analysis of Organic Carbon in Outer Slope Sediments of Yongle Atoll, Xisha Islands

Abstract

Organic carbon burial constitutes a critical component of the global carbon cycle, yet research on organic carbon in coral reef sediments remains scarce, hindering accurate assessment of coral reef carbon cycling processes. This study investigates modern surface sediments from the outer slope of Yongle Atoll in the Xisha Islands, South China Sea, analyzing total organic carbon (TOC) content, total nitrogen (TN) content, organic carbon isotope

($ 13$C)values, sedimentgrainsize, chlorophyllcontent, andrelatedparameters.TheecologicalconditionofYong$
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1}$.(2)C/Nratiosrangefrom6.16to7.59, averaging6.75\pm$0.34; $ 13$Cvaluesrangefrom-$
$17.49to-15.85‰, averaging-16.61\pm0.49‰, demonstratingthatsedimentorganiccarbonispredominantlymari$
$a*andpheophytinconcentrations, indicatingthatbenthicplant-controlledprimaryproductivityrepresentsthep$
$a^{\{-1\}), weestimateorganiccarbonburialfluxonYongleAtoll'soutersloperangesfrom1.12to2.61g \cdot m}${-
2}$\cdot a^{\{-1\}, averaging1.93\pm0.49g \cdot m}${-2}$\cdot a^{-1}. This study provides new insights for evaluating the contribution of South China Sea coral reefs to the carbon cycle.

Keywords: coral reef; sediment; organic carbon; carbon isotope; Yongle Atoll; Xisha Islands

Introduction

Quantifying the capacity of natural ecosystems to capture and store CO_2 provides both theoretical foundations for understanding global climate change and practical guidance for ecosystem management strategies to mitigate and adapt to climate impacts (Macreadie et al., 2017). As the largest carbon reservoir after the lithosphere, the ocean absorbs approximately one-third of anthropogenic CO_2 emissions (McLeod et al., 2011), demonstrating substantial "negative emissions" potential and playing a crucial role in global climate regulation (Post et al., 1990; Falkowski et al., 2000; Jiao et al., 2021). Marine sediments constitute a vital component of the oceanic carbon pool (Keil, 2017) and serve as an important storage site for organic carbon (Seiter et al., 2004; Chen et al., 2022), where organic carbon can remain buried for millions of years under natural conditions (Estes et al., 2019), representing the ultimate net effect of marine carbon sequestration (Berger et al., 1989). Current research on sedimentary organic carbon predominantly focuses on coastal ecosystems such as mangroves and seagrass beds (Gao et al., 2019; Alemu I et al., 2022), while coral reef sediments—another typical shallow marine ecosystem—have received minimal attention (Schrimm et al., 2004).

Although coral reefs occupy only about 0.2% of the global ocean area in tropical-subtropical shallow seas, they represent the most biodiverse and highest primary productivity marine ecosystems (Hatcher, 1988; Tanaka et al., 2011; Gove et al., 2016), potentially photosynthetically fixing 700 million tons of organic carbon annually (Crossland et al., 1991) and exhibiting potential carbon sink functionality (Shi et al., 2021). Research indicates that as global coral reef health declines, these ecosystems are experiencing coral cover loss and/or ecological phase shifts toward algae-dominated systems, with increasing community organic metabolism (Page et al., 2016). Since 1970, coral reef community calcification rates have declined at 4.3$\pm1.9\pm0.8mmol \cdot m^{\{-2\} \cdot d}${-1}$ per year, signaling a fundamental metabolic transition (Davis et al., 2021). The organic composition of coral reef sediments can indicate benthic community structure (Miyajima et al., 1998; Kaczmarsky and Richardson, 2011; Yogesh Kumar et al., 2014) and nutrient sources (Umezawa et al., 2008; Briand et al., 2015), serving as a powerful tool for recording local environmental conditions and assessing reef "health" status (Schrimm et al., 2004; Kaczmarsky and Richardson, 2011; Marques et al., 2019). Analyzing the content, composition, and source-sink processes of organic carbon in coral reef sediments is therefore essential for evaluating the current role of coral reefs in the carbon cycle and their ecological health. However, insufficient understanding of organic matter and other environmental information in coral reef sediments impedes accurate assessment of coral reef carbon source-sink functions (Ke et al., 2018).

