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ARTICLE

Reconstructing sediment sources in Sorsogon Bay, Philippines using stable isotope characterization and mixing model techniques

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ABSTRACT

Sorsogon Bay, Philippines, has experienced declining water quality, harmful algal blooms (HABs), and shallowing water depth in the past decades, which could be attributed to pollution from terrestrial origins such as human settlements, farming, industrial and urban activities, and groundwater inflow. These pollutants and excess nutrients are associated with suspended fine sediments, which can be transported to the bay, especially during typhoons and flood events. In this study, the application of stable carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$) isotopes and other sediment characteristics such as %OC, %N, dry bulk density (DBD), mass accumulation rates (MAR), organic carbon accumulation rate (OCAR), nitrogen accumulation rate (NAR) and calculated % terrestrial contributions in dated sediment cores were used for retrospective assessment of transport of sediment-associated nutrients before and after 1960, the start of population increase and land-use change in the catchments. The records indicate that, in the post-1960 sediments, sediment cores receiving inputs from Sorsogon City and Juban-Irosin show increased terrestrial contribution by 3-10%, a change that coincides with population growth, forest loss, expansion of built-up and agricultural land, and eruptions of Mt. Bulusan. Changes in the Cadacan River delta may also have altered the DBD and MAR profiles. The first recorded HAB in 1983 followed decades of rapid population growth, which is consistent with a role for nutrient loading in HAB development.

INTRODUCTION

Sorsogon Bay, Philippines, has been under environmental pressure in recent decades, with declining water quality, harmful algal blooms (HABs) and increasing sediment deposition (Sta. Maria et al., 2020; Judicpa and Abrahan, 2021). Human settlements, farming, sewage and animal waste disposal, atmospheric deposition, wastewater and other wastes from industrial and mining activities, and traffic exhaust all add to the pollution load that degrades water quality (Anderson et al., 2002; Zhou et al., 2020). Marine sediments are a sink of pollutants and nutrients that are carried to coastal waters especially during typhoon and flooding events, and thus reflect an integrated pollution level in an area (Spagnoli et al., 2021). Sorsogon Bay is on the watch list of Bureau of Fisheries and Aquatic Resources (BFAR) for HABs or red tide occurrences. The first recorded HABs occurrence in Sorsogon Bay was in 1983, and paralytic shellfish poisoning (PSP), caused by *Pyrodinium bahamense var. compressum* (Pbc), was reported until 2011, with several deaths, mostly of children (Estudillo and Gonzales, n.d.; Montealegre et al., 2009). The blooms are attributed to high nutrient levels, fecal coliform and contamination caused by agriculture, manufacturing, and indiscriminate dumping of wastes in rivers and creeks discharging into the bay (Judicpa and Abrahan, 2021; CLUP 2007-2012, personal communication, 2009).

In recent years, awareness has grown of the importance of sediment loads on the transport of nutrients and contaminants to water systems. From a management perspective, sediment control strategies can be effective only once the origin of the sediment, and how much each land-based source contributes to the inputs to the water body, are known. Stable isotopes techniques are widely used to characterize, identify and help quantify land-based pollutants of aquatic ecosystems (Jankowski et al., 2012; Rogers, 2013), especially in non-point sources (Krause et al., 2023) such as excess fertilizer or wastes from agricultural, domestic, and urban activities, erosion in channel banks, atmospheric deposition, mining, sediments from construction sites and land clearance, and

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KEYWORDS

Sedimentation, sediment provenance, carbon and nitrogen stable isotopes, two-source mixing model, land use change

crop and forest lands. Stable isotopes such as $\delta^{13}C$ and $\delta^{15}N$ exhibit source-specific signatures that serve as fingerprints of their provenance. Trends in the elemental organic carbon (%OC), nitrogen (%N) and their accumulation rates in sediments can support the identification of sediment sources and of changes in terrestrial vegetation, aquatic productivity, hydrology, and ecology in river-catchment systems (Fan et al., 2017; Rumolo et al., 2011). The relative terrestrial contribution to sediments can also be estimated with a mixing model utilizing locally calibrated end members (Rogers, 2013; Silva et al., 2011).

Several studies have applied these techniques to investigate sediment provenance (Dittmar et al., 2001; Rogers, 2013; Silva et al., 2011). In the Philippines, the Bureau of Soils and Water Management and Philippine Nuclear Research Institute (BSWM & PNRI, 2013) used the stable isotopes and mixing model techniques to identify pollutant sources and estimate nutrient loading in the Pampanga River Basin and near major river mouths draining to Manila Bay. A three-source mixing model with the end-member values: 1) domestic – $\delta^{13}C$ = -24.73‰ and $\delta^{15}N$ = 5.12‰; 2) livestock – $\delta^{13}C$ = -29.61‰ and $\delta^{15}N$ = 13.54‰; and 3) cropland – $\delta^{13}C$ = -27.25‰ and $\delta^{15}N$ = 2.16‰, showed that cropland contibuted 22 - 98% of the pollutant load in the wet season and domestic waste contributed 55 - 65% in the dry season. A two-source model for offshore surface sediments in Manila Bay indicated that more than 30% of organic matter deposited in Manila Bay came from agricultural activities in Pampanga River Basin.

Sediment cores record the isotopic and elemental composition of buried organic matter in coastal environments that are influenced by natural (terrestrial and marine) and anthropogenic sources, such as population growth and increasing land-based activity. This study integrates carbon and nitrogen stable isotope analyses, a two-source mixing model, and published sediment age profiles (Ramirez et al., 2026) to reconstruct changes in sediment sources and assess their contributions to sediment and nutrient inputs in Sorsogon Bay, Philippines, from 1930 to 2009, in relation to population growth, land-use change, and volcanic activity, to inform sediment and pollution management in the bay.

MATERIALS AND METHODS

Three sediment core samples from Sta. Maria et al. (2020) were further analyzed in this study (Figure 1). The cores were collected, collected in 2009 near the mouths of major rivers in three municipalities: 1) Sampaloc River, Sorsogon City (SAM); 2) Dulangan-Nasipit River or Castilla River, Castilla (CAS); and 3) Cadacan River, Juban-Irosin (CAD). Subsamples were taken from each sediment core every 5 to 10 cm layer. The age profiles were established using ^{210}Pb method and Constant Initial Concentration (CIC) age dating model, and were validated by Ramirez et al. (2026) through correlation of dry bulk density (DBD) and mass accumulation rates (MAR) with past typhoon events and eruptions of Mt. Bulusan. The age profiles were used to place the $\delta^{13}C$ and $\delta^{15}N$ measurements and the two-source mixing results in time and so to reconstruct sedimentation history and possible sediment sources.

