Secondary Production of Macrobenthos in Typical Coastal Ecosystems: A Case Study of the Oujiang River Estuary and Dongtou Islands (Postprint)

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Abstract

To better understand and estimate the secondary productivity of macrobenthos in estuarine and island ecosystems, this study investigated macrobenthic communities in two typical nearshore ecosystems—the Oujiang Estuary and the Dongtou Islands—during April and October 2015. Three Brey empirical models were employed to estimate macrobenthic secondary productivity, and the relationship between secondary productivity and environmental factors was analyzed. The results showed: (1) Expressed as ash-free dry weight (AFDW), the Brey empirical formula estimated annual average secondary productivity of 0.48 g(AFDW) m^{-2} a^{-1} and 0.70 g(AFDW) m^{-2} a^{-1} for the Oujiang Estuary and Dongtou Islands waters, respectively; the Brey model estimated 0.51 g(AFDW) m^{-2} a^{-1} and 1.55 g(AFDW) m^{-2} a^{-1}, respectively; and the Brey model estimated 0.25 g(AFDW) m^{-2} a^{-1} and 0.99 g(AFDW) m^{-2} a^{-1}, respectively. (2) The three empirical models revealed consistent spatial distribution trends in annual average macrobenthic secondary productivity: the Oujiang Estuary had one high-value zone located in the southern part of the estuary; the Dongtou Islands area had two high-value zones, one located between Sanpan Island and Huagang Island to the northeast of Dongtou Main Island, and the other among the islands to the southeast of Donghuang Island. (3) The main contributing species to annual average macrobenthic secondary productivity in the Oujiang Estuary were Aglaophamus dibranchis, Glycera chirori, Heteromastus filiforms, Potamocorbula ustulata, Yoldia similis, and Eocylichna braunsi, which together contributed over 54.2% of the secondary productivity. In the Dongtou Islands waters, the main contributing species were Aglaophamus dibranchis, Heteromastus filiforms, Yoldia similis, Raphidopus ciliatus, Eucrate crenata, Cerebratulina sp., and Odontamblyopus rubicundus, which together contributed over 57.1%

of the secondary productivity. (4) Correlation analysis between secondary productivity and environmental factors revealed that chemical oxygen demand, suspended matter, and median grain size of surface sediments were important environmental factors influencing annual average macrobenthic secondary productivity in the Oujiang Estuary, whereas the relationships between environmental factors and macrobenthic secondary productivity in the Dongtou Islands waters were not significant. (5) In the Oujiang Estuary, the estimation results from the Brey empirical formula and the Brey model were basically consistent, and in the Dongtou Islands waters, the estimation results from the Brey empirical formula and the Brey model were also basically consistent.

Full Text

Preamble

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Secondary Productivity of Macrobenthos in Typical Coastal Ecosystems: Examples from the Oujiang River Estuary and Dongtou Islands

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Abstract

To better understand and estimate the secondary productivity of macrobenthos in estuarine and island ecosystems, we conducted investigations on macrobenthos in two typical coastal ecosystems—the Oujiang River estuary and the

Dongtou Islands—in the East China Sea during April and October 2015. In the Oujiang River estuary, 81 species were identified, including 39 polychaete species, 23 crustacean species, 9 mollusk species, 4 echinoderm species, and 6 other species. In the Dongtou Islands, 111 species were found, comprising 50 polychaete species, 30 crustacean species, 18 mollusk species, 5 echinoderm species, and 8 other species. Three different empirical formulas were applied to calculate the secondary productivity of these macrobenthos, and the relationships between secondary productivity and environmental factors were analyzed.

