Seasonal variation of shelf macrobenthos and sediment ecological function adjacent to a small mountainous river

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Highlight

Abstract

Keywords

1. Introduction
   1. Macrofauna in the river-influenced ocean margins

River-influenced ocean margins (RiOMar) are continental margins receiving considerable amounts of freshwater, nutrients, organic matter, and sediments from nearby lands and are hence biogeochemical hotspots for primary production, carbon sequestration, carbon remineralization, nutrient recycling, and carbon export (Geyer et al., 2004; McKee et al., 2004). (Add some data, this is already written in your thesis). Macrobenthos, sediment fauna larger than 300 µm, plays a big role in mediating biogeochemical processes at the sediment-water interface (SWI) in RiOMars. Through physical activities such as biodeposition (Kautsky and Evans, 1987), bioresuspension (Graf and Rosenberg, 1997), and bioturbation (Meysman et al., 2006), macrobenthos redistribute sediment particles, facilitate material flux, and stimulate microbial processes (Bertics and Ziebis, 2009), enhancing biogeochemical processes in the SWI. Furthermore, macrobenthos are food sources for higher trophic groups, channeling the energy from detritus into higher trophic levels (cit.). (Add a closing.)

## Early conceptual models of macrofauna distribution in the river-dominated ocean margins

Early studies of riverine influence on shelf macrobenthos have found their diversity, functional traits, and standing stock varying with the distance along the land-sea gradient (Aller and Stupakoff, 1996; Alongi et al., 1992; Rhoads et al., 1985). Rhoads et al. (1985) proposed a conceptual model describing that the varying sedimentation stress and food supply along the land-sea gradient shape the benthic community patterns. In brief, episodic flood events of the river would discharge mass sediments and effluents into the coastal waters, causing intense sedimentation near the river mouth. Sediment deposition would then cause local extinctions of the sediment fauna near the river mouth, suppressing the benthic standing stock and the material exchange at the SWI. As further away from the river mouth, improved water clarity and still abundant nutrients from the river would stimulate primary production in the water column, increasing the phytodetritus flux to the seafloor. The benthic communities could then thrive on the increased food supply and reduced sedimentation stress, resulting in higher benthic standing stocks and hence greater material fluxes. Such increase of benthic standing stock and biological activity would reduce further offshore due to declining nutrients and food supply in the open waters.

## Current evidence and knowledge gaps in the river-dominated ocean margins

Later studies generally echoed Rhoads et al. (1985) conceptual model, finding that macrofauna were subject to riverine sedimentations and their abundance would drastically decrease during high river discharge (Akoumianaki et al., 2006; Aller and Stupakoff, 1996; Alongi et al., 1992; Bonifácio et al., 2014).

Despite past efforts in investigating macrobenthic assemblages in RiOMars, most of the studies focused on continental shelves adjacent to large rivers (e.g. Aller and Aller, 1986; Hermand et al., 2008). Small mountainous rivers, by comparison, received less attention (but see Akoumianaki et al., 2013). Changes in the seabed environment fundamentally shape the macrobenthic assemblage and alter their patterns of abundance and diversity. Nevertheless, its consequence in sediment ecological functioning (i.e., material exchange), to our knowledge, has not been discussed in literature.

Furthermore, many of these studies were conducted in either tropical or temperate climates, while the monsoon influenced subtropical setting.

## Study objective

The objective of this study is to investigate the spatiotemporal changes of the residing macrobenthos, and sediment ecological functioning adjacent to a small mountainous river at a subtropical climate.

Specifically, we are interested in the following questions: (1) How does macrofauna abundance, biomass, and

1. Material and Methods
   1. Study area

Located on the east side of the northern South China Sea (nSCS), the Gaoping river-shelf (GRS) comprises the Gaoping River and Gaoping shelf. The Gaoping River is a small mountainous river (SMR) and the second-longest river in Taiwan. The drainage area of the Gaoping River is 3,250 km2 with annual sediment discharged ~36-49 Mt, equivalent to a sediment yield of 11,000 t km2 yr-1 (Liu et al., 2009; Milliman and Syvitski, 1992). The Gaoping shelf is a narrow shelf with a length of 100 km and a width of 20 km (Yu and Chiang, 1997). The Gaoping Shelf can be further separated into northern and southern lobes by the incision of the Gaoping Submarine canyon at the vicinity of the Gaoping River mouth (Yu and Chiang, 1997).