Organic carbon isotopes ($ $13C) and the elemental ratio of total organic carbon to total nitrogen (C/N ratio) serve as effective indicators for assessing organic matter sources in marine sediments, as different organic matter sources exhibit distinct characteristics due to environmental differences in their parent materials (Remeikaitė-Nikienė et al., 2016; Li et al., 2021). Terrestrial vegetation, composed primarily of lignin and cellulose (low nitrogen content), typically exhibits high C/N ratios (up to 20 or more), whereas algal organic matter, rich in protein and lacking cellulose (high nitrogen content), shows relatively low C/N ratios (between 4 and 10; Meyers, 1994; Meyers, 1997). $ $13C values for terrestrial plants generally range from -30 to -26‰ or lower; freshwater phytoplankton from -30 to -25‰; and marine phytoplankton from -22 to -18‰ (Boutton, 1991; Ku et al., 2007; Yu et al., 2010).

The South China Sea (SCS), the largest marginal sea in the western Pacific, ranks eighth globally in coral reef resources, with extensive reef distribution (4°N–21°N) including atolls, island reefs, and fringing reefs, representing a significant coral reef region (Yu, 2012; Yu, 2018). The outer reef slope, a primary geomorphic unit of coral reefs located at the reef's seaward edge with a seaward dip, hosts the best coral growth and highest species diversity, forming the "coral growth zone" (Storlazzi et al., 2005; Zhao et al., 2017). Against the backdrop of overall degradation in South China Sea coral reef ecosystems, the outer slope of Yongle Atoll in the Xisha Islands maintains relatively good ecological condition (Zhao et al., 2016; Chen et al., 2019). This study therefore examines surface sediments from Yongle Atoll's outer slope to represent sedimentary characteristics under relatively healthy ecological conditions, specifically analyzing organic carbon and nitrogen content (TOC, TN), organic carbon isotopic composition ($ $13C), sediment grain size, chlorophyll content, and other indicators to provide new information for accurately assessing the contribution of South China Sea coral reefs to the carbon cycle.

1.1 Study Location

Yongle Atoll, located 300 km southeast of Hainan Island (16°26 –16°37 N, 111°34 –111°48 E), comprises 13 coral islands and reefs including Lingyang Reef, Ganquan Island, Coral Island, Quanfu Island, and Yinyu Island, surrounding a central lagoon. As the largest atoll in the western Xisha Islands, it is a discontinuous open-type atoll oriented NE-SW, approximately 22 km long and 16 km wide [Figure 1: see original paper].

Situated in a key position within the East Asian monsoon region, Yongle Atoll experiences strong, continuous northeasterly monsoons in winter (November–February) and weaker, variable southwesterly monsoons in summer (June–October) (Yang et al., 2015). Wind-driven currents dominate, with direction and velocity varying seasonally, and the atoll's geomorphology has been shaped by these monsoonal currents (Wang, 2006; Yan et al., 2010; Zhao et al., 2017). Because northeasterly monsoons are stronger than southwesterly ones, the atoll exhibits pronounced east-west asymmetry: the eastern reef is wide, thick, and low, with a shallow, complex lagoon featuring patch reefs that coalesce into banks; the western reef is narrow and high, with a deep, simple lagoon where tidal action facilitates active water exchange, creating favorable reef-building conditions and forming coral growth zones on inner slopes similar to outer slopes, such as east of Ganquan Island and northeast of Lingyang Reef (Wang, 2006; Zhao, 2010).

