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Modeling the temporal dynamics of intertidal benthic infauna biomass with environmental factors: Impact assessment of land reclamation

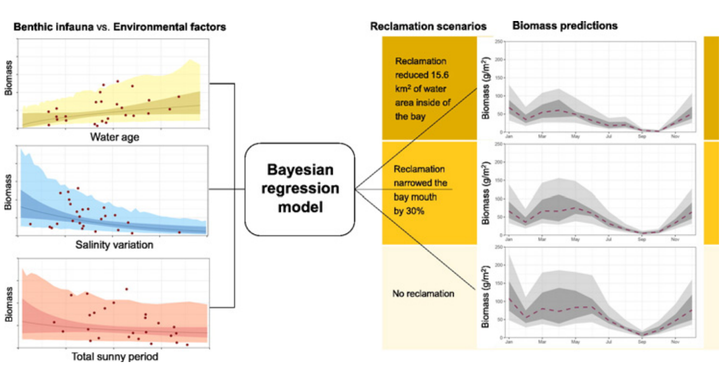
Ye Yang [a], Ting Fong May Chui [a,*], Ping Ping Shen [b], Yang Yang [a], Ji Dong Gu [c]

[a] Department of Civil Engineering, The University of Hong Kong, Room 6-18A, Haking Wong Building, Pokfulam, Hong Kong
[b] Key Laboratory of Marine Bio-resources and Ecology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, PR China
[c] Laboratory of Environmental Toxicology, School of Biological Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong

HIGHLIGHTS

- Models the temporal dynamics of benthic infauna biomass with environmental factors
- Uses coastal numerical models to produce hydrodynamic data for ecological model
- Shows that water age governs the dynamics of intertidal benthic infauna biomass
- Shows potential threat of hydrodynamic response to reclamation on benthic infauna
- Offers Bayesian regression model to evaluate anthropogenic impact on tidal marshes

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic activities such as land reclamation are threatening tidal marshes worldwide. This study's hypothesis is that land reclamation in a semi-enclosed bay alters the seasonal dynamics of intertidal benthic infauna, which is a key component in the tidal marsh ecosystem. Mai Po Tidal Marsh, Deep Bay, Pearl River Estuary, China was used as a case study to evaluate the hypothesis. Ecological models that simulate benthic biomass dynamics with governing environmental factors were developed, and various scenario experiments were conducted to evaluate the impact of reclamations. Environmental variables, selected from the areas of hydrodynamics, meteorology, and water quality based on correlation analysis, were used to generate Bayesian regression models for biomass prediction. The best-performing model, which considered average water age (i.e., a hydrodynamic indicator of estuarine circulation) in the previous month, salinity variation (i.e., standard deviation of salinity), and the total sunny period in the current month, captured well both seasonal and yearly trends in the benthic infauna observations from 2002 to 2008. This model was then used to simulate biomass dynamics with varying inputs of water age and salinity variation from coastal numerical models of different reclamation scenarios. The simulation results suggest that the reclamation in 2007 decreased the spatial and annual average benthic infauna biomass in the tidal marsh by 20%, which agreed with the 28% biomass decrease recorded by field survey. The range of biomass seasonal variation also decreased significantly from 2.1 to 230.5 g/m^2 (without any reclamation) to 1.2 to 131.1 g/m^2 (after the 2007 reclamation), which further demonstrates the substantial ecological impact of reclamation. The ecological model developed in this study could simulate seasonal biomass dynamics and evaluate the ecological impact of reclamation projects. It can therefore be applied to evaluate the ecological impact of coastal engineering projects for tidal marsh management, conservation, and restoration.

* Corresponding author.
E-mail address: maychui@hku.hk (T.F.M. Chui).

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1. Introduction

Tidal marshes provide essential ecosystem services for the global ecosystem and human society (Barbier et al., 2011). However, they are affected by anthropogenic activities (e.g. resource exploitation, land reclamation, coastal engineering, pollution, and climate change), and the ecosystem services of the remaining tidal marshes are insufficient for growing coastal populations (Bromberg Gedan et al., 2009). To meet the demand for land in fast-developing coastal regions, land reclamation has been carried out worldwide in recent decades to create land in sea areas. Reclamation has become one of the largest threats to the ecosystem of tidal marshes, particularly in Europe and Asia (Cui et al., 2016). In China, 5139 km^2 of land area was acquired by reclamation from 1990 to 2008, and the State Council of China has approved another 2500 km^2 of reclamation projects for 2010 to 2020 (Wang et al., 2014).

Various coastal studies have demonstrated that reclamation projects introduce substantial changes in hydrodynamics, estuarine circulation, and solute transport, which all imply considerable environmental effects on the estuarine ecosystem (Liang et al., 2015; Okada et al., 2011; Yang and Chui, 2017). Although our understanding of the mechanisms that underlie the environmental impact of reclamation on estuarine ecosystems is still limited (Cui et al., 2016), a comparison of field surveys in estuarine regions confirms the worldwide environmental stress of reclamation projects. In the Forth River Estuary, Scotland, land reclamation considerably decreased the productivity of the estuarine ecosystem (Elliott and Kingston, 1987). Based on a 3-year field survey at Sungei Punggol in Singapore, Lu et al. (2002) suggested that reclamation had damaging effects on the macrobenthic community and decreased the productivity of macrobenthos in the region close to the reclamation project. In Tianjin Harbor, China, a continuous field survey from 2006 to 2008 indicated that the amount of phytoplankton, zooplankton, and benthic animals all decreased considerably after reclamation projects and suggested that changes in the living environment were the main cause (Li et al., 2010). Therefore, for the purposes of tidal marsh management, conservation, and restoration, it is important to better understand the ecological responses to land reclamation and the associated environmental changes.