Surface sediments were collected with a locally fabricated Van Veen sediment grab sampler at two sites chosen as end members: near Brgy. Bulabog, Sorsogon City, far from the open sea, where $\delta^{13}C$ is the most negative (-26.9‰) and which represents the terrestrial end member; and at Malawmawan Island, close to the open sea, where $\delta^{13}C$ is the most positive (-17.6‰) and which represents the marine end member (Rogers, 2013; Silva et al., 2011). All sediment samples were freeze-dried, homogenized, and kept in a desiccator prior to analysis.

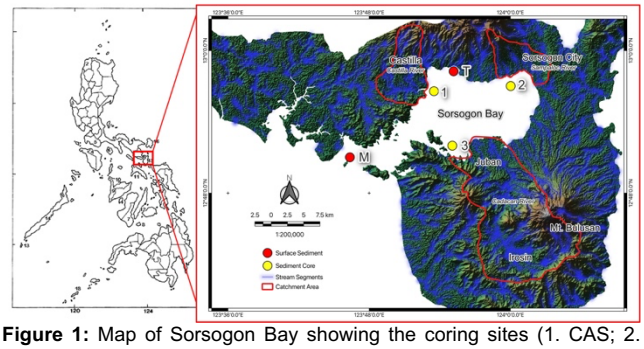


Figure 1: Map of Sorsogon Bay showing the coring sites (1. CAS; 2. SAM; 3. CAD) and terrestrial (T) and marine (M) end member sites, and catchments.

Study Areas

Sorsogon Bay is bordered by the municipalities of Sorsogon City, Castilla, Juban, Casiguran, and Magallanes. These areas are characterized by diverse land uses: urban settlements, agricultural lands, forested uplands, and aquaculture farms. The province ranges from low-lying plains to mountainous terrain, and its soils from sandy loam to hydrosol. Population growth, economic activity, waste discharge, and the conversion of forests and mangrove areas into cultivated lands and fishponds have degraded the bay (Judicpa and Abrahan, 2021). Previous studies reported substantial siltation and sediment accumulation near the coast (Montealegre et al., 2009).

The three catchments differ in drainage area, urbanization, topography, slope, soil characteristics, and land-use patterns, which all control sediment transport and erosion (Jing et al., 2022). Among the three sites illustrated in Figure 1, CAD has the largest catchment area (254 km²), followed by CAS (63 km²) and SAM (44 km²).

Castilla, CAS

The terrain of Castilla is mostly plain (0–8% slope) to rolling (8–18% slope). Its only soil type, Castilla clay loam, suits crops such as rice, corn, various root crops, abaca, coconut, and fruit-bearing trees. About 79% of the land area is agricultural (coconut 60% and rice 20% of the farmland). Other crops grown in the area include corn, cassava, sweet potato, abaca, coconut and other fruit bearing trees. Castilla has three industries: small-scale poultry farms, organic fertilizer farms, and small-scale feed mills. A 2008 municipal survey gave a population growth rate of 0.83% in 2000 to 2008 and a population density of about 2.89 persons per hectare.

Sorsogon City, SAM

The SAM catchment is in Sorsogon City, the provincial capital and commercial center. The terrain is flat to undulating (slopes of 0–8%) with silty clay loam to sandy loam soils suitable for cultivation. Sorsogon City is mainly of agricultural land (73%) and forestland (23%), with smaller portions allocated to built-up areas and fishponds. Although largely rural, it has urbanized and grown, and mining and quarrying began in 1983 (National Statistics Office, 1990). These activities may contribute to increased sediment and contaminant inputs into adjacent coast.

Juban and Irosin, CAD

The CAD catchment, in the municipalities of Juban and Irosin, includes the Mount Bulusan, the fourth most active volcano in the Philippines (PHIVOLCS, 2022). The Cadacan River, the largest river system in the province, receives most of the volcanic materials (Siringan et al., 2018). The terrain is hilly to mountainous, with slopes of 30% to more than 50%, and soils are mainly silt loam and sandy loam. Land use is mostly agricultural and forest; in Juban about 95% of the land is farmed, and urban

areas in both municipalities are small. The steep slopes, volcanic deposits, and cultivated land make the catchment highly susceptible to erosion and sediment transport. The population grew fastest between 1960 and 1970 (2.29% per year).

Population growth and land-based activities

The SAM catchment in Sorsogon City had the largest population among the study sites, which rose from 19,781 in 1930 to 155,144 in 2010. The combined population of CAD (Juban and Irosin) rose from 24,482 to 61,330 over the same period, while that of CAS (Castilla) from 7,873 to 30,595 (Philippine Statistics Authority, personal communication, 2018). Population growth accelerated in all three catchments between the 1950s and 1970s, together with agricultural expansion and urban development. The periods before and after 1960 were therefore defined as pre-disturbance and post-disturbance.

Stable isotope analysis

About 14 mg of each sediment samples were weighed into tin capsules on a micro analytical balance and crimpled, following IAEA-TECDOC-1870 (International Atomic Energy Agency, 2019).

The $\delta^{13}C$, $\delta^{15}N$, %OC, and %N of the samples were measured with a Sercon 20–22 continuous flow Isotope Ratio Mass Spectrometer (IRMS) coupled to a Sercon GSL elemental analyzer (Sercon Limited, UK) at the Philippine Nuclear Research Institute (PNRI). All results are reported with respect to standard materials Vienna Pee Dee Belemnite (VPDB) and N-air for carbon and nitrogen isotope ratios, respectively. A standard reference material, Low Organic Content Soil Standard OAS IAEA (Cat. No. B2153) and a duplicate sample were analyzed every 5 runs to ensure reliability and accuracy of results. The analytical precision of measurement was better than 0.2‰ for both $\delta^{13}C$ and $\delta^{15}N$.