The results showed that: (1) The average annual secondary productivity of macrobenthos, expressed as ash-free dry weight (AFDW) and calculated using three empirical formulas—Brey' s empirical formula (1990) and Brey' s empirical models (2001 and 2012)—was 0.48, 0.51, and 0.25 g(AFDW) m^{-2} yr^{-1}, respectively, in the Oujiang River estuary, and 0.70, 1.55, and 0.99 g(AFDW) m^{-2} yr^{-1}, respectively, in the Dongtou Islands. (2) The spatial distribution of average annual secondary productivity estimated by the three empirical formulas was consistent. A zone with high average annual secondary productivity was found in the southern waters of the Oujiang River estuary. Two such zones were identified in the Dongtou Islands, one located in the sea area between Sanpan Island and Huagang Island northeast of the main Dongtou Island, and the other in the sea area between islands southeast of Donghuang Island. (3) Six species—*Aglaoophamus dibranchis*, *Glycera chiroi*, *Eocylichna braunsi*, *Heteromastus filiformis*, *Raphidopus ciliatus*, and *Eucrate crenata*—contributed more than 54.2% of the total average annual secondary productivity in the Oujiang River estuary. In the Dongtou Islands, *A. dibranchis*, *H. filiformis*, *Potamocorbula ustulata*, *Odontamblyopus rubicundus*, *R. ciliatus*, and *Cerebratulina* contributed more than 57.1% of the total. (4) Correlation analysis indicated that chemical oxygen demand (COD), suspended solids, and median sediment grain size were important environmental factors affecting the average annual secondary productivity of macrobenthos in the Oujiang River estuary, while environmental factors showed no significant relationship with secondary productivity in the Dongtou Islands. (5) The average annual secondary productivity estimated by Brey' s empirical formula (1990) was consistent with that estimated by Brey' s empirical model (2001) for the Oujiang River estuary, and with that estimated by Brey' s empirical model (2012) for the Dongtou Islands.

Keywords: secondary productivity; macrobenthos; Dongtou Islands; Oujiang River estuary; Brey' s empirical model

Introduction

Secondary productivity of macrobenthos is a fundamental parameter for quantifying material cycling and energy flow in ecosystems and serves as an important indicator of ecosystem function [1-2]. Estimating secondary productivity not only helps understand functional changes in macrobenthos communities but also holds significant importance for studying ecosystem material flow, sustainable utilization of marine biological resources, and evaluating marine environmental stress [3-5].

Estuaries and islands represent two typical nearshore ecosystems characterized by high nutrient levels and unique circulation patterns. Located at the interface between land and sea, estuaries are influenced by terrestrial sediments, organic matter, and inorganic nutrients carried by rivers, making them hotspots for research [6]. Islands, situated at the forefront of coastal zones, play important roles in national defense, coastal economic development, and marine environmental protection. However, studies on macrobenthos secondary productivity in island and estuarine ecosystems remain limited in China [7], with few comparative reports on these two typical ecosystems.

Most domestic estimates of macrobenthos secondary productivity have employed Brey' s empirical formula [7-12], with only two reports using Brey' s estimation model—for Jiaozhou Bay intertidal zones [13] and the western Liaodong Bay [14]. These estimation models yield relatively rough results. While foreign scholars have proposed numerous macrobenthos secondary productivity estimation models [3-4, 15-18] and compared different models [4, 19], some have limited applicability due to small modeling data ranges unsuitable for low-latitude waters [18], while others employ parameters like lifespan that are difficult to determine, hindering practical application [4, 16].

Brey' s empirical model has been widely applied in macrobenthos community secondary productivity estimation both domestically and internationally [5, 8, 10, 12-14]. Foreign secondary productivity estimation models have evolved from Brey' s empirical formula [3] to Brey' s estimation model [1] and more recently to Brey' s estimation model [15]. The latter considers up to 20 parameters, making the model more sophisticated. Although its calculation spreadsheet features input, hidden, and output layers, operation is convenient as results are automatically displayed after data entry.