Comprehensive quantitative study is critical in understanding the mechanism that underlies the environmental changes and ecological responses of tidal marshes. Hydrodynamic indicators such as tidal current velocity, inundation period, salinity, and water depth have all been reported to be highly correlated with the productivity of tidal marshes (Habdija et al., 2004; Lui et al., 2002; Schonberg et al., 2014; Sousa et al., 2008). However, many critical hydrodynamic factors are rarely observed or continuously monitored at the same time or location as biological surveys, especially those that involve large-scale processes. Hydrodynamic models can be used in this case to simulate hydrodynamic conditions that coincide in both space and time with biological surveys, even with a very limited amount of observed hydrodynamic data. Ysebaert et al. (2003) used an estuarine hydrodynamic model to generate data on water depth, tidal current, and salinity for a large-scale spatial analysis of benthic infauna using 3112 samples in the Schelde estuary in northwestern Europe. Such an estuarine hydrodynamic model can also provide data on a large region and the regional average, which are hard to obtain with field observations. In addition, recent studies have suggested that water age, an output of hydrodynamic models, can be used to indicate estuarine circulation and nutrient retention time scale. Some studies have used water age in estuarine regions to investigate eutrophication problems (Basu and Pick, 1996; Shen and Wang, 2007) and have found that the growth of phytoplankton and zooplankton was correlated with water age (Phlips et al., 2012; Wan et al., 2013). Camacho et al. (2014) and Ferreira et al. (2005) further suggested that water age is an important indicator of ecological vulnerability in estuarine ecosystems and that it governs phytoplankton productivity. Because the amount of phytoplankton and zooplankton accounts for a large part of the primary productivity of estuarine ecosystems, it can be hypothesized that water age may reveal or explain the environmental changes and ecological responses of tidal marshes. Moreover, reclamation was found to alter the estuarine circulation of bays (Yang and Chui, 2017; Shi et al., 2011). Water age can therefore be used to quantify hydrodynamic changes and further deduce the potential ecological impact of reclamation.

Bayesian inference is increasingly being used to model the dynamics of ecological processes with environmental factors, from predicting species population dynamics to understanding ecosystem processes (Kattwinkel et al., 2016; Reichert et al., 2015). Bayesian models treat model parameters as random variables, whose posterior probability distribution can be generated from the prior probability distribution and the likelihood derived from observation data (Gelman et al., 2014). Therefore, the Bayesian inference allows ecological models to quantify and predict the uncertainty of each parameter through model generation and simulation (Ellison, 2004). Kattwinkel et al. (2016) used Bayesian inference in an ecotoxicological model and successfully simulated the density dynamics of benthic animals in an experimental stream contaminated with a pesticide, in which the benthos was stressed by varying pollutant concentrations. However, it is more challenging to simulate the dynamic ecological process in a natural environment because the ecological process is stressed by a wide range of environmental factors of various levels of influence (Palanisamy and Chui, 2013).

Benthic infauna is a critical component in the estuarine food web, as infauna is a vital food supply to wading birds, large crustaceans, and fish (Day, 1989). In tidal wetlands, it is available to wading birds as food at low tide and available to fish, crustaceans, and aquatic mammals at high tide. The amount of benthic infauna is critical to the sustainability and health of an estuarine ecosystem. Numerous studies have used benthic infauna as an indicator of the health of an estuarine ecosystem and have indicated that the biomass of benthic infauna in tidal wetlands is sensitive to the total regional environment (Luckenbach et al., 1990; Schonberg et al., 2014; Ysebaert et al., 2003). Recent studies have further demonstrated that temporal evolution of benthic infauna biomass is substantially correlated with the temporal variations of environmental factors (Shojaei et al., 2016). Therefore, in this study, biomass of benthic infauna is used as an ecological indicator of the productivity of tidal marshes to evaluate the impact of land reclamation. The hypothesis of this study is that reclamation alters the biomass dynamics of intertidal benthic infauna and influences the tidal marsh ecosystem.

The aims of this study are (1) to identify the governing environmental factors in benthic infauna biomass dynamics using correlation analysis, (2) to simulate the temporal dynamics of benthic infauna biomass with a Bayesian regression model based on time-varying environmental variables selected from correlation analysis, (3) to investigate the ecological impact of reclamation by predicting the dynamics of benthic infauna biomass in different reclamation scenarios, and (4) to understand the mechanism that underlies eco-hydrological changes in the tidal marsh ecosystem. This study is, to the authors' best knowledge, the first attempt to directly examine and quantify the relationship between intertidal benthic infauna biomass and estuarine circulation and to predict the temporal dynamics of benthic infauna biomass using time-varying environmental variables in a tidal marsh.

2. Methods

An ecological model was generated for the case study to predict benthic infauna biomass dynamics and evaluate the hypothesis. The model was developed using a Bayesian regression method based on the temporal sequences of several environmental variables. These variables were selected based on their correlation with the temporal variation of benthic infauna biomass. The model was validated with field observations and then used to predict the biomass dynamics under different reclamation scenarios. Coastal numerical models were used to generate hydrodynamic results, which were used as inputs of the ecological model during the reclamation simulations.