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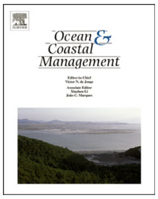

The Saemangeum tidal flat: Long-term environmental and ecological changes in marine benthic flora and fauna in relation to the embankment

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ABSTRACT

The present article presents a historical overview of the Saemangeum reclamation projects and key findings from the ecological studies of the Saemangeum tidal flat, highlighting the ecological impact against the grand reclamation project, as a model example, in Korea. First, the scientific efforts given to the area of interest, mainly the inner part of the dikes, during the construction periods of series of four dikes (1991–2006) were summarized in terms of the change of environmental condition followed by the ecological responses over the past 20 years. As part of review, we selected and reanalyzed our series of the Saemangeum data including the current works relating to the microphytobenthos and macrozoobenthos, where the spatio-temporal variations cross the benthos in association with dike effects were carefully discussed in detail. The species composition in the upper intertidal zone, situated relatively far from the dikes, have been lesser changed between the periods of before (1988) and during the dike construction (2003–05). However, the benthic assemblages appeared to be changed in the mid to the lower intertidal zones of several transects and such phenomenon strengthened for the locations near the completed dike, e.g., Sandong transect near the dike of sector IV. Meanwhile, changes of the representative zoning in benthic assemblages during the dike construction were much clearly observed for the faunal species rather than flora. Such long-term ecological impacts including the timely increase of the opportunistic species during the dike construction were further evidenced the compositional change of the dominant benthos spanning two decades or so. In general, a long-term change in benthic community structure clearly reflected the community level impact apparently due to the attenuation of tidal energy by the embankment, varying the degree of impacts depending on the geographical location. Interdisciplinary monitoring and modeling studies are highly recommended to track natural variations in water quality and ecosystem health. Overall a long-term ecological monitoring should be applied to direct sound policy toward conservation of tidal wetlands, by emphasizing the significant biodiversity decline and coastal landscape depreciation.

1. Introduction

Estuaries are recognized as one of the important ecological transition zones, with functional linking terrestrial to marine aquatic ecosystem (Gray, 2002). This ecological allocation would be a key reason for the highest value of significance in the estuarine and coastal regions supported by the enriched nutrient cycling in terms of ecosystem services (Costanza et al., 1997). Tidal flats (or wetlands) in such linking ecosystem are known to play an important role as one of the principal energy transfers from primary producers to high-level consumers, including fish, waterfowls, and finally to human (Levin et al., 2001; Wall et al., 2001). In particular, the benthic ecosystem inhabiting various tidal flat organisms plays a central role in the food web, encompassing primary producers, consumers, and also decomposers. Further, the importance of tidal flats for migratory birds, say the top predator in the food chain of

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tidal flats, has also been highly acknowledged (Ryu et al., 2011a). For above reasons, the estuarine tidal flats should have been considered as a critical ecosystem zone, warranting the protection of the nature and wildlife.

However, unfortunately, the Saemangeum tidal flat located in the Mangyeong-Dongjin estuary disappeared in the late 2000s by the embankment from the Saemangeum reclamation project. The area is recognized as one of the largest uniscale wetlands in Korea possessing valuable ecosystem services such as biodiversity, fisheries, and coastal landscape etc. (Koh et al., 2010). In particular, the provisioning service for waterfowl resting area in the Saemangeum tidal flat should have supported large populations of internationally migratory shorebirds following the East Asian/Australasian pathways (Rogers et al., 2006). Meanwhile, this area was also economically acknowledged in terms of local fisheries on tidal flats, particular for artisanal fisheries such as clam harvesting (Koh and Khim, 2014). With such socio-economic recognition and concerns over the human use of the Saemangeum area, many benthic ecological studies have been concentrated in the given area during the past two decades, in Korea (An and Koh, 1992; Oh and Koh, 1995; Koo et al., 2008a, b, c; Ryu et al., 2011a, b).