1.2 Sample Collection

Samples were collected from coral habitats on Yongle Atoll in the Xisha Islands during July–September 2021. To minimize habitat disturbance, all surface sediment samples (0–8 cm depth) were collected by SCUBA divers at 14 stations on the outer reef slope (5–30 m water depth) within the coral reef framework facies [Figure 1c: see original paper]. Sediment samples were sealed in sample bags and frozen at -20°C for laboratory analysis.

1.3.1 Sediment Grain Size Analysis

Dry sediments were sieved using six mesh screens (0.063, 0.125, 0.25, 0.5, 1, and 2 mm) to determine grain size distribution. Based on the Udden-Wentworth phi-scale classification, sediments were divided into three categories: gravel (>2 mm), sand (2–0.063 mm), and silt (<0.063 mm), where ϕ = -$\log_2 d$ (d in mm). Mean grain size and sorting coefficients were calculated using the Manus moment formula.

1.3.2 Organic Carbon, Nitrogen, and Carbon Isotope Analysis

Freeze-dried samples were ground and homogenized to pass a 100-mesh sieve, then acidified with 1M HCl added dropwise in small aliquons until bubbling ceased. Samples were washed with Milli-Q water to neutrality, centrifuged to remove supernatant, and the enriched material was freeze-dried and weighed for analysis.

TOC and TN content were measured at the Marine College/Coral Reef Research Center of Guangxi University using a vario MACRO cube elemental analyzer (Elementar, Germany) with sulfanilamide standards. Results were corrected by mass conversion, achieving precision $ $0.01%. $ $13C analysis was conducted at the Third Institute of Oceanography, Ministry of Natural Resources, using a Flash EA 1112-ConFlo IV-Delta V Plus IRMS system (Thermo

Fisher Scientific, USA). Internal standards were acetanilide (ACET; \$ $13C = 26.85\pm$\$0.1‰) and caffeine (IAEA-600; \$ $13C = -27.77\pm$\$0.05‰), with precision \$ $0.06‰. Resultswerecalibratedagainstinternationalstandards($ \$13CV-PDB). All analyses were performed in duplicate and averaged.

1.3.3 Sediment Chlorophyll Content Analysis

Freeze-dried, ground samples were extracted with 90% acetone via ultrasonication for 15 min, then held at 4°C in darkness for 20 h with intermittent shaking. After centrifugation, supernatants were analyzed (Li, 2006). Measurements were performed at the Marine College/Coral Reef Research Center of Guangxi University using a Shimadzu UV-Vis spectrophotometer with 90% acetone as the standard. Samples in 1-cm cuvettes were measured at 750 nm and 665 nm, then acidified with 1–2 drops of 0.5M HCl, shaken gently for 1–2 min, and re-measured. Chlorophyll *a* and pheophytin concentrations were calculated using Lorenzen's equations (Lorenzen, 1967).

1.4 Statistical Analysis

Data were analyzed using Origin 2021 and ArcGIS 10.8 for graphical analysis, and SPSS 22.0 for statistical analysis. Pearson correlation analysis described parameter relationships with significance set at $p<0.05$. All data are presented as mean±standard deviation (SD).

2.1 Sediment Grain Size

Sand dominates the outer slope sediments of Yongle Atoll, comprising 84.81–97.62% (average 92.43\$±3.89±0.42 \$ (lower ϕ values indicate coarser sediment), averaging 0.73\$±0.28 \$, with the coarsest sediments occurring on Yinyu Reef's outer slope [FIGURE:2; TABLE:1]. Sediments show moderate to poor sorting. Pearson correlation analysis reveals a significant positive correlation between mean grain size and water depth (R=0.58, $P<0.05$; [FIGURE:2; TABLE:2]), indicating coarser sediments on the upper reef slope in shallow water.