C/N Ratio

The measurement of C/N ratio helps to distinguish terrestrial and marine nature of the sediments. Terrestrial materials (e.g., C3 and C4 plants and soil) have C/N ratio above 15, higher than those of marine materials typically 4-10 (e.g., algae, phytoplankton, macrophytes) because vascular plants contain cellulose and lignin and algae are rich in protein (Silva et al., 2011; Dittmar et al., 2001; Rumolo et al., 2011). The C/N (atomic) ratio was calculated using Eq. 1.

$$\boldsymbol{C/N} = \frac{\%\boldsymbol{OC}}{\%\boldsymbol{N}} \boldsymbol{x} \frac{\mathbf{14}}{\mathbf{12}} \quad \text{(Eq. 1)}$$

Where %OC = percentage of organic carbon by mass in sediment samples
%N = percentage of nitrogen by mass in sediment samples

Organic carbon and nitrogen accumulation rates

Marine sediments accumulate organic carbon and nitrogen from marine or terrestrial inputs, which depend on precipitation and human activities such as urbanization and deforestation (Yu et al., 2018). The organic carbon and nitrogen accumulation rates (OCAR and NAR) at each depth were estimated using Eq. 2:

$$XAR = MAR\ x\ \varphi \quad \text{(Eq. 2)}$$

Where XAR = organic carbon accumulation rate (OCAR) or nitrogen accumulation rate (NAR) at each depth, g m^{-2} y^{-1}
MAR = mass accumulation rate at each depth, g m^{-2} y^{-1}
φ = %OC or % N
The MAR values of Ramirez et al. (2026) were utilized (Table S1).

Estimation of terrestrial contribution using a two-source mixing model

A two-source mixing model uses mass balance equations and the isotopic signatures of various sources to estimate their fractions in a mixture (Fry, 2006). The fractions of terrestrial and marine organic matter were calculated from $\delta^{13}C$ with Eqs. 3 and 4:

$$f_T + f_M = 1 \quad \text{(Eq. 3)}$$

$$f_M x\ \delta^{13}C_M + f_T x\ \delta^{13}C_T = \delta^{13}C_{sample} \quad \text{(Eq. 4)}$$

where f_T and f_M are the terrestrial and marine fractions, $\delta^{13}C_T$ = -26.9‰ and $\delta^{13}C_M$ = -17.6‰ are the end members, and $\delta^{13}C_{sample}$ is the measured value.

Data Analysis

Sediment characteristics, DBD (Sta. Maria et al., 2020; Table S1), MAR (Ramirez et al., 2026), $\delta^{13}C$ and $\delta^{15}N$ signatures, %OC, %N, OCAR, NAR, C/N ratio, and % terrestrial contribution were plotted against the sediment age profiles (Ramirez et al., 2026) to reconstruct sedimentation history and sources. The C/N ratio was also plotted against $\delta^{13}C$ on the source fields of Rogers (2013) to distinguish more clearly the characteristics of terrestrial and marine sources.

RESULTS AND DISCUSSION

The sediment records of the three cores differ in all measured proxies (Figure 2): $\delta^{13}C$, $\delta^{15}N$, C/N ratio, %OC, %N, DBD, MAR, OCAR, NAR, and % terrestrial contribution. The site-specific sections below consider how sedimentation processes, catchment characteristics (e.g., soil type, topography, slope, and vegetation), population growth, and land-based activities may explain these differences.