Currently, the artificial lake created inside the dikes of the Saemangeum lowered 1.5 m below the mean sea level for the next step of landfilling, and this resulted in drying up the significant areas of tidal flat followed by collapsing the entire tidal flat ecosystem. The present article aimed to address the long-term ecological changes in marine benthic flora and fauna of the Saemangeum against the environmental changes due to the embankment. To do this, a set of selected data from our previous and current works relating to the microphytobenthos (MPB) and macrozoobenthos (MZB) in the given area was scrutinized targeting their species composition and spatio-temporal distributions. A detailed description of previous natural ecosystems would be meaningful to fully restore the ecological structure and function of the tidal flat, like the Saemangeum, by sound restoration efforts, if necessary. Chronological description on the dominant benthos species in the given area over the past 20 years are highlighted in order to find the long-term ecological changes against the timely events including the construction of series of four dikes. Finally, the future research and policy directions challenging the conservation of tidal wetlands and/or possible restoration campaign in the Saemangeum area are carefully suggested, by emphasizing the significant loss of biodiversity and coastal landscape.

2. History of the Saemangeum project

2.1. Geographical and oceanographical settings

Along the west coast of Korea (West Sea), several types of tidal flats including embayed, semi-enclosed, estuarine, and open-coastal groups are extensively developed totaling ~2 500 km^2 of wetland areas. In general, the Korean tidal flats belong to the macro tidal regime, with maximum of ca. 10 m tidal height in several places around the Gyeonggi Bay. Similar to the Gyeonggi Bay, the Saemangeum tidal flat (35°30′ to 35°50′ N and 125°40′ to 126°00′ E) have experienced the macrotidal condition up to ~7 m tidal height at spring tide, until the world longest seawall (33.9 km spanning four dikes) created in 2006 (Fig. 1).

The Saemangeum area formerly covered ~233 km^2 of tidal wetland in the 1980s, with >5 km width in many places, extending up to 15 km offshore direction from the mouth of the Mangyeong and Dongjin estuary in the 1980s (Fig. 1A). The large amount of freshwater flows into the tidal flat area through the well developed tidal channels along the two major rivers, subsequently flowing into the West Sea. Before the dikes completed, it was reported that the year-round freshwater input reached ~6.4 billion tonnes and more than half (~60%) was concentrated during the summer monsoon period only (Kim and Chung, 1988). Strong year-round salinity gradient from 10 to 24 due to intermittent discharges from those rivers and possible submarine groundwater discharges would be the typical characteristics in the estuarine tidal flat of the Saemangeum (Kim et al., 2010; Waska and Kim, 2011). Meantime, sediment bottom in the Saemangeum area used to be muddy in the upper intertidal zone and sand-dominated in the lower part, which represents a typical sedimentary distribution of the Korean tidal flats. As a result of the embankment, the sedimentation and topography of the tidal flat particularly in the subtidal regions have been totally changed (Lee and Ryu, 2007, 2008), subsequently disturbing the marine benthic assemblages in the given area (Ryu et al., 2011a).

