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# Effects of hypoxia caused by mussel farming on benthic foraminifera in semi-closed Gamak Bay, South Korea

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ABSTRACT

Seawater monitoring and geochemical and benthic foraminiferal analysis of sediments were conducted to identify the effects of hypoxia created by a mussel farm on benthic foraminifera in a semi-closed bay. Extremely polluted reductive conditions with a high content of organic matter (OM) at $>12.0\%$ and oxygen minimum zones (OMZs) with dissolved oxygen (DO) $<0.4$ mg·L$^{-1}$ were formed below the mussel farm in the northwest area of Gamak Bay, and gradually diffused toward the south. Highly similar patterns of variation were observed in species diversity, abundance frequency, and benthic foraminiferal assemblage distributed from *Elphidium subarcticum*–*Ammonia beccarii* in the northwest area through *E. subarcticum*–*A. beccarii*–*Trochammina hadai*, *E. subarcticum*–*A. beccarii*–*Elphidium clavatum*, and *E. clavatum*–*Ammonia ketienziensis* in the southern area. These phenomena were caused by hydrodynamics in the current water mass. It was thought that *E. subarcticum* is a bioindicator of organic pollution caused by the mussel farm.

## 1. Introduction

Although they have existed throughout geological time, hypoxic and anoxic environments have increased in occurrence in estuarine and coastal areas on a global scale (Diaz and Rosenberg, 2008; Gilbert et al., 2010). In addition to the negative ecological impacts of human activities on coastal ecosystems, ecological impacts of aquaculture activities, increased frequency and intensity of harmful algal blooms, and depleted oxygen concentrations are a growing problem in many coastal ecosystems (Diaz, 2001).

Aquaculture is the fastest growing sector of the food industry, increasing at a rate of about 8% per year since the 1970s and accounting for 43% of the total annual fisheries production of 160 million metric tons in 2008 (McKindsey et al., 2011). Of the 20.5 million metric tons of mollusks produced worldwide annually, about 11.5 million metric tons, including more than 4 million metric tons each of clams and oysters and about 1.5 million metric tons each of scallops and mussels, are bivalves from aquaculture production (FAO Fisheries and Aquaculture Department, 2010).

Mussel farming throughout the world is practiced using 2 main approaches: bottom culture, accounting for approximately 15% of overall production, and suspended and off-bottom culture, accounting for approximately 85%. The suspended and off-bottom culture methods employ rafts, bouchots, and longline systems (McKindsey et al., 2011). Mussels have evolved by developing better morphological and behavioral anti-predator defenses such as strong byssus attachments (Reimer and Tedengren, 1996), increasing the volume of the byssus (Cote, 1995). Mussel farms situated in sheltered sites can excrete biodeposits such as feces, pseudofeces, and shell parts at a build-up rate of 10 cm·year$^{-1}$, which results in changes to the seabed approximately 20 m from the farm boundaries (D from the farm boundarie1981; Mattsson and Linden, 1983). The quantity of biodeposits beneath suspended cultures can reach 3000 metric tons·ha$^{-1}$·year$^{-1}$ (Grenz, 1989). Mussel shell accumulation of $2800 \pm 970$ ind·m$^{-2}$·year$^{-1}$ has been reported on the seabed beneath a farm in Sweden (Mattsson and Linden, 1983). The fecal pellet sinking velocity ranges from 0.27 cm$^{-1}$ to 1.81 cm$^{-1}$ for mussels 3–7 cm in size and is best correlated with fecal pellet width. Sedimentation rates were greater within the farm than at reference sites, supporting the theory that mussel farming increases sedimentation rates (Callier et al., 2006).