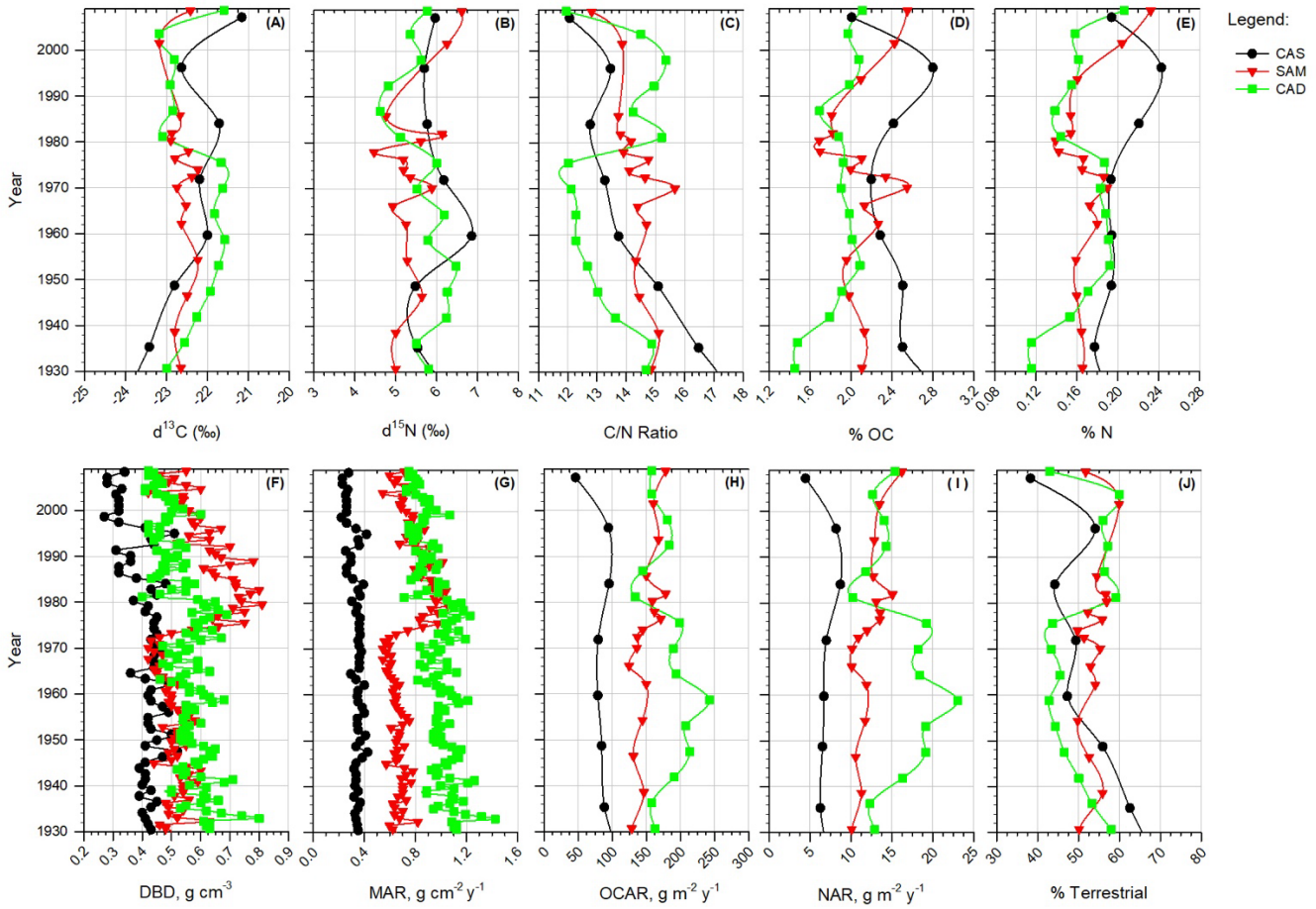


Figure 2: Sediment profile characteristics of CAS, SAM, and CAD sediment cores.

Castilla, CAS

The CAS sediment core has relatively high organic matter content, as shown by the %OC and %N profiles in Figure 2D and Figure 2E. This is consistent with the high ^{210}Pb activity concentrations (18 ± 4.4 to 150 ± 15 Bq kg^{-1}) and low DBD (Figure 2F; 0.27 to 0.52 g cm^{-3}) reported by Sta. Maria et al. (2020) and Ramirez et al. (2026). CAS had the highest %OC (2.39 ± 0.26%; range 2.01 to 2.80%) and %N (0.20 ± 0.02%; range 0.18 to 0.24%) of the three cores which may reflect fine, organic-rich materials from clay loam soils of farmlands in the catchment. They may also reflect the land use in Castilla, which is mostly under vegetation, small-scale poultry, and organic-fertilizer farms. The CAS sedimentation rate (0.82 ± 0.13 cm y^{-1}; Sta. Maria et al. 2020), MAR (0.33 ± 0.05 g cm^{-2} y^{-1}; ranging from 0.22 to 0.43 g cm^{-2} y^{-1}) (Ramirez et al., 2026; Sta. Maria et al., 2020), OCAR (80.94 ± 16.67 g m^{-2} y^{-1}; ranging from 46.12 to 95.21 g m^{-2} y^{-1}) and NAR (6.83 ± 1.37 g m^{-2} y^{-1}; ranging from 4.46 to 8.70 g m^{-2} y^{-1}) are lower than measured values in SAM and CAD. Castilla is the most rural of the three municipalities, and field observations indicated that it is the least disturbed and most vegetated. The effects of the population increase in the 1960s on %OC and %N were observed starting from the 1970s. This is further supported by the positive correlation between %OC and %N in all three sites (Figure 3A, r^2 = 0.25), suggesting that the nitrogen in sediment layers was mainly in the form of organic nitrogen that could be from domestic and/ or agricultural wastes (Yu et al., 2018) and that the two had a common source (Tang et al., 2020). However, δ^{15}N varied little (Figure 2B; 4.98 - 6.85‰), which is consistent with natural variability or with soil-derived nitrogen from the catchment, which has lower δ^{15}N (Fan et al., 2017). Consequently, any δ^{15}N enrichment linked to HABs starting 1983 is not evident in the CAS sediment core, which is consistent with Castilla being far from the affected sites, which include Sorsogon City and Casiguran (Montealegre et al., 2009). The δ^{13}C signature (Figure 2A; -23.42 ‰ to -21.16 ‰), on the other hand, indicates that the vegetation in the catchment area is dominated by C3 plants. This includes permanent crops such as coconut, pili, abaca, and temporary crops such as rice and cassava. The slight δ^{13}C enrichment in Figure 2A could also reflect the 73% increase in number of land conversions to agricultural farms in Castilla from 1971 to 1980 (National Statistics Office, 1990), when the production of C4 plants such as corn was also expanded. Human settlements, building constructions, and anthropogenic activities may have caused the alteration of δ^{13}C (Das et al., 2008). Alternatively, this shift could mean enhanced aquatic productivity (Fan et al., 2017) or increasing marine contribution, which could also explain the decrease in C/N ratio from 15.1 to 12.9 (**Error! Reference source not found.**A; Papanicolaou et al., 2003; Tang et al., 2020; Zhan et al., 2012). Before 1960 the isotopic composition of the sediment lies in the C3 plants field; after 1960 it moves toward the marine and riverine field, mainly C3 soil and riverine material. This is further supported by the calculated terrestrial fraction, which decreases from 62.56% in the deepest sediment to 38.28% in the top sediment layer (Figure 2J) in top sediment layers. Further investigation is needed to determine the causes of this observation.

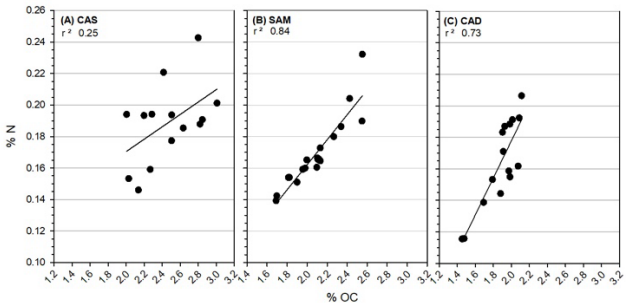


Figure 3: Plot of %OC vs. %N in CAS (A), SAM (B), and CAD (C) sediment cores.

Sorsogon City, SAM

The low ^{210}Pb activity concentrations (1.74 – 61.37 Bq kg^{-1}) and high DBD in SAM (Figure 2F; 0.42 – 0.81 g cm^{-3}) were attributed to intensified land-based activities and rapid population growth in Sorsogon City, the urban center of Sorsogon Province (Sta. Maria et al., 2020; Ramirez et al., 2026). Rapid urbanization and construction activities between 1970 and 1980, a decade in which the number of residential and commercial buildings in the city rose by 25.37%, coincided with the increased DBD. The conversion of agricultural lands to residential and commercial land may have reduced organic-rich soils and increased the input of coarser sediments. Consequently, δ^{15}N values decreased from 5.88 to 4.47‰, %OC from 2.55% to 1.69%, and %N from 0.19% to 0.14% (Figures 2B, 2D, and 2E). Although two sand and gravel quarrying sites opened in the 1980s, their contribution to sediment input in SAM and Sorsogon Bay was probably minor compared to the impacts of urban construction activities.