2.2 Sediment Organic Carbon, Nitrogen, and Carbon Isotope Values

Surface sediments from Yongle Atoll's outer slope contain TOC of 0.71–1.66 $mg \cdot g^{-1}$ (average 1.23\$$\pm 0.31 mg \cdot g^{\{-1\})andTNof0.12–0.28mg \cdot g}$\{-1\}\$ (average 0.20\$$\pm 0.05 mg \cdot g$^\{-1\}\$). Spatially, TOC and TN contents are highest on Yinyu Reef's outer slope in northeastern Yongle Atoll, followed by Shiyu [FIGURE:3a; TABLE:1]. Shallow upper reef slopes exhibit higher TOC and TN than deeper lower slopes, with significant negative correlations to water depth (TOC: R=-0.56, $P<0.05$; TN: R=-0.54, $P<0.05$; [FIGURE:4a,b; TABLE:2]).

Corrected via linear regression of TOC and TN, C/N ratios range from 6.16–7.59 (average 6.75\$±\$0.34), while \$ $13Cvaluesrangefrom - 17.49to -$

15.85‰(*average* − 16.61±$0.49‰). TOC and TN show significant positive correlation (R=0.98, *P*<0.001; [FIGURE:3b; TABLE:2]), and C/N ratios correlate positively with $ $13C values (R=0.54, *P*<0.05; [FIGURE:5; TABLE:2]), indicating strong source homogeneity.

2.3 Sediment Chlorophyll Content

Chlorophyll *a* (Chl *a*) concentrations in Yongle Atoll surface sediments range from 0.90–8.01 g·g^{-1} (average 3.48$±1.99*μg*·*g*{-1}), *whilepheophytin*(*Pheo*)*rangesfrom*0.83–3.98*μg* · *g*{-1}$ (average 2.16$±0.90*μg* · *g*^{-1}$). Pearson correlation shows moderate negative relationships between chlorophyll content (Chl *a*, Pheo) and water depth (Chl *a*: R=-0.49, *P*=0.08; Pheo: R=-0.55, *P*<0.05;). TOC content correlates strongly and significantly with both Chl *a* and Pheo (Chl *a*: R=0.75, *P*<0.01; Pheo: R=0.78, *P*<0.01; [FIGURE:4c,d; TABLE:2]), demonstrating that primary productivity, as indicated by chlorophyll content, influences organic carbon concentrations.

3.1 Representative Significance of TOC Content on Yongle Atoll's Outer Slope

Based on 14 modern surface sediment samples from the outer reef slope, this study reports, for the first time, TOC content in sediments of Yongle Atoll, South China Sea, ranging from 0.71–1.66 mg·g^{-1} (average 1.23$±0.31*mg* · *g*^{-1}$). Compared with previous studies , TOC content in Yongle Atoll's outer slope sediments is relatively low.

Miyajima et al. (1998) suggested that TOC content in reef sands typically falls below 2–4 mg·g^{-1}, reflecting background levels derived primarily from carbonate skeletons of corals, foraminifera, and calcareous algae. Sorokin (1995b) proposed that TOC in coral sands generally remains below 3–6 mg·g^{-1}, rarely exceeding 10 mg·g^{-1}. While these metrics provide broad guidelines, their representativeness remains unclear. This study therefore selected surface sediments from Yongle Atoll's outer slope to represent sedimentary characteristics under relatively healthy ecological conditions (Zhao et al., 2016). As shown in , our TOC values (0.71–1.66 mg·g^{-1}) fall below 2 mg·g^{-1}, similar to many healthy coral reef ecosystems such as coral-rich areas around Agatti Island (India), the Great Barrier Reef (Australia), and Moorea Island (French Polynesia) (Schrimm et al., 2004; Alongi et al., 2008; Shekhar et al., 2019). The relatively low TOC burial in healthy coral reefs is intimately linked to the low-nutrient, relatively clear waters where corals thrive, requiring tight organic matter recycling to sustain the community (Schrimm et al., 2004; Miyajima et al., 2007). Studies demonstrate that coral mucus release is crucial for energy and nutrient recycling in these oligotrophic environments (Wild et al., 2004). While coral mucus can trap suspended material and accelerate particulate organic matter deposition (Wild et al., 2005), it also contains microbial concentrations 100 times higher than seawater, with oxidation consumption rates of 130–445 mol·L^{-1}·d^{-1} compared to only 5–41 mol·L^{-1}·d^{-1} in ambient water (Hung et al., 2003). Coral mucus shedding enriches nearby sediments with organic matter and microorganisms, and the well-aerated, illuminated upper layers of coral sand provide ideal habitat for microalgae, bacteria, and meiofauna, making coral sand one of the most active zones in coral reef ecosystems and resulting in substantial organic matter mineralization (Sorokin, 1995b; Sorokin, 1995a). Furthermore, elevated nutrients and organic carbon can drive coral disease and mortality (Kaczmarsky and Richardson, 2011). While organic matter recycling provides nutrients, excessive nutrient production, particularly combined with warming temperatures, significantly impacts coral health (Kaczmarsky and Richardson, 2011; Page et al., 2023), making relatively low TOC content more favorable for coral growth.