The study area is located at 27°41 -28°13 N, 120°52 -121°16 E in southern Zhejiang, including the Oujiang River estuary and Dongtou Islands waters. Currently, no reports exist on macrobenthos secondary productivity in this region, nor comparative studies between these two typical ecosystems. This study employs Brey' s empirical formula [3], Brey' s estimation model [1], and Brey' s estimation model [15] to calculate macrobenthos secondary productivity in the Oujiang River estuary and Dongtou Islands waters. We compare the magnitude of secondary productivity between the two regions, examine discrepancies among the three estimation methods, and analyze relationships with environmental factors to provide a theoretical foundation for functional studies and environmental protection of macrobenthos in these two typical ecosystems.

1. Station Distribution and Sample Collection

Macrobenthos sampling was conducted in April and October 2015. Survey stations were located in the Oujiang River estuary (S1-S7, S9-S13, S18-S24, S31, S35) and Dongtou Islands waters (S14-S17, S25-S30, S32-S34) [Figure 1: see original paper]. A 0.1 m^2 Van Veen grab sampler was used, with duplicate samples collected at each station and combined into one sample. Samples were sieved through a 0.5 mm mesh screen, and the retained organisms were fixed in 5% formalin solution and brought back to the laboratory for species identification, weighing, and data compilation according to the "Specifications for Oceanographic Survey" (GB/T 12763.6—2007) [20].

Environmental factors were measured synchronously at each station, including salinity, dissolved oxygen (DO), chemical oxygen demand (COD), dissolved inorganic nitrogen (DIN), active phosphates (PO_4-P), active silicates (SiO_3-Si), and median grain size (MdΦ) and organic carbon content (OC) of surface sediments. Measurements followed the "Specifications for Marine Monitoring" (GB 17378.4—2007) [21].

According to empirical model requirements, wet weight biomass data must be converted to ash-free dry weight (AFDW) or energy equivalents. Brey' s empirical formula [3] uses AFDW, while Brey' s estimation model [1] and Brey' s estimation model [15] use energy equivalents. Conversion relationships between wet weight, AFDW, and energy are shown in Table 1 .

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2. Data Processing

Species identification, counting, and wet weight (WW) measurement were conducted. Conversion factors between wet weight, ash-free dry weight, and energy for different macrobenthos groups are presented in Table 1 [13-15].

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3. Empirical Models for Secondary Productivity Estimation

3.1 Brey' s Empirical Formula

Brey' s empirical formula [3] calculates the average annual AFDW biomass and average individual AFDW for all species, then computes secondary productivity species by species:

$$P = a + b_{1B} + b_{2W}$$

where P is the average annual secondary productivity of macrobenthos (g(AFDW) m^{-2} yr^{-1}), B is the average annual AFDW biomass (g(AFDW)

m^{-2}), W is the average individual AFDW (g(AFDW) per individual), and a, b_1, and b_2 are coefficients for different macrobenthos groups (Table 2).

3.2 Brey' s Empirical Model

Compared with Brey' s empirical formula [3], Brey' s empirical model [15] considers not only biological factors such as macrobenthos density and biomass but also environmental factors including habitat conditions:

$$\begin{aligned}\log(P) = 7.947 + \log(B) - 2.294\log(M) - 2409.856/(T + 273) \\ + 0.168D^{-1} + 0.194\text{SubT} + 0.180\text{InEpi} + 0.277\text{MoEpi} \\ + 0.174\text{Taxon1} - 0.188\text{Taxon2} + 0.33\text{Taxon3} \\ - 0.062\text{Habitat1} + 582.851\log(T + 273)\end{aligned}$$

where P is the average annual secondary productivity (kJ m^{-2} yr^{-1}), B is the annual average biomass energy equivalent (kJ m^{-2}), M is the annual average individual body weight energy equivalent (kJ per individual), T is the average bottom water temperature (°C), D is the average water depth (m), SubT: subtidal habitat value is 1, other habitats are 0; InEpi: infauna value is 1, other groups are 0; MoEpi: mobile epifauna value is 1, other groups are 0; Taxon1: echinoderm value is 1, other groups are 0; Taxon2: mollusk value is 1, other groups are 0; Taxon3: annelid or crustacean value is 1, other groups are 0; Habitat1: lake habitat value is 1, other habitats are 0.