Located at the Tropic of cancer, the rainfall patterns of the Taiwan orogen receive strong influences from seasonal monsoons and typhoons, demonstrating distinct dry and wet seasonal precipitation patterns (Chen et al., 2010; Liu et al., 2016; Water Resource Agency, 2020). On average, 89% of southern Taiwan’s annual precipitation occurs during the wet season (May-October, Water Resource Agency 2020). As the largest river in south Taiwan, the Gaoping River, on average, exports 78% of its annual water discharge from June to September (Liu et al., 2002). The sediment discharge of the Gaoping River during the wet season is also two to three orders of magnitude larger than those during the dry season (Hung et al. 2004; cited in Liu et al. 2016). Typhoons frequently visit Taiwan during the wet season (~4 per year; Liu et al. 2013) and bring significant precipitation, accounting for 47.5% of the total annual rainfall (Chen et al., 2010). The typhoon-driven floods in the Gaoping River export large quantities of sediment comparable to the annual sediment load in a matter of days, hence playing a significant role in sediment transport (Liu et al., 2013). For instance, the Gaoping River exported 48 Mt of sediments within three days during the passing of typhoon Herb in 1996 (Milliman and Kao, 2005). Such a high sediment load within a short period is comparable to its annual sediment flux (49 Mt; Liu et al. 2009), highlighting the event-driven sediment discharge pattern of SMRs. The typhoon-driven floods also bear high concentrations of suspended sediments (> 40 g L-1; Milliman & Kao 2005), initiating hyperpycnal flows that plunge the sediments into the Gaoping Submarine Canyon (Liu et al., 2012). In addition, suspended sediments carried by the typhoon-driven floods would gradually settle on the shelf and slope seafloor, forming flood sediment layers with thicknesses ranging 2-12 cm weeks after the typhoons (Huh et al., 2009).

Regarding the particulate organic carbon (POC) flux, the Gaoping river transports 5.98 X 106 g C d-1 in the dry seasons and 1.25 to 276 X 107 g C d-1 in the wet seasons (Hung et al., 2012). Modern terrestrial carbon composes around 30% of the riverine POC, while fossil carbon contributes the remaining 70% (Kao et al., 2014). Furthermore, the amount of modern carbon export correlates well with the magnitude of water discharge, indicating a hydrological control on the terrestrial POC export (Kao et al., 2014). Under normal water discharge conditions, dispersive hypopycnal plumes (i.e., lighter than seawater) carry and spread the terrestrial organic matter all over the shelf seafloor. The seafloor sediments contain a mixture of riverine and marine carbon signals (Kao et al., 2014, 2006). By contrast, flood events mobilize massive terrestrial deposits, triggering hyperpycnal plumes (i.e., heavier than seawater) that transport the sediments and the riverine POCs directly into the Gaoping submarine canyon, eventually delivered to the deep sea (Kao et al., 2014; Liu et al., 2016; Sparkes et al., 2015). Significant accumulation of modern carbon was also found in the shallow inner shelf after typhoons, suggesting that extreme river discharge is the prime mechanism for terrestrial biomass export into the deep sea and the shelf sediments (Sparkes et al. 2015). Despite the massive sediment influx from the Gaoping river, the modern carbon seemed restricted to the inner shelf and the canyon (Sparkes et al., 2015). The sediment flux further into the open margins was mainly contributed by hemipelagic sedimentation (Huh et al., 2009; Zheng et al., 2017). Moreover, only ~24% of the river POC was sequestrated into the shelf and slope sediments (Hsu et al., 2014). The remaining 76% of missing river POC were either degraded or exported further to the open waters (Hsu et al., 2014). Within the deposited fraction, less than 30% of the total terrestrial organic matter was lost (i.e., through remineralization) during transportation (Kao et al., 2014).