Conversely, degraded coral reef communities may exhibit higher TOC content. As shown in , coastal bay areas and coral reefs with low coral cover or disease outbreaks, such as those near Negros Island (Philippines), show substantially higher TOC than our study sites (Schrimm et al., 2004; Kaczmarsky and Richardson, 2011; Lin et al., 2021). Research indicates that silty and clayey sediments and nutrient-rich deposits stress corals, whereas sandy or nutrient-poor sediments have minimal impact (Yogesh Kumar et al., 2014). Terrestrial nutrient input effects on coral reef metabolism have been identified as causing relatively high organic productivity in fringing reefs (Suzuki and Kawahata, 2003; 2004). Even minor nutrient additions can promote phytoplankton and benthic algal growth, triggering major community structural changes (Riegl et al., 2015) and ultimately increasing sediment organic carbon content (Jaikumar, 2010; Yogesh Kumar et al., 2014). Seagrass- and macroalgae-dominated reef sediments are typically organic-rich (Miyajima et al., 1998; Atwood et al., 2018), and compared to bacterial decomposition of coral secretions and phytoplankton, seagrasses, turf algae, and macroalgae have higher C/N ratios, lower nutritional quality, and higher refractory organic matter content (Nicolas and Pergent, 2006; Umezawa et al., 2008; Fey et al., 2020). Consequently, TOC content in coral-dominated healthy reefs is generally low, whereas elevated TOC may indicate community phase shifts and/or eutrophication risk.

Watanabe and Nakamura (2019) reported that organic carbon content in coral reef sediments is typically lower than in shelf ecosystems like mangroves and seagrass beds, being 1/18 that of mangroves and 1/2 to 1/5 that of seagrass beds. Chen et al. (2022) found TOC content in Hainan's Dongzhai Port mangrove surface soils ranging from 6.57–74.87 $mg \cdot g^{-1}$ across different communities. Yang et al. (2022) reported TOC content of 2–11.9 $mg \cdot g^{-1}$ in Hainan's Li'an Bay seagrass bed surface sediments. Liu et al. (2017) summarized global seagrass bed TOC data, finding an average of 15 $mg \cdot g^{-1}$, with approximately 70% of seagrass beds containing less than 15 $mg \cdot g^{-1}$. Thus, TOC burial in typical shallow marine ecosystems follows the general trend: coral reefs < seagrass beds < mangroves. This disparity stems not only from organic matter supply but also from differences in decomposition and preservation pathways. The coarse-grained, highly permeable nature of coral reef sediments allows oxygen penetration via porewater flow in the upper few centimeters, promoting TOC mineralization and maintaining low TOC levels (Werner et al., 2006).

Organic geochemical proxies serve as powerful indicators of coral reef health (Umezawa et al., 2008; Kaczmarsky and Richardson, 2011; Vaughan et al., 2021). Controlled by nutrient conditions and efficient carbon cycling, corals thrive in relatively low-organic-carbon environments. Our relatively low TOC values suggest Yongle Atoll shows no eutrophication and remains suitable for coral growth. In summary, Yongle Atoll's outer slope exhibits relatively good ecological condition, with TOC content representing baseline background values for organic carbon in healthy coral reef carbonate sediments.