3.3 Brey' s ANN Model

Building upon Brey' s empirical model [15], Brey' s ANN model [1] incorporates macrobenthos feeding habits and other parameters, providing better predictions of macrobenthos secondary productivity [23]. Due to the numerous parameters, coefficient values can be referenced from the model calculation spreadsheet. The spreadsheet has input, hidden, and output layers, making operation convenient. During calculation, input data for each species is placed in a separate table and then copied to the calculation form, with results automatically displayed.

The model structure is:

$$\begin{aligned}&\text{Input layer} \rightarrow \text{Hidden layer} \rightarrow \text{Output layer} \\ P/B &= a_0 + a_1 \times \text{Tan}(b_0 + b_1\log(B) + b_2/T + b_3\log(M) + \cdots) \\ &+ a_2 \times \text{Tan}(c_0 + c_1\log(B) + c_2/T + c_3\log(M) + \cdots)\end{aligned}$$

The input layer includes parameters such as average individual body weight energy equivalent, average bottom water temperature, average water depth, annual average biomass energy equivalent, taxonomic groups (Mollusca, Annelida, Crustacea, Echinodermata, Insecta), lifestyle categories (infauna, sessile, crawler, facultative swimmer), feeding habits (herbivore, omnivore, carnivore), and habitats (lake, river, marine, subtidal, exploited). For this study, spring and autumn macrobenthos density and biomass data were averaged for input into Brey’ s empirical formula [3], Brey’ s model [15], and Brey’ s model [1] to calculate average annual secondary productivity. Model [15] and Model [1] results were converted to AFDW using conversion factors for comparison.

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2. Results

2.1 Species Composition

The two surveys in the Oujiang River estuary collected 81 macrobenthos species, including 39 polychaete species (48.1%), 23 crustacean species (28.4%), 9 mollusk species (11.1%), 4 echinoderm species (4.9%), and 6 other species (7.4%). In the Dongtou Islands waters, 111 species were collected, comprising 50 polychaete species (45.0%), 30 crustacean species (27.0%), 18 mollusk species (16.2%), 5 echinoderm species (4.5%), and 8 other species (7.2%). Polychaetes dominated the species composition in both areas.

2.2 Density, Biomass and Secondary Productivity

The average annual density of macrobenthos in the Oujiang River estuary was 150.18 individuals m^{-2}, with an average annual biomass of 2.06 g m^{-2} (AFDW). In the Dongtou Islands, the average annual density was 214.29 individuals m^{-2}, with an average annual biomass of 4.96 g m^{-2} (AFDW).

Using Brey’ s empirical formula [3], the average annual secondary productivity was estimated at 0.48 g(AFDW) m^{-2} yr^{-1} for the Oujiang River estuary and 0.70 g(AFDW) m^{-2} yr^{-1} for the Dongtou Islands. Brey’ s model [15] yielded 0.51 g(AFDW) m^{-2} yr^{-1} and 1.55 g(AFDW) m^{-2} yr^{-1}, respectively, while Brey’ s model [1] gave 0.25 g(AFDW) m^{-2} yr^{-1} and 0.99 g(AFDW) m^{-2} yr^{-1}, respectively (Table 3).

Brey’ s empirical formula [3] and Brey’ s model [1] produced similar estimates for the Oujiang River estuary, with Brey’ s model [15] results being 49.5% lower than the average of the first two. For the Dongtou Islands, Brey’ s empirical formula [3] and Brey’ s model [1] gave similar estimates, while Brey’ s model [15] results were 45.5% higher than their average. Overall, the Dongtou Islands showed higher macrobenthos secondary productivity than the Oujiang River estuary.