The δ^{13}C values was relatively stable throughout the core, ranging from −23.17 to −22.23‰ (Figure 2A; −22.62 ± 0.28‰), indicating minimal long-term changes in vegetation cover and continued dominance of terrestrial organic matter derived from C3 plants in the catchment. In contrast, δ^{15}N values ranged from 4.47 to 6.61‰ (5.39 ± 0.54‰) and exhibited gradual enrichment in the upper sediment layers beginning in the 1980s. This enrichment likely reflects increasing anthropogenic influence associated with population growth and the expansion of agricultural farms, which the National Statistics Office (1990) reports as a 107% increase between 1970s to 1980s. Disturbed agricultural landscapes are known to exhibit elevated δ^{15}N signatures relative to undisturbed ones (Michener and Lajtha, 2007).

The strong positive correlation between %OC and %N in Sorsogon City sediments (Figure 3B; $r^2 = 0.84$) further suggests that nitrogen was primarily derived from organic sources such as domestic sewage and agricultural wastes (Yu et al., 2018). Informal settlements without proper sewage and waste disposal were observed near the coast and the Sampaloc River mouth during sampling. This is consistent with the historical sanitation data where in 1980, 39.4% of households lacked toilet facilities, while 13% and 10% relied on open-pit and closed-pit toilets, respectively. By 2000, approximately 21% of the population still had no access to sanitary toilets.

A noticeable increase in δ^{15}N from 4.47‰ in 1978 to 6.13‰ in 1982 suggests nutrient enrichment in the bay, potentially stimulating phytoplankton growth and HABs (Fan et al., 2017). This is consistent with the first recorded paralytic shellfish poisoning (PSP) event in Sorsogon, from June to September 1983, which resulted in two deaths and 49 reported cases (Estudillo and Gonzales, n.d.).

%OC and %N declined during the peak of construction and land disturbance, but they increased again from the 1980s, together with δ^{15}N, OCAR, and NAR, as urban activities intensified and construction projects were completed. OCAR and NAR were already elevated in the early 1970s, during continuous population growth. OCAR first peaked in 1976 (171.10 g m^{-2} y^{-1}) and NAR in 1978 (13.57 g m^{-2} y^{-1}), while maximum values were recorded in the 1982 sediment layer.

The C/N ratio ranged from 12.82 to 15.66 (Figure 2C), indicating that sediment is within the range of mixed riverine and terrestrial organic matter (Rogers, 2013). The gradual decrease in C/N ratios beginning in the 1970s suggests increasing nutrient enrichment and sewage influence in the bay (Rumolo et al., 2011; Van Den Hende et al., 2011). This trend may also reflect declining forest soil contribution associated with extensive land conversion. From 1971 to 1980, forestland in Sorsogon Province decreased by approximately 60%, while the number of agricultural farms in Sorsogon City increased from 1,316 to 2,730 to meet growing food demands of the expanding population.

Post-disturbance sediments exhibited higher OCAR (158.51 ± 15.15 g m^{-2} y^{-1}) and NAR (13.05 ± 1.72 g m^{-2} y^{-1}) compared with pre-disturbance levels of 133.87 ± 11.10 g m^{-2} y^{-1} and 10.64 ± 0.89 g m^{-2} y^{-1}, respectively. By the late 1980s δ^{15}N, %OC, and %N began to return toward pre-disturbance levels after the completion of major construction activities, accompanied by decrease in DBD and MAR. These parameters increased again at times that correspond to later HABs occurrences in 1998, 1999–2000, and 2007, indicating the continued influence of anthropogenic nutrient loading on sediment composition and coastal productivity.

Juban – Irosin, CAD

CAD receives substantial volcanic materials and debris from Mt. Bulusan, which gives it relatively high MAR and, probably, coarser sediments (**Error! Reference source not found.**F and **Error! Reference source not found.**G). Two distinct periods, before 1980 and after 1980, were evident in the DBD and MAR profiles. Before the 1980s, DBD ranged from 0.46 to 0.71 g cm^{-3} (0.58 ± 0.05 g cm^{-3}), while MAR ranged from 0.82 to 1.26 g cm^{-2} y^{-1} (1.03 ± 0.10 g cm^{-2} y^{-1}). After 1980, both parameters declined to 0.40–0.65 g cm^{-3} (0.49 ± 0.05 g cm^{-3}) and 0.71–1.15 g cm^{-2} y^{-1} (0.86 ± 0.10 g cm^{-2} y^{-1}), respectively. Quarrying may influence sediment delivery, but the decrease in DBD and MAR was more likely controlled by natural geomorphic processes than by human activities. As of 2017, there were four quarrying sites in Irosin and five in Juban, and mining and quarrying activities in Sorsogon Province had already been reported by 1990 (Mines and Geoscience Bureau - Regional Office V, 2017). Sand and gravel extraction can reduce the transport of coarse sediments to coastal areas (Ozcan et al., 2012). However, the timing and magnitude of the sedimentary changes in CAD do not match the onset of major civil works and road construction, which began mostly in 1989. Instead, the decline in DBD and MAR may reflect river-course migration or deflection of the Cadacan River mouth away from the sampling site. Unlike the Castilla and Sampaloc rivers, which directly deliver sediments to the CAS and SAM cores, sediment transport in CAD is strongly influenced by the complex morphodynamic behavior of the Cadacan River delta (Oyedotun and Nedd, 2023). River deltas are dynamic coastal systems that continuously adjust to river discharge, sediment supply, tidal and wave processes, sea-level variation, and human influence. High sediment supply from upstream sources promotes the formation of distributary channels and shifting depositional environments over time (Oyedotun and Nedd, 2023). A similar transition from sandy, high-density to finer, low-density sediment followed the 1976 river-mouth deflection of the Yellow River delta, China, as the delta prograded eastward (Zhou et al., 2016).