3.2 Organic Carbon Source Analysis

Our results show C/N ratios of 6.16–7.59 (average 6.75$±$0.34) and $ 13Cvaluesof − 17.49to − 15.85‰(average − 16.61±$0.49‰) in Yongle Atoll outer slope sediments. Compared with open ocean deep-sea sediments, C/N ratios are similar, but $ 13Cvaluesaresubstantiallyhigherthanopenoceanvalues(average− 21.0±$0.7‰) (Chen et al., 2023).

Marine sedimentary organic carbon sources can be broadly divided into terrestrial input and marine sources, with distinct chemical compositions (Ge et al., 2007; Briand et al., 2015). Studies demonstrate that C/N ratios and $ 13Cvaluesserveasimportanttracersfororganiccarbonsources.MarinesedimentswithC/Nratios < 8aregenerallyconsideredmarine−dominated, whileratios > 12indicateterrestrialdominance(Bordovskiy, 19
0‰)forphotosynthesis, whichisisotopicallyheavierthanatmosphericCO_{2}$ used by terrestrial plants ($ $13C = -7.8‰), resulting in more positive marine $ $13C values (O'Leary, 1988). For example, end-member $ $13C values of -19.0‰ and -26.0‰ have been used for marine and terrestrial sources in the Leizhou Peninsula and Daya Bay (Baoxiao et al., 2018; Xia et al., 2022), and -20.8‰ and -27.0‰ in Zhanjiang Bay (Lu, 2020). In our study area, C/N ratios of 6.16–7.59 are far below terrestrial vegetation values, and $ $13C values of -17.49 to -15.85‰ are substantially more positive than terrestrial end-members, indicating predominantly marine autochthonous organic carbon sources without terrestrial influence.

However, low marine sediment C/N ratios may be influenced by inorganic nitrogen (TIN), requiring assessment of TIN effects on TN (Yu and Zhang, 2017). The linear relationship between TOC and TN is widely used to evaluate constant TIN backgrounds (Kienast et al., 2005). Our results show similar spatial distributions of TOC and TN with significant positive correlation (R=0.98, $P<0.001$;), indicating source homogeneity. The TN intercept near zero ($0.013\ \mathrm{mg \cdot g^{-1}}$) when TOC=0 suggests most TN is organic nitrogen, and TIN is not the primary cause of low C/N ratios. Additionally, C/N and $ $13C may be affected by early diagenesis, as nitrogen-rich proteins (with heavier $ $13C) are more readily degraded, increasing C/N ratios and decreasing $ $13C values (Chen et al., 2023). In our study area, $ $13C correlates positively with C/N but shows no clear correlation with TOC or TN (), indicating minimal early diagenetic alteration and confirming both parameters as reliable source indicators.

To more intuitively assess organic carbon sources, we compiled published C/N and $ $13C values for benthic and phytoplankton communities in central and western Pacific coral reefs and constructed a C/N versus $ $13C plot to distinguish marine organic carbon types [Figure 5: see original paper]. Benthic plants exhibit higher $ 13CvaluesthanphytoplanktonduetopreferentialuptakeofisotopicallyheavierHCO_{3}$^− during photosynthesis (Raven et al., 2002). Our Yongle Atoll sediments fall within the benthic plant end-member range [Figure 5: see original paper], confirming benthic plant sources as the dominant contributor. As "rainforests of the sea," coral reefs support rich benthic community structures (Zhao et al., 2006; Yu, 2018). Contributions of seagrasses, turf algae, and macroalgae to sediment organic carbon have been documented, attributed to high nutrient cycling and primary production combined with low degradation rates due to structural characteristics, enabling long-term storage (Nicolas and Pergent, 2006; Umezawa et al., 2008; Fey et al., 2020). Furthermore, sediment trap studies show >93% of particulate organic carbon is recycled before burial, explaining the scarcity of phytoplankton-derived organic carbon in sediments (Song et al., 2003). Thus, C/N ratios and $ $13C values demonstrate that Yongle Atoll receives no terrestrial material, with sediment organic carbon predominantly marine-sourced and primarily from benthic plants.