* 1. Onboard sampling

Two cruises were conducted to collect biological and geochemical data of the Gaoping Shelf (GS). The Cruises OR1-1219 and OR1-1242 sampled the shelf in March and October 2019, respectively. Four of the stations, S3, S5, S6, and S7, were revisited in the southern lobe of the Gaoping Shelf. Several typhoons were generated between Cruises OR1-1219 and OR1-1242 near Taiwan, and the Central Weather Bureau issued four sea warnings (Central Weather Bureau, 2019). Among these typhoons with the sea warning, the typhoon Bailu, made landfall in the southwest region of Taiwan on August 24th and caused extreme precipitation in southeast and southwest Taiwan (Figure). Within its three-hour stay, Typhoon Bailu caused several floods and landslides in southern and eastern Taiwan; the disaster also damaged harbors and caused around 170 million NTD in agricultural losses (Lin et al., 2020). Despite the immense economic loss, the typhoon Bailu provided a rare opportunity to examine the benthic community’s response to extreme weather events.

In each station, Conductivity-Temperature-Depth (CTD) sensors were deployed to collect the profiles of salinity, temperature, water transmission, fluorescence, and dissolved oxygen from the surface water to 5 m above the seafloor. The rosette bottles on the CTD also collected bottom water for sediment incubation. For sediment sampling, multi-corers with diameter of 10 cm were deployed in the GS to preserve the integrity of the SWI. For each station, two core tubes were sectioned into 1-cm slices from top to bottom. Each sediment slice was then portioned to analyze geochemical markers such as grain size composition, sediment porosity, and other bulk sediment compounds, while only the top 1 cm fraction were included in data analysis. Another three core tubes with longer sediment length and better integrity were chosen to extract the benthic communities after shipboard incubation (Glud, 2008).

Three sediment cores for each station were incubated in a temperature-controlled water bath under dark conditions to measure the total oxygen utilization (TOU) of the sediment communities. The water bath temperature was set to be within the range of the bottom water temperatures measured with CTD. Each sediment core was sealed by a plastic lid with a magnetic stir bar attached inside. After removing the air bubbles in the overlying water by carefully adding bottom water collected with CTD Rosettes, another magnetic stir bar attached to a motor was placed above the plastic lid, coupling to the stir bar underneath. Both motor and magnet bars rotated and stirred the overlying water at 60 rpm to prevent water stratification. For every four to six hours, we used a miniature oxygen optode (PreSens PSt7) to measure oxygen concentration through a small resealable sampling port and a temperature sensor (PreSens Pt100) for the water bath temperature. The oxygen optode was calibrated for each cruise by scanning the product-specific barcode. We used PreSens Microx 4 data logger to record the dissolved oxygen and temperature until the oxygen levels dropped below 85% of the initial concentration, signaling the end of the incubation experiment (Glud, 2008).

After incubation, Unisense oxygen microelectrodes and temperature sensors were lowered into the sediment by a step motor to measure oxygen concentration profiles. Both the oxygen electrodes and the temperature sensors were calibrated using endpoint methods (Unisense A/S, 2020). The oxygen saturation endpoint was made by air-pumping the seawater with known salinity and temperature for at least 10 minutes. The oxygen depletion endpoint was made by adding sodium dithionite (Na­2S2O4), a strong reducing agent, into the seawater with known volume, salinity, and temperature. The calibration was done every 24 hours. Sediment oxygen concentration profiling started from roughly 1 cm above the sediment surface, with the step motor moving downward for 100 µm per step until the oxygen readings of both the microelectrodes reached zero. At each step, the microelectrodes stopped for 3 seconds to stabilize themselves before taking measurements. According to Fick’s law of diffusion, we used the oxygen concentration profiles compensated by temperature, salinity, and sediment porosity to estimate dissolved oxygen utilization (DOU).

Once sediment profiling was completed, the upper 10 cm of the sediment were retained on a 300-µm mesh sieve and washed with filtered seawater to obtain macrofauna. The retained sediment residuals were then fixed with a 1:1 ratio of filtered seawater and a 10% formaldehyde solution (pre-stained by Rose Bengal). The fixed samples were allowed to sit at least a week before sorting and body size measurements.