In contrast to the physical sediment parameters, the organic carbon and nitrogen proxies (%OC, %N, OCAR, and NAR; Figure 2D, 2E, 2H, and 2I) exhibited different trends. Finer sediments generally contain more organic matter, but any human influence in CAD may be masked by the large supply of volcanic material from Mt. Bulusan. %OC, %N, OCAR, and NAR were lower during the major eruption periods in 1933 and 1978–1983 (VEI 2 – 3). During these eruptions $\delta^{13}C$ values was more depleted , −22.78 ± 0.31‰ before the 1930s and −22.76 ± 0.58‰ during the mid-1970s, compared with −21.80 ± 0.23‰ in the quiescent periods between 1933 and 1978 (Figure 2A). C/N ratio (Figure 2C) and % terrestrial contribution (Figure 2J) were also higher during the eruptions, with C/N ratio of 14.94 ± 0.37 and terrestrial contribution reaching 55.60 ± 4.80%. In the quiescent periods, C/N ratios (13.41 ± 1.25) and terrestrial fraction (45.19 ± 2.52%) were lower. These patterns may indicate enhanced terrestrial organic matter input associated with volcanic activity and erosion within the Mt. Bulusan catchment. Pyroclastic flows and lahar deposits generated during eruptions probably increased surface runoff and carried large amounts of eroded terrestrial materials into CAD, shifting $\delta^{13}C$ signatures toward the C3 terrestrial value (Fan et al., 2017). In the quiescent periods, the variations in these geochemical proxies were more probably driven by precipitation and typhoon runoff.

From the mid-1980s, increasing trends in $\delta^{15}N$, %OC, %N, OCAR, and NAR (Figure 2B, 2D, 2E, 2H, and 2I) suggest enhanced nutrient enrichment and organic matter accumulation in CAD sediments. This coincides with HABs that affected the coast of Juban and nearby Casiguran (Estudillo and Gonzales, n.d.; Montealegre et al., 2009). %OC and %N are strongly correlated (r^2 = 0.73; Figure 3C), which indicates that nitrogen is mostly organic, which could be domestic sewage or agricultural runoff (Yu et al., 2018). Overall, the increases in C/N ratio, $\delta^{15}N$, %OC, and %N point to greater terrestrial organic matter input and nutrient enrichment through runoff, which may have supported phytoplankton growth and HAB development (Fan et al., 2017). The $\delta^{13}C$ vs. C/N ratio also shows dominant signatures within the terrestrial fields (C3 soil and plants, emergent plants, riverine material; Figure 4C).

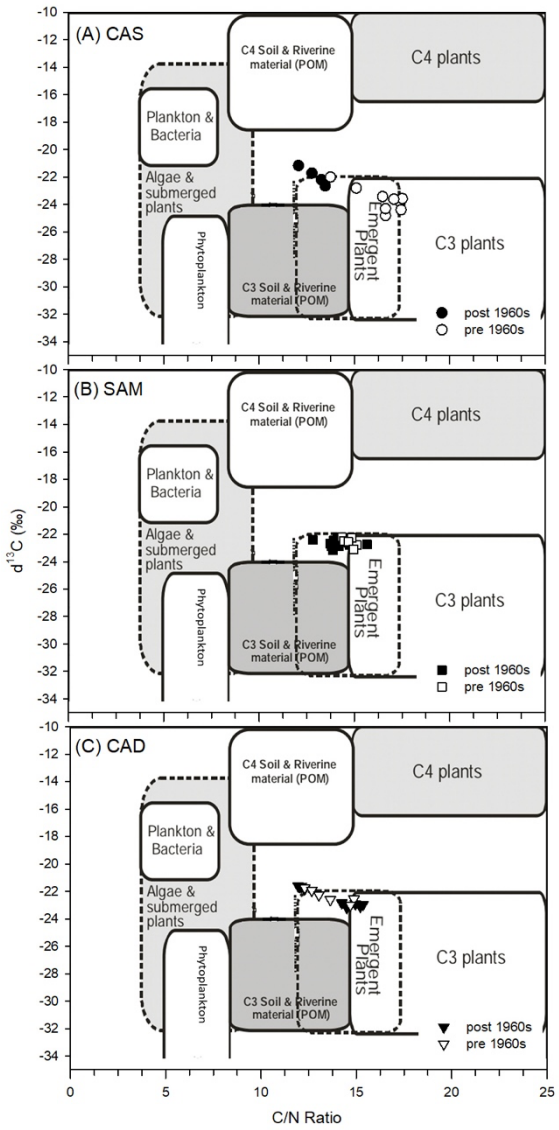


Figure 4: C/N ratio and $\delta^{13}C$ of sediments in CAS (A), SAM (B) and CAD (C) before and after 1960 (terrestrial and marine source fields adapted from Rogers (2013)).

CONCLUSION

Stable carbon and nitrogen isotopes, a two-source mixing model coupled with ^{210}Pb dating were combined to reconstruct historical sediment and nutrient inputs to Sorsogon Bay over 1930 – 2009 period. Across the three sediment cores, changes in sediment composition coincide with both anthropogenic pressures (population growth, land-use conversion, agricultural expansion) and natural processes (typhoon runoff, eruptions of Mt. Bulusan, and geomorphic changes in the Cadacan River system).

The SAM and CAD cores show higher terrestrial and nutrient-related proxies during the post-disturbance period, reflecting the growing influence of human activities in their catchments. In SAM, higher $\delta^{15}N$, %OC, and %N are consistent with increasing urbanization, domestic wastewater inputs, and agricultural land expansion. The results further support the interpretation that anthropogenic nutrient loading contributed to HABs occurrence in the bay. In CAD the terrestrial contribution was also higher, but the record is dominated by the eruptions of Mt. Bulusan and, possibly, by shifts in the Cadacan River delta that altered sediment delivery. In contrast, the terrestrial contribution in CAS decreased from

62.56% to 38.28%, which was not expected and needs further study.

Overall, the sediment record preserved clear evidence of the link between land-based activities and coastal environmental change in Sorsogon Bay. The study illustrates the potential of sediment archives and isotope-based source reconstruction for identifying long-term trends in sediment provenance, nutrient enrichment, and ecosystem stress in tropical coastal systems. As one of the first studies in the Philippines to integrate these nuclear analytical techniques for reconstructing sediment sources in a coastal environment, this work provides a useful basis for improving wastewater management, land-use planning, and sediment control strategies in Sorsogon Bay and similar coastal systems.