2.3 Spatial Distribution

All three empirical models showed consistent spatial distribution trends for average annual secondary productivity. The Oujiang River estuary had one high-productivity zone in its southern waters. The Dongtou Islands had two high-productivity zones: one in the sea area between Sanpan Island and Huagang Island northeast of the main Dongtou Island, and another in the sea area between islands southeast of Donghuang Island. This pattern mirrors macrobenthos biomass distribution.

The lowest secondary productivity values occurred at station S31 in the northern Oujiang River estuary, where Brey' s empirical formula [3] and Brey' s model [1] calculated values of 0.01 and 0.04 g(AFDW) m^{-2} yr^{-1}, respectively, due to low species richness and extremely low biomass. Brey' s model [15] calculated 0.01 g(AFDW) m^{-2} yr^{-1} at this station. The highest value in the Oujiang River estuary southern waters (station S25) reached 2.62 g(AFDW) m^{-2} yr^{-1} according to Brey' s empirical formula [3] and 6.25 g(AFDW) m^{-2} yr^{-1} according to Brey' s models [15] and [1], attributed to the high biomass and density of *Potamocorbula ustulata* at this station, which contributed over 90% of the secondary productivity.

2.4 Main Contributing Species

All three models identified similar top-ranking species for secondary productivity. In the Oujiang River estuary, the main contributors were *Aglaoophamus dibranchis*, *Glycera chiroi*, *Eocylichna braunsi*, *Heteromastus filiformis*, *Raphidopus ciliatus*, and *Eucrate crenata*, collectively contributing over 54.2% of total secondary productivity (Table 4).

In the Dongtou Islands, the primary contributors were *A. dibranchis*, *H. filiformis*, *P. ustulata*, *O. rubicundus*, *R. ciliatus*, and *Cerebratulina*, contributing over 57.1% of the total (Table 5). *A. dibranchis* and *G. chiroi* were widely distributed with high biomass, while *P. ustulata* showed extremely high density and biomass at individual stations but low occurrence elsewhere. *Cerebratulina* had low frequency and density, whereas *E. crenata* and *O. rubicundus* had relatively low frequency and density.

2.5 Relationship Between Secondary Productivity and Environmental Factors

Pearson correlation analysis between secondary productivity estimates and environmental factors revealed significant correlations among the three models' results ($P<0.01$). In the Oujiang River estuary, Brey' s model [15] estimates showed significant negative correlation with suspended solids ($P<0.05$), while Brey' s model [1] estimates showed significant negative correlation with suspended solids ($P<0.05$) and significant positive correlation with median sediment grain size ($P<0.05$). No significant correlations were found between environmental factors and secondary productivity in the Dongtou Islands.

3. Discussion

3.1 Spatial Distribution Patterns and Comparison with Other Regions

Secondary productivity spatial distribution is primarily influenced by macrobenthos community structure and habitat environmental conditions [23]. The Oujiang River estuary showed low secondary productivity except in the southern region. Due to riverine influence, estuarine areas typically have high sedimentation rates that strongly disturb the substrate, limiting survival of certain macrobenthos. Only species insensitive to substrate changes, such as some polychaetes and crustaceans, can survive, resulting in lower species richness and secondary productivity [7, 14].

High secondary productivity in the southern Oujiang River estuary resembles patterns near Xiamen's Gulangyu Island [25], where high secondary productivity resulted from abundant *Potamocorbula laevis*. The high productivity in the sea areas between islands northeast of Dongtou Island and southeast of Donghuang Island may be attributed to their distance from the estuary, providing stable habitats suitable for macrobenthos. Island ecosystems generally exhibit high productivity as currents flowing around islands create local upwelling that uniformly mixes organic matter, providing abundant food for benthos. These inter-island sea areas also offer diverse habitats through local upwelling or current branches [6].