* 1. Macrofauna analysis

Back in the lab, the liquid of the fixed fauna samples was replaced with 70% ethanol for long-term storage. Macrofauna samples were sorted into major taxa and measured using a stereo microscope (Olympus SZ61). The relevant body dimensions of each specimen were measured with an ocular micrometer for biomass estimation. Only intact specimens with at least one of its main body parts (i.e., head, thorax, abdomen, pygidium) were measured. The condition of each specimen was then classified into four types: complete specimens with all their main body segments in place (denoted C); fragmented specimens with only their cephalic or caudal part intact (denoted FH and FT, respectively); and fragmented body parts without neither their cephalic nor their caudal parts (denoted F). Only specimen with their head intact (i.e., C and FH) were included in data analysis. As an exception, colonial specimens such as hydroids, bryozoans, and entoprocts were treated as solitary individuals to simplify the enumeration process.

Various methods were used to estimate taxon-specific biovolume. The biovolumes of polychaetes were estimated with each individual’s body shape. The body shapes of vermiform polychaetes were assumed to be cylinder, while sternaspid polychaetes were assumed to be ellipsoids. The biovolumes for some common benthic taxa such as Tanaidacea and Isopoda were calculated with the Length-Width Relationship (LWR) using published conversion factors: V =cLW2, where V is the individual volume; c is the taxon-specific conversion factor; L and W are the maximum length and width of the individual (Feller and Warwick, 1988). The biovolumes of some other taxa with relatively simple body shapes were approximated with geometric shapes (i.e., cylinder, cone, ellipsoid) (e.g., Hillebrand et al. 1999). For the rest of the odd-shaped taxa, the biovolumes were estimated using the LWR conversion factors from taxa with similar body shapes (e.g., bivalves using ostracods conversion factors). The rest of the taxa were assumed to be cylindrical during measurement following the general volumetric method (Benoist et al., 2019). The derived biovolumes were then converted to wet weight by assuming a specific density of 1.13 (Gerlach et al., 1985).

* 1. Oxygen utilization measurements

The total oxygen utilization (TOU) was estimated as the decrease of oxygen concentration as a function of time using simple linear regression. The calculation followed the equation (Song et al., 2016), , where m is the regression slope, V is the water column volume, and A is the sediment-water interface area. The constant 24/1000 adjusts the units of TOU from O2 mmol L-1 m-2 hr-1 to O2 mmol m-2 d-1. The sediment oxygen concentration profiles were converted to the diffusive oxygen utilization (DOU) using the software Unisense SensorTrace Suite (Berg et al., 1998). In brief, the software calculates the oxygen consumption of the depth profile by intervals and then integrates these rates to yield the DOU. The average DOU by microelectrode was then taken as the best estimator for each core. Another indicator for fauna activities, the oxygen penetration depth (OPD), was defined as the distance from the sediment-water interface (the depth where the oxygen concentration is identical to the water column) to where the oxygen is depleted. Since the TOU and DOU were measured ex-situ, they were adjusted by temperature coefficient (Q10) (Valiela 2015). The adjusted TOU or DOU (Rin situ) was computed followed the equation, , where Q10 was assumed to be 2 for most ectotherms, Rincub. is the measured oxygen utilization rate at the water bath temperature Tincub., and Tin situ is the bottom water temperature from CTD measurements. Assuming TOU is the overall oxygen consumption of the sediment community and DOU is the diffusive oxygen consumption by microorganisms and chemical reactions, we can derive the benthos-mediated oxygen utiliztion (BOU) by subtracting the DOU from TOU (Glud, 2008). In other words, BOU represents the summation of the direct and indirect metazoan contributions to the sediment oxygen consumption, including the metazoan respiration and bioturbation-enhanced microbial respiration (Glud, 2008). After retrieving TOU, DOU, BOU, and OPD, these factors were averaged by station and treated as environmental variables for later analysis.