It is widely accepted that the primary benthic environmental impact of suspended mussel farming is the buildup of biodeposits directly below the culture area (Jaramillo et al., 1992; Hargrave, 2003). This topic has received global attention because of the negative impacts of eutrophication and hypoxia on coastal systems, which occur at $<0.2$ mg·L$^{-1}$ or mL·L$^{-1}$ $O_2$ (Rabalais et al., 1991; Breitburg et al., 2001; Diaz and Rosenberg, 2008; Doney, 2010; Gilbert et al., 2010; Kalantzi et al., 2013). Because a major fraction of primary production in the surface water reaches the sea floor, anoxic and hypoxic events frequently occur in the bottom waters, particularly in late summer and autumn when the combination of high downward organic flux

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and elevated microbial decay rates are responsible for a high benthic oxygen demand.

Foraminifera have specific ecological niches and are found in virtually all marine ecosystems that support eukaryotic life (Goldstein, 1999). Populations of foraminifera react quickly to environmental changes (Hallock et al., 2003; Ward et al., 2003). Foraminiferal assemblages in oxygen-depleted habitats typically exhibit the following characteristics. As a group, foraminifera are more tolerant of hypoxia than most metazoans. Although most foraminifera tolerate fairly low oxygen concentrations, a relatively small number of genera and species dominate the assemblages in strongly hypoxic conditions. Moreover, in hypoxic settings, taxa with hyaline calcareous tests, such as rotaliids and buliminids, are usually predominant. In hypoxic environments, foraminifera typically live close to the sediment–water interface. Further, the elimination of hypoxia-sensitive foraminiferal species reduces the species richness, whereas the abundance of a few hypoxia-tolerant species increases dominance (Sen Gupta and Machain-Castillo, 1993; Jorissen, 1999; Bernhard and Sen Gupta, 1999; Gooday, 2003; Murray, 2006; Jorissen et al., 2007; Gooday et al., 2009). Several taxa of benthic foraminifera, particularly those living deep in the sediment, react favorably in strongly hypoxic to anoxic conditions, by using anaerobic metabolism based on nitrate respiration (Risgaard-Petersen et al., 2006) or perhaps by establishing a symbiotic relationship with anaerobic bacteria (Bernhard, 2003).

The northwest area of Gamak Bay, which has received abundant sewage from Yeosu City since 1970 and frequently contains anoxic water masses in summer (Kim et al., 2014), has been a main site for mussel culturing (*Mytilus galloprovincialis*) since the late 1970s. A sewage treatment plant that began operation in 2004 has prevented a considerable load of pollutants from being dumped directly into the bay from adjacent areas. Eutrophication and hypoxia, however, still frequently occur in the bay (Kim et al., 2010, Seo et al., 2012). This recurrent seasonal hypoxia is critical when studying benthos and sediment biogeochemistry. Organisms that have evolved in permanently hypoxic settings such as oxygen minimum zones (OMZs) appear to thrive at very low levels of dissolved oxygen (DO) (Childress and Siebel, 1998; Levin, 2003; Middelburg and Levin, 2009). The purpose of this study is to identify the effects of organic pollutants on species composition and the distribution of benthic foraminiferal assemblages in a mussel farm in a semi-closed bay.

## 2. Study area

Gamak Bay, a type of ria located at the center of the South Sea in Korea, is a semi-closed bay surrounded by Yeosu and Dolsan islands (Fig. 1). It has an area of 148 km$^2$ extending over roughly 15 km in length and 9 km in width (Kim et al., 2006). The average water depth is 9 m, with relatively shallow water in the central part at <5 m increasing to ~30 m at the mouth of the bay. The tide is semidiurnal, and the tidal fluctuation in the bay is quite large, with minimum and maximum tidal amplitudes of ~1 m and ~4 m during neap and spring tides, respectively. Due to its high tidal range, the water depth is shallower than 5 m at low tide. The currents are generally counterclockwise and clockwise in the northwest and central areas, respectively. The bay has 2 channels at the east and the south connected to the open sea, although most of the sea water is changed through the south channel (Lee and Kim, 2009).