RECOMMENDATION

This work also identified several directions for further studies to maximize the information that can be derived from ^{210}Pb dating and stable isotope measurements in sediments and improve understanding of how anthropogenic and natural processes influence coastal sedimentation: 1) Conduct higher-resolution carbon and nitrogen stable isotope analyses; 2) Measure sediment grain-size distribution; 3) Correlate the proxies with historical aerial imagery and land-use records; and 4) Investigate the potential influence of local sea-level rise on sediment dynamics and pollutant inputs to coastal sediments.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

JDR: Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Data curation, Formal analysis. **ATBVII**: Writing – review & editing, Formal analysis. **SSC**: Writing – review & editing, Formal analysis. **MGC**: Writing – review & editing, Formal analysis.

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SUPPLEMENTAL INFORMATION

Table S1: Dry bulk density (DBD) and mass accumulation rates (MAR) at each depth in sediment cores CAD, SAM and CAS.

CAD				SAM				CAS			
Depth cm	[a]Year	[b]DBD g cm^{-3}	[a]MAR g cm^{-2} y^{-1}	Depth cm	[a]Year	[b]DBD g cm^{-3}	[a]MAR g cm^{-2} y^{-1}	Depth cm	[a]Year	[b]DBD g cm^{-3}	[a]MAR g cm^{-2} y^{-1}
0.5	2009	0.42	0.75	0.5	2009	0.55	0.70	0.5	2008	0.34	0.28
1.5	2008	0.44	0.78	1.5	2008	0.46	0.58	1.5	2007	0.28	0.23
2.5	2008	0.42	0.75	2.5	2007	0.51	0.65	2.5	2006	0.28	0.23
3.5	2007	0.45	0.80	3.5	2006	0.49	0.62	3.5	2005	0.33	0.27
4.5	2006	0.46	0.82	4.5	2005	0.55	0.70	4.5	2004	0.31	0.25
5.5	2006	0.47	0.83	5.5	2005	0.6	0.76	5.5	2002	0.32	0.26
6.5	2005	0.44	0.78	6.5	2004	0.42	0.53	6.5	2001	0.32	0.26
7.5	2005	0.41	0.73	7.5	2003	0.54	0.69	7.5	2000	0.32	0.26
8.5	2004	0.41	0.73	8.5	2002	0.54	0.69	8.5	1999	0.27	0.22
9.5	2004	0.45	0.80	9.5	2002	0.52	0.66	9.5	1997	0.32	0.26
10.5	2003	0.48	0.85	10.5	2001	0.53	0.67	10.5	1996	0.41	0.34
11.5	2003	0.51	0.91	11.5	2000	0.56	0.71	11.5	1995	0.51	0.42
12.5	2002	0.49	0.87	12.5	1999	0.6	0.76	12.5	1994	0.43	0.35
13.5	2001	0.51	0.91	13.5	1998	0.6	0.76	13.5	1993	0.44	0.36
14.5	2001	0.51	0.91	14.5	1998	0.57	0.72	14.5	1991	0.31	0.25
15.5	2000	0.54	0.96	15.5	1997	0.58	0.74	15.5	1990	0.36	0.30
16.5	2000	0.5	0.89	16.5	1996	0.67	0.85	16.5	1989	0.36	0.30
17.5	1999	0.6	1.07	17.5	1995	0.63	0.80	17.5	1988	0.32	0.26
18.5	1999	0.48	0.85	18.5	1994	0.56	0.71	18.5	1986	0.32	0.26
19.5	1998	0.49	0.87	19.5	1994	0.63	0.80	19.5	1985	0.38	0.31
20.5	1997	0.48	0.85	20.5	1993	0.52	0.66	20.5	1984	0.48	0.39
21.5	1997	0.42	0.75	21.5	1992	0.7	0.89	21.5	1983	0.43	0.35
22.5	1996	0.46	0.82	22.5	1991	0.63	0.80	22.5	1982	0.45	0.37
23.5	1996	0.42	0.75	23.5	1991	0.65	0.83	23.5	1980	0.37	0.30
24.5	1995	0.42	0.75	24.5	1990	0.67	0.85	24.5	1979	0.42	0.34
25.5	1995	0.46	0.82	25.5	1989	0.78	0.99	25.5	1978	0.41	0.34
26.5	1994	0.45	0.80	26.5	1988	0.7	0.89	26.5	1977	0.45	0.37
27.5	1994	0.44	0.78	27.5	1987	0.61	0.78	27.5	1976	0.44	0.36
28.5	1993	0.53	0.94	28.5	1987	0.64	0.81	28.5	1974	0.44	0.36
29.5	1992	0.52	0.92	29.5	1986	0.65	0.83	29.5	1973	0.45	0.37
30.5	1992	0.55	0.98	30.5	1985	0.71	0.90	30.5	1972	0.43	0.35
31.5	1991	0.45	0.80	31.5	1984	0.72	0.91	31.5	1971	0.44	0.36
32.5	1991	0.48	0.85	32.5	1983	0.72	0.91	32.5	1969	0.46	0.38
33.5	1990	0.52	0.92	33.5	1983	0.8	1.02	33.5	1968	0.44	0.36
34.5	1990	0.51	0.91	34.5	1982	0.77	0.98	34.5	1967	0.44	0.36
35.5	1989	0.48	0.85	35.5	1981	0.73	0.93	35.5	1966	0.44	0.36
36.5	1988	0.55	0.98	36.5	1980	0.74	0.94	36.5	1965	0.36	0.30
37.5	1988	0.47	0.83	37.5	1979	0.81	1.03	37.5	1963	0.41	0.34
38.5	1987	0.54	0.96	38.5	1979	0.71	0.90	38.5	1962	0.49	0.40
39.5	1987	0.48	0.85	39.5	1978	0.75	0.95	39.5	1961	0.43	0.35