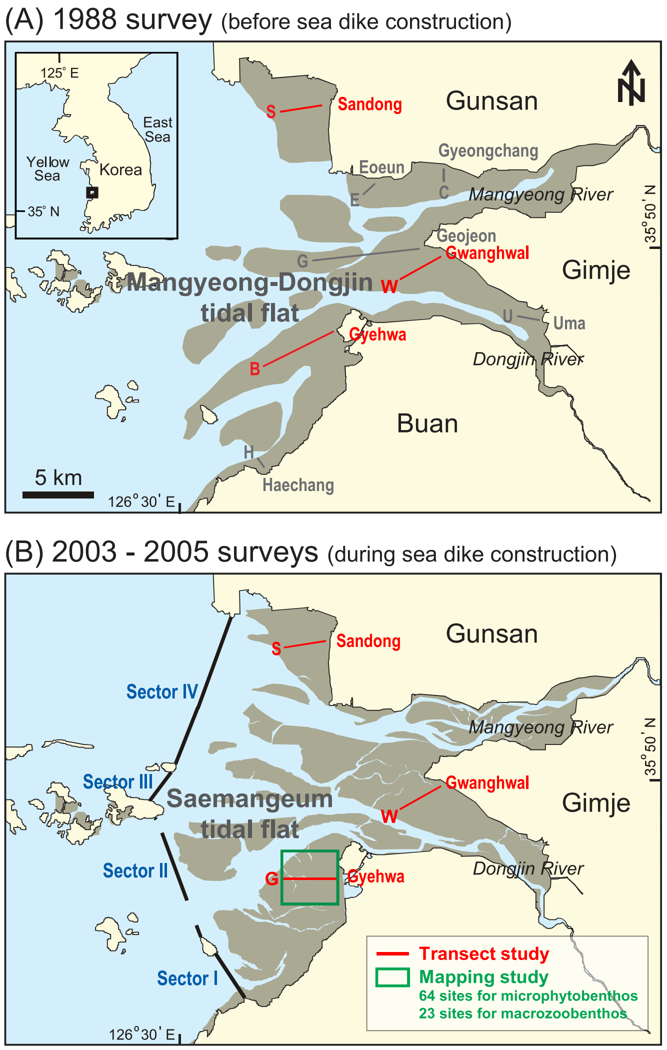


Fig. 1. Map of the Saemangeum tidal flat showing the boundary of tidal flat and dike construction, and the location of transect lines studied in (A) 1988 and (B) 2003–05.

2.2. Chronological description on long-term socio-political conditions

The historical understanding of the key environmental conditions related to the Saemangeum reclamation project, including political, administrative, sociological, and legal activities would be of critical backgrounds to link scientific demands into its outcome

Table 1
Chronological descriptions of the issues and actions relating to the Saemangeum reclamation project by the four categories of political issues, administrative actions, sociological & legal aspects, and scientific efforts, since the 1980s to the present (modified from Koh, 2014).

Year	Political issues	Administrative actions	Sociological & legal aspects	Scientific efforts
1987–89	Highlighted Saemangeum project as presidential election pledge, by 2 candidates (87)	Set a basic plan for Saemangeum development (farmland 100%) (89)		Performed Environmental Impact Assessment & Economic Evaluation (87)
1991–93	Saemangeum project continued to be presidential election pledge, by 3 candidates (93)	Issued reclamation permit and began dike construction began (91)		
1994–95	Jeollabuk-do governor announced Saemangeum Industrial Complex plan (95)		Televised a documentary film “Getbol is alive” (94)	
1996–97	Saemangeum project continued to be presidential election pledge again, by 3 candidates (97)		Highlighted Lake Shihwa pollution after 2 yrs of dike completion (96); argued reasonable fishery compensation (97)	
1998	Presidential transition team (Present Roh Moo-hyun) stated Shihwa and Saemangeum projects as two of three poor businesses (98)	Yeongsan river project (phase IV) withdrawn (98)	Continued media report on Lake Shihwa pollution issue (98) launched Citizen's Committee against Saemangeum Project (98)	
1999	Jeollabuk-do governor suggested Saemangeum Expert Review Panel (SERP) (99)	SERP organized (w/30 experts) holding for dike construction (99)		Investigated environment, economy, and water quality by SERP (99)
2000			Buan 1 000 people's Declaration against Saemangeum project (00) Citizen's Declaration, called “Life and Piece” (00) boomed various NGOs campaigns against Saemangeum project (00)	
2001		SERP concluded by voting 18 for and 9 against for the project (01) stepwise development plan followed by resuming construction (01) Open media discussion on SERP result (three times) (01)	lawsuit against implementing the project (01) started the Alliance for Saemangeum Life and Peace (01) started the Korean Society for the Life of Saemangeum (01)	
2002–03	A protest led by Jeollabuk-do governor for developing Saemangeum towards hub in pan-Yellow Sea region (03)		Televised a documentary film “Ocean wants to be flowing” (03) “3-steps 1-bow” campaign from Saemangeum to Seoul by religious and NGO groups (03)	Environmental monitoring (02–12)
2005–06		Seoul Administrative Court (SAC) proposed mediation, rejected by the government (05) government lost the first trial, but appealed to win the second of SAC (05) government won at the final trial (06)		
2007–08	Established the Special Act for Promotion of the Saemangeum Project (SAPSP) (07)	Future land use plan changed, less farmland (100%–72%), and more industrial and urban use (remaining 28%) (07) Land use plan finalized (farmland: 30%, industry and urban: 70%) (08)		
2011–12	Amended to the SAPSP (11)	Confirmed Saemangeum Master Plan (11)		
2013		Launched the Korea Agency for Saemangeum Development and Investment (13)		Environmental monitoring (14–23)