* 1. Geochemical data measurements

Physical sediment properties such as grain size and porosity are known to be correlated with the macrofauna distribution and sediment ecological functioning (Gray, 1974; Snelgrove and Butman, 1995). Median grain size (D50), sand fraction, silt fraction, and clay fraction were measured with a laser diffraction size analyzer (Model LS-13320; Beckman Coulter Inc.). Sediment porosity (Por) and water content were measured following the drying method described in Blum (1997){Citation}. In brief, the pre-weighted sediments were sent to a 100oC convection oven for 24 hours; the weight difference was then used to estimate water content and porosity by assuming the pore waters with a specific density of 1.024 g cm-3.

Other than the physical aspects of the benthic habitat, the quantity, quality, and source of the organic carbon are also known to affect the standing stock, species, and functional composition (Campanyà-Llovet et al., 2017; Dauwe et al., 1998). In this study, total organic carbon (TOC) and total nitrogen (TN) were used as a proxy for food quantity, while the carbon-to-nitrogen ratio (CN) was used as an indicator of food quality. As terrestrial plants typically have higher CN ratios (CN > 20) than marine algae (CN between 4 and 10), the C/N ratio of the sediments can also be used as a tracer of carbon source from the land and sea (Meyers, 1994). Since terrestrial C3 plants typically have carbon stable isotope values (δ13C) around -27 ‰ and the marine algae typically have δ13C ranging from -22 to -20‰ (Meyers, 1994), δ13C was also used as a carbon source tracer in tandem with the CN ratio (Hu et al. 2006, Hsu et al. 2014). Despite the, do note that fossil carbon can have a wide range of C/N and δ13C. For example, the two organic carbon indicators in the Taiwan orogen can have C/N and δ13C ranging from 2.6 to 17.1 and -25.4 to -19.7‰, respectively (Hilton et al., 2010). Sediment chlorophyll-a concentration (Chla) is another indicator of fresh marine algae availability at the sediment surface. In brief, the sediment subsamples were first acidified with 6 N HCl and then sent to the Flash 2000 elemental analyzer in tandem with a GC-Isolink interface to a Delta V Plus isotope ratio mass spectrometer (both from Thermo Fisher Scientific) to measure TOC and δ13C. The TOC was reported in percent weight contribution. δC13 values were calculated using Vienna-PeeDee Belemnite as the reference point and reported in ‰ differences. The total nitrogen (TN) measurements were similar to TOC and δ13C, except that no acid pretreatments were applied before sending the sediment samples into the same instruments. The TOC was then divided by TN to derive the CN ratio. For the sediment Chla, the sediment samples were first sitting in 10-ml acetone- water solution with a volumetric ratio of 9:1 in the dark at 4°C for 24 hours. The chlorophyll extracts were then measured with a fluorometer (Model 10-AU; Turner Designs, Inc.) and reported in nanogram per gram dry weight.

* 1. Data analysis

The Wilcoxon test was performed on all the environmental variables to test significant differences between the two cruises. The environmental variables were then screened with prior knowledge and pairwise correlation prior further analyses. Salinity was removed since snapshots of salinity records could not describe its influence to benthic communities. Dissolved oxygen was removed as the bottom water of all stations were oxic (> 2 mg L-1). Water density and σθ were removed since density-related features were not known to affect macrobenthos. Bottom water transmission were removed due to its strong negative correlation with temperature (Temp) (r = -0.87). Median grain size (D50) was selected as the sole variable to represent sediment granulometry; sand, silt, and clay fractions were hence omitted. As water content and porosity (Por) were both derived from evaporation techniques with unit differences, only porosity was kept in later analyses. Total nitrogen (TN) were removed due its correlation with porosity (r = 0.73). Sediment chlorophyll a concentration (Chla) and stable isotopic carbon (δ13C) were inversely correlated (r = -0.76). Chla was included in later analyses since it indicates fresh portion in the sedimentary organic matter pool. δ13C, on the other hand, were omitted due to its anomalous signals in the Gaoping River-Shelf region due to uncertain portions of marine, terrestrial, and fossilized organic matter (ref.). The remaining variables were water depth (*Depth*), the distance to river mouth (*DRM*), temperature (*Temp*), fluorescence (*Fluo*), median grain size (*D50*), total organic carbon (*TOC*), carbon-to-nitrogen ratio (*C/N*), sediment chlorophyll a (*Chla*), and porosity (*Por*). Quantile-quantile plots were used to examine the normality of each variable. The environmental variables were centered and scaled to unit variance. To achieve multivariate normality across taxa, Box-Cox-chord transformation with the exponent of 0.3 and 0.1 were applied on macrofauna abundance and biomass assemblage data, respectively (Legendre and Borcard, 2018). Euclidean distance was used to calculate the environmental and macrofaunal dissimilarity between samples.