40.5	1986	0.46	0.82	40.5	1977	0.66	0.84	40.5	1960	0.42	0.34
41.5	1986	0.45	0.80	41.5	1976	0.64	0.81	41.5	1958	0.43	0.35
42.5	1985	0.43	0.76	42.5	1976	0.75	0.95	42.5	1957	0.47	0.39
43.5	1985	0.55	0.98	43.5	1975	0.66	0.84	43.5	1956	0.49	0.40
44.5	1984	0.58	1.03	44.5	1974	0.57	0.72	44.5	1955	0.42	0.34
45.5	1983	0.55	0.98	45.5	1973	0.5	0.64	45.5	1954	0.42	0.34
46.5	1983	0.5	0.89	46.5	1972	0.46	0.58	46.5	1952	0.43	0.35
47.5	1982	0.55	0.98	47.5	1972	0.43	0.55	47.5	1951	0.5	0.41
48.5	1982	0.46	0.82	48.5	1971	0.46	0.58	48.5	1950	0.45	0.37
49.5	1981	0.4	0.71	49.5	1970	0.42	0.53	49.5	1949	0.41	0.34
50.5	1981	0.59	1.05	50.5	1969	0.44	0.56	50.5	1947	0.52	0.43
51.5	1980	0.65	1.15	51.5	1968	0.47	0.60	51.5	1946	0.47	0.39
52.5	1979	0.61	1.08	52.5	1968	0.42	0.53	52.5	1945	0.41	0.34
53.5	1979	0.62	1.10	53.5	1967	0.47	0.60	53.5	1944	0.39	0.32
54.5	1978	0.66	1.17	54.5	1966	0.46	0.58	54.5	1943	0.41	0.34
55.5	1978	0.57	1.01	55.5	1965	0.44	0.56	55.5	1941	0.41	0.34
56.5	1977	0.69	1.23	56.5	1965	0.45	0.57	56.5	1940	0.4	0.33
57.5	1977	0.63	1.12	57.5	1964	0.47	0.60	57.5	1939	0.43	0.35
58.5	1976	0.61	1.08	58.5	1963	0.49	0.62	58.5	1938	0.39	0.32
59.5	1975	0.58	1.03	59.5	1962	0.52	0.66	59.5	1937	0.45	0.37
60.5	1975	0.59	1.05	60.5	1961	0.49	0.62	60.5	1935	0.43	0.35
61.5	1974	0.59	1.05	61.5	1961	0.48	0.61	61.5	1934	0.4	0.33
62.5	1974	0.64	1.14	62.5	1960	0.5	0.64	62.5	1933	0.41	0.34
63.5	1973	0.55	0.98	63.5	1959	0.5	0.64				
64.5	1973	0.58	1.03	64.5	1958	0.49	0.62				
65.5	1972	0.67	1.19	65.5	1957	0.5	0.64				
66.5	1972	0.6	1.07	66.5	1957	0.52	0.66				
67.5	1971	0.53	0.94	67.5	1956	0.53	0.67				
68.5	1970	0.47	0.83	68.5	1955	0.56	0.71				
69.5	1970	0.56	0.99	69.5	1954	0.58	0.74				
70.5	1969	0.55	0.98	70.5	1954	0.54	0.69				
71.5	1969	0.49	0.87	71.5	1953	0.47	0.60				
72.5	1968	0.52	0.92	72.5	1952	0.52	0.66				
73.5	1968	0.52	0.92	73.5	1951	0.52	0.66				
74.5	1967	0.59	1.05	74.5	1950	0.51	0.65				
75.5	1966	0.47	0.83	75.5	1950	0.5	0.64				
76.5	1966	0.49	0.87	76.5	1949	0.55	0.70				
77.5	1965	0.59	1.05	77.5	1948	0.51	0.65				
78.5	1965	0.63	1.12	78.5	1947	0.49	0.62				
79.5	1964	0.55	0.98	79.5	1946	0.52	0.66				
80.5	1964	0.53	0.94	80.5	1946	0.5	0.64				
81.5	1963	0.46	0.82	81.5	1945	0.44	0.56				
82.5	1963	0.5	0.89	82.5	1944	0.55	0.70				
83.5	1962	0.54	0.96	83.5	1943	0.6	0.76				
84.5	1961	0.56	0.99	84.5	1942	0.56	0.71				

85.5	1961	0.6	1.07	85.5	1942	0.53	0.67
86.5	1960	0.56	0.99	86.5	1941	0.59	0.75
87.5	1960	0.61	1.08	87.5	1940	0.54	0.69
88.5	1959	0.63	1.12	88.5	1939	0.54	0.69
89.5	1959	0.68	1.21	89.5	1939	0.54	0.69
90.5	1958	0.64	1.14	90.5	1938	0.51	0.65
91.5	1957	0.55	0.98	91.5	1937	0.56	0.71
92.5	1957	0.57	1.01	92.5	1936	0.48	0.61
93.5	1956	0.58	1.03	93.5	1935	0.49	0.62
94.5	1956	0.55	0.98	94.5	1935	0.54	0.69
95.5	1955	0.55	0.98	95.5	1934	0.49	0.62
96.5	1955	0.54	0.96	96.5	1933	0.52	0.66
97.5	1954	0.54	0.96	97.5	1932	0.63	0.80
98.5	1954	0.6	1.07	98.5	1931	0.46	0.58
99.5	1953	0.56	0.99	99.5	1931	0.48	0.61
100.5	1952	0.55	0.98	100.5	1930	0.5	0.64
101.5	1952	0.54	0.96				
102.5	1951	0.53	0.94				
103.5	1951	0.56	0.99				
104.5	1950	0.53	0.94				
105.5	1950	0.54	0.96				
106.5	1949	0.57	1.01				
107.5	1948	0.61	1.08				
108.5	1948	0.65	1.15				
109.5	1947	0.63	1.12				
110.5	1947	0.63	1.12				
111.5	1946	0.64	1.14				
112.5	1946	0.61	1.08				
113.5	1945	0.58	1.03				
114.5	1945	0.59	1.05				
115.5	1944	0.54	0.96				
116.5	1943	0.52	0.92				
117.5	1943	0.55	0.98				
118.5	1942	0.54	0.96				
119.5	1942	0.6	1.07				
120.5	1941	0.71	1.26				
121.5	1941	0.68	1.21				
122.5	1940	0.56	0.99				
123.5	1939	0.62	1.10				
124.5	1939	0.5	0.89				
125.5	1938	0.5	0.89				
126.5	1938	0.61	1.08				
127.5	1937	0.62	1.10				
128.5	1937	0.66	1.17				
129.5	1936	0.6	1.07				

139.5	1930	0.63	1.12

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