The surface sediments of Gamak Bay consist mainly of fine-grained sediment with silt and clay facies, whereas coarse-grained sediments predominate at the mouth of the bay (Lee et al., 1995). The deposition rates are higher than erosion rates in most areas of the bay (Kim et al., 2014). The geological strata around Yeosu and Dolsan islands are Cretaceous, composed mostly of volcanic rock with low permeability and granite, respectively (Lee et al., 1995). The bay sea water can be divided into 3 water masses: (1) water in the northwest area, which is quite stagnant due to the bottom topography and a deficiency of oxygen in the bottom water during summer (Lee, 1992); (2) the Yeosu harbor water in the northeast area, which has lower salinity due to the influence of some small streams and ditches; and (3) the central water and that near the mouth of the bay (Lee and Cho, 1990).

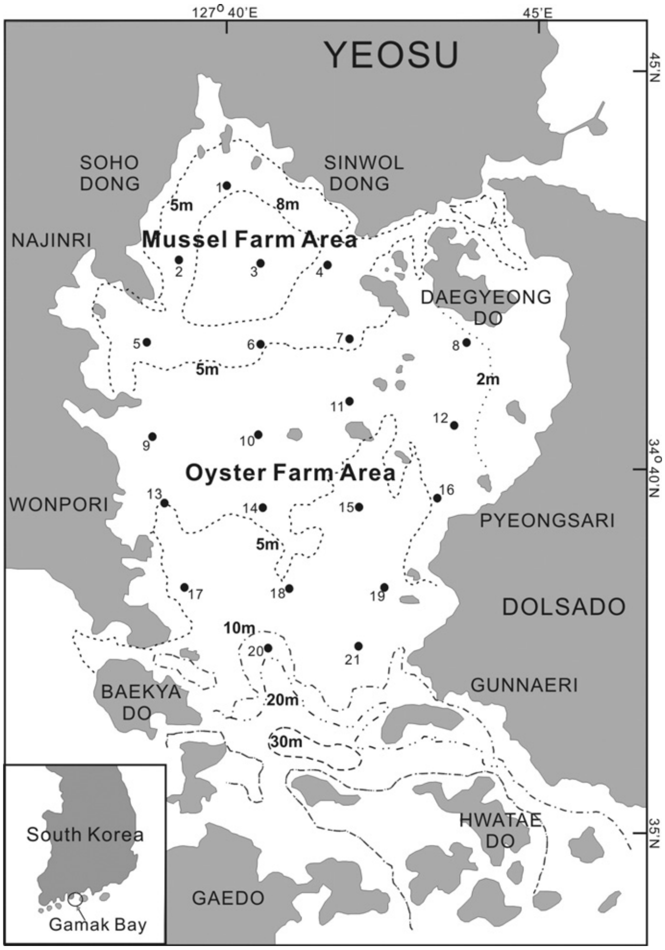

**Fig. 1.** Sample location and bathymetric map of Gamak Bay, located on the south coast of South Korea.

Various aquatic products including mussels and oysters are farmed mostly in the northwest and central areas of Gamak Bay, which makes it important to the fishing industry. Mussel farming, covering 428 ha and producing 40,000 metric tons each year (Yeosu-si, 2014), is conducted by suspended and off-bottom culture, mostly using the longline system. This bay was designated by the Korean government (Ministry of Land Transport and Maritime Affairs, MLTM) as an environmental conservation area in February 2000 due to its ecological importance as a habitat for fish and shellfish (Kim, 2003). However, increases in human activities after the expansion of urban areas nearby, in addition to the development of various aquaculture industries such as oyster and mussel farming during recent decades, have gradually increased the influx of anthropogenic pollutants with mostly organic matter. These pollutants cause coastal environmental problems such as eutrophication, hypoxia, and red tide, mostly during the summer (Seo et al., 2012; Lee et al., 2009, 2012). These phenomena have continuously occurred, although a sewage treatment plant began operation in 2004 to restrain the influx of sewage from urban areas (Lee et al., 2009; Kim et al., 2006; Lee and Moon, 2006).

## 3. Materials and methods

### 3.1. Sediment sampling and water quality monitoring

Sediment sampling and water quality monitoring were conducted at 21 locations in August 2014 (Fig. 1).