PERMANOVA with a Station-Cruise nested design was used to test the spatiotemporal difference of the seabed environment and the macrofauna assemblages. PERMDISP were used to test whether the variance of the environment and macrofauna assemblage were significantly different between cruises. The first two axes of the principal component analysis (PCA) were used to visualize the multivariate dispersions of the seabed environment and the macrofauna assemblage. Redundancy analysis (RDA) with backward stepwise selection were used to sought a best subset of environmental variables to describe the assemblage matrices. For the macrofauna assemblage PCA figures and RDA figures, only taxa with over 40% of the variance explained by the first two axes were shown to highlight those taxa droves between-sample variations.

Depth and DRM were fitted on macrofauna abundance, biomass, TOU, DOU, and BOU to test their spatial variations. Environmental variables were fitted on the same set of dependent variables with ordinary linear regression to find factors that best describe the patterns.

1. Results

CTD profile

* The CTD profiles showed notable hydrographic differences between the two cruises.
* By comparison, profiles of temperature, salinity, density, oxygen, and fluorescence showed larger variations along water depth in OR1-1242.
* Bottom water light transmission were notably lower in the shallower stations of OR1-1242.
* The hydrography across stations were consistent within cruises.

Env PCA and PERMANOVA-PERMDISP

* PC1 and PC2 explained 36.63% and 25.62% of the total variance, respectively.
* PC1 had higher loadings of bottom water characteristics (*Temp*, *Fluo*) and organic carbon quality (*Chla*, *CN*), while PC2 had higher loadings of organic matter quantity (*TOC*) and sediment characteristics (*Por*, *D50*).
* PERMANOVA showed moderate evidence that the environmental condition of the two cruises were different (p = 0.03). Only 21% of the variance can be explained by the cruise factor.
* PERMDISP showed no evidence in the multivariate dispersion of the environmental difference of the two (= = 0.4).

Count PCA

* PC1 and PC2 explained 18.14% and 15.94% of the total variance, respectively.
* The two PCs explained more than 40% of the abundance variance of aplacophorans, tanaids, isopods, amphipods, and hydrozoans.

Biomass PCA

* PC1 and PC2 explained 20.57% and 13.69% of the variance, respectively.
* The two PCs explained more than 40% of the biomass variance of decapods, mysids, aplacophorans, and ophiuriods.

1. Discussion

In an experimental setting, Mestdagh et al. (2018) tested how various degrees of sediment deposition affect the contribution of macrofauna to sediment community oxygen consumption. They found that . In contrary to the results of Mestdagh et al. (2018), we found that sediment oxygen consumption drastically increased in the station experiencing intense sedimentation. However, as Mestdagh et al. (2018) used sediments free of organic matter to simulate sediment deposition, . terrigenous sediments discharged from the Gaoping River might carry allochthonous organic matter to the Gaoping Shelf.

The low DOU and high BOU in S3 suggested that sediment infauna strongly influenced sediment oxygen flux despite low macrofauna abundance. A possible explanation is the meiofauna stimulates.

Furthermore, meiofauna might be transported via currents and tides, replenishing the .

* 1. Sedimentary environment
  2. Macrofauna assemblage

Macrofauna biomass did not correlate well with any of the environmental variables, suggesting that macrofauna biomass is less sensitive to environmental disturbances in the GRS.

* 1. Sediment oxygen utilization paradox near the river mouth

Despite the lowest abundance, we found the highest BOU near the river mouth. This contradicts the prediction in Rhoads et al. (1985), stating that the loss of sediment macrofauna under strong physical disturbance would result in low material flux at the SWI.

1. Conclusions
2. References