3.3 Primary Productivity as the Determinant of TOC Production on the Reef Slope

In Yongle Atoll outer slope sediments, TOC content shows significant negative correlation with water depth and highly significant positive correlation with sediment chlorophyll content (Chl *a*, Pheo) [FIGURE:4; TABLE:2]. Spatially, TOC content is highest on Yinyu Reef's outer slope in northeastern Yongle Atoll, followed by Shiyu .

As established, outer slope surface sediments are dominated by marine benthic plant sources, necessitating examination of the relationship between coral reef community primary productivity and TOC content. Depth variations comprehensively affect TOC through influences on photosynthetic rates, plant abundance, and sediment accumulation. Studies show lower irradiance at deeper sites reduces organic carbon content (Serrano et al., 2014; Samper-Villarreal et al., 2016). The negative correlation between TOC and water depth suggests depth-regulated community primary productivity significantly influences TOC content. Plant pigments persist in detrital material from living/dead marine plants and animal fecal pellets, with carbonate sediments showing higher chlorophyll concentrations than silicate or terrestrial sediments (Rasheed et al., 2011). Benthic microalgae are key coral reef ecosystem components, with sediment Chl *a* serving as a robust indicator of benthic microalgal standing stock for primary productivity estimation, while Pheo, as a Chl *a* degradation product, also indicates productivity (Heil et al., 2004; Sanders et al., 2012). The relationship between TOC and chlorophyll content thus confirms that community primary productivity determines TOC content on Yongle Atoll's outer slope.

Additionally, the East Asian monsoon influences Yongle Atoll's geomorphology, enhancing water mass exchange at northeastern stations and delivering more external nutrients, thereby promoting community primary productivity and active carbon cycling.

Sediment grain size characteristics can reveal environmental factors controlling particle size variation, particularly material sources and hydrodynamic conditions (McLaren and Bowles, 1985; Yu et al., 1995; Xiao et al., 2016). The positive correlation between outer slope grain size and water depth indicates stronger hydrodynamic conditions in shallow areas [FIGURE:2b; TABLE:2]. While calm hydrodynamics generally favor particle deposition and fine-grained content that preserves organic matter (Köster and Meyer-Reil, 2001; Han et al., 2020), Yongle Atoll shows the opposite pattern: shallow stations have coarser, more hydrodynamically energetic sediments yet higher organic matter and chlorophyll content [FIGURE:4; TABLE:2]. Rasheed et al. (2011) demonstrated that porous carbonate reef sediments can trap more plant detritus. Yin and Yan (2012) showed that coarse-grained substrates with high light transmittance and large interparticle spaces are more suitable for algal growth. Previous surveys of Yongle Atoll algal cover also reported higher coverage on upper versus lower reef slopes (Zhao et al., 2016), consistent with our findings. Therefore, while hydrodynamic conditions are energetic in shallow reef areas, they support greater algal growth and organic carbon sources. Sedimentary dynamics are not the primary control on TOC content; rather, primary productivity appears to be the dominant factor determining TOC content on Yongle Atoll's outer slope.

3.4 Potential Organic Carbon Sink Capacity of Coral Reefs

Based on AMS^{14}C-derived average sedimentation rates of 1.27 $mm \cdot a^{-1}$ over the past 3,500 years (Yue et al., 2019) and an average dry bulk density of 1.24 $g \cdot cm^{-3}$ for coral sand (Xun et al., 2009), we estimated organic carbon burial flux (burial flux = sedimentation rate × dry density × TOC). Yongle Atoll's organic carbon burial flux ranges from 1.12–2.61 $g \cdot m^{-2} \cdot a^{-1}$, averaging $1.93 \pm 0.49 g \cdot m^{\{-2\} \cdot a}\{-1\}$.