Compared with other regions, secondary productivity in the Oujiang River estuary and Dongtou Islands is relatively low, falling below values reported for Xiangshan Harbor port area [27] (0.99 g(AFDW) m^{-2} yr^{-1}), Jiaozhou Bay [8] (3.82 g(AFDW) m^{-2} yr^{-1}), western Liaodong Bay [14] (3.41 g(AFDW) m^{-2} yr^{-1}), and the Yangtze River estuary and adjacent waters [7] (3.52 g(AFDW) m^{-2} yr^{-1}). Historical data [28] indicate that the Dongtou Islands waters have the lowest macrobenthos biomass in Zhejiang Province, with density only higher than Liuhang Island waters. The low secondary productivity may be related to recent reclamation and siltation projects, such as the Wenzhou shallow tidal flat reclamation project connecting Lingkun Island and Niyu Island, which created new sedimentary substrates with few macrobenthos species. Studies on reclamation impacts [24] show that such projects can reduce species richness and biomass, thereby decreasing secondary productivity.

3.2 Relationship Between Secondary Productivity and Environmental Factors

Environmental factors such as water depth and dissolved oxygen affect secondary productivity by influencing metabolic rates and species life histories [23]. Understanding these relationships is crucial for comprehensive marine ecosystem function assessment [18]. Besides density and biomass, secondary productivity is closely related to water depth and bottom temperature, which affect food quality and animal metabolic rates [18]. Many studies show that macrobenthos secondary productivity decreases with increasing depth [3-4, 8, 10-11].

Various environmental factors affect secondary productivity, including substrate type, organic matter content, and total phosphorus in sediments [10, 12, 18]. Yuan et al. [10] found that sediment organic matter content was an important factor affecting secondary productivity in the western Jiaozhou Bay. Yan et al. [12] used canonical correspondence analysis to examine relationships between macrobenthos secondary productivity and environmental variables in the Yangtze River estuary intertidal zone, finding that water total nitrogen and sediment organic matter affected productivity, though influencing factors varied among sections.

Our study identified COD and median sediment grain size as important factors affecting secondary productivity in the Oujiang River estuary. Estuarine ecosystems, located at land-sea interfaces, receive terrestrial pollutants that increase organic contamination. Microbial decomposition of organic pollutants consumes substantial dissolved oxygen, deteriorating water quality [29]. Suspended solids affect water transparency and euphotic zone thickness, influencing phytoplankton photosynthesis and primary productivity, thereby affecting secondary productivity [30]. Sediment grain size is recognized as an important factor influencing macrobenthos species distribution, density, and biomass [31], and our finding of significant positive correlation between secondary productivity and median grain size in the Oujiang River estuary supports this.

The lack of significant correlation between environmental factors and secondary productivity in the Dongtou Islands may be due to the complex geography and varying environmental influences among different sea areas. Different marine environments affect benthos groups differently, requiring long-term data accumulation and comparative analysis for specific regions.

3.3 Comparison of Secondary Productivity Estimation Models

Empirical models for secondary productivity estimation represent syntheses of individual population studies and have greatly advanced research in this field. The evolution from Brey' s empirical formula [3] to Brey' s model [15] and then to Brey' s ANN model [1] shows two trends: (1) increasing model complexity with more parameters considered, progressing from basic biological factors to environmental factors, and (2) refinement of wet weight-to-energy conversion from uniform ratios for all benthos to group-specific conversion factors.

Methodologically, Brey' s empirical formula [3] and Brey' s model [15] use multiple linear regression, whereas Brey' s ANN model [1] employs artificial neural networks. Multiple linear regression is sensitive to interactions among independent variables, while ANN can simulate complex, discontinuous relationships between independent and dependent variables [1], proving superior for predicting macrobenthos P/B ratios [32].

As empirical models provide estimates rather than true values, discrepancies exist among different models. However, they generally agree on spatial distribution trends and top-contributing species. When different models produce consistent results, these can be considered reliable estimates [13]. In this study, Brey's empirical formula [3] and Brey's model [1] produced consistent results for the Oujiang River estuary, while Brey' s empirical formula [3] and Brey' s model [1] agreed for the Dongtou Islands, suggesting these estimates are reliable.

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