Estimating organic carbon burial flux enhances our understanding of coral reef carbon sequestration capacity. Yan et al. (2018) reported air-sea CO_2 fluxes of 3.94 $g \cdot m^{-2} \cdot a^{-1}$ at Shiyu outer slope and 5.26 $g \cdot m^{-2} \cdot a^{-1}$ at Ganquan Island channel slope. While Yongle Atoll appears to be a CO_2 source to the atmosphere based on air-sea fluxes, our estimated organic carbon burial flux can offset approximately 1/5 to 1/3 of this CO_2 release. Horizontal organic carbon export fluxes are not yet considered. Yang et al. (2011) found net POC export to the open ocean from Zhubi Reef of 5.11 $g \cdot m^{-2} \cdot a^{-1}$. Thus, although coral reefs are typical calcifying systems, their organic carbon sink capacity plays a crucial role in evaluating coral reef carbon cycling functions.

Our Yongle Atoll burial flux estimate is lower than that for the Herbert River region of the Great Barrier Reef (9.6 $g \cdot m^{-2} \cdot a^{-1}$; Brunskill et al., 2002), likely due to greater riverine material delivery to the Great Barrier Reef. It is comparable to some seagrass ecosystems, such as the Baltic Sea's Gdansk Bay (0.84–3.85 $g \cdot m^{-2} \cdot a^{-1}$; Jankowska et al., 2016) and Western Australia's Oyster Harbor (average 3.45 $g \cdot m^{-2} \cdot a^{-1}$; Rozaimi et al., 2016), but substantially lower than the global seagrass bed average (138.00 $g \cdot m^{-2} \cdot a^{-1}$; McLeod et al., 2011). In both seagrass and coral reef systems, interacting factors drive specific variations in organic carbon burial across environments (Cartapanis et al., 2016). For example, the Great Barrier Reef lagoon leeward side contains carbonate mud belts with TOC burial ~4 times higher than Yongle Atoll's outer slope (Alongi et al., 2006), and Madagascar's southwest coast closed lagoons show highest TOC content while high-carbonate-phase sediments show lowest (Thomassin and Cauwet, 1985). Although Yongle Atoll's outer slope burial flux is relatively low, lagoons and nearshore areas may have higher fluxes. With global coral reef area reaching 617,000 km^2 (Smith, 1978)—4.5 times global mangrove area (137,000 km^2; Giri et al., 2011) and comparable to or exceeding seagrass beds (300,000–600,000 km^2; Claude and Sournia, 1990; Duarte et al., 2005)—coral reef ecosystems collectively possess significant potential as organic carbon sinks, warranting enhanced monitoring and analysis of coral reef organic carbon burial.

4 Conclusions and Outlook

Based on investigation and analysis of sediments from Yongle Atoll's outer slope in the Xisha Islands, South China Sea, we conclude:

1. TOC content ranges from 0.71–1.66 $mg \cdot g^{-1}$ (average 1.23\$±0.31mg · g{-1}); TNcontentrangesfrom0.12–0.28mg · g{-1}\$ (average 0.20\$±0.05mg · g^{-1}\$).
2. C/N ratios range from 6.16–7.59 (average 6.75\$±\$0.34) and \$ 13Cvaluesfrom−17.49to − 15.85‰(average − 16.61±\$0.49‰), revealing no terrestrial influence, with organic carbon predominantly marine-sourced and primarily derived from benthic plants.
3. TOC content correlates negatively with water depth and positively with chlorophyll *a* and pheophytin content, suggesting primary productivity is the main determinant of organic carbon content on the reef slope.
4. Yongle Atoll's outer slope organic carbon burial flux ranges from 1.12–2.61 $g \cdot m^{-2} \cdot a^{-1}$ (average 1.93\$±0.49g · m{-2}·a{-1}\$), indicating potential organic carbon sink capacity.

References

[References section preserved exactly as provided in the original text]

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.