(Table 1). The Saemangeum issue would date back to the late 1980s, when its developmental policy was first exposed to the public as a presidential election pledge in 1987. To implement the Saemangeum developmental policy that supported by the Public Waters Management and Reclamation Act (Koh and Khim, 2014), the government performed the environmental impact assessment in 1987 as a precedent required step. Later, a basic plan for the reclamation including the construction of dikes has been suggested in 1989 and practiced since 1991 in which year the reclamation permit finally issued. The project planned to build a total of 33.9 km of the series of four fragmented dikes (sector I–IV) to enable landfilling of ~400 km^2 of tidal flat being converted to farmland (Fig. 2A).

At the beginning, the Saemangeum project was supposed to strengthen agricultural infrastructure, say the purposes of farmland earning and water resources securing, which assumedly supports the welfare for local community farming and fishing. The dike construction has proceeded smoothly until the local conflicts developed in the late 1990s, of which debate was stimulated by the Lake Shihwa issue in 1995 (Lee et al., inpress). Because the central environmental issue between two cases was about the same, viz., water pollution inside of the dike by physicochemical changes in hydrodynamics followed by biochemical disturbance.

The construction temporarily stopped in 1999, but eventually resumed by the governmental top-down decision in 2001. Against the government's decision, the second phase of the Saemangeum debate was developed and prolonged over the following 5 years supported by various citizen's activities from the NGOs and also professional scientific society. However, the government had won at the final trial of the Seoul Administrative Court in 2006, which have unfortunately brought the completion of world longest notorious seawall (33.9 km) in the given area. Later, the Special Act on Promotion of the Saemangeum Project (SAPSP) was legislated in 2007 followed by establishment of the Saemangeum Master Plan (SMP) in 2011, further promoting the development of reclaimed areas. It should be noted that the proportion of agricultural land use have been reduced from 100% to 72% in 2007, and further down to ~30% in 2008 (reflected on the SMP in final), clearly indicating the failure of original planning of farmland creation (Table 1).

In anyhow, the Saemangeum reclamation project is still under the progress with different title, say “the Saemangeum development project” and currently being faced into a new stage of landfilling the former vast tidal flat areas. Before the project in the 1980s, the Saemangeum area has been recognized as a representative Korean tidal flat having been the greatest in geographical scale as an uniscale tidal flat ecosystem. For this reason, relatively great scientific attention given to the natural ecosystem of the given area would not be surprising in the 1980s when the tidal flat ecology was first introduced to the scientific society in Korea (Koh and Khim, 2014). However, upon the progress in embankment and more recent development in landfilling stage, the scientific concerns seemed to move concerning the pollution issues, similar to the Lake Shihwa case (Lee et al., inpress). Altogether, the Saemangeum tidal flat has been suffered from the environmental deterioration during the past 20 years, which should have been avoided not repeating the second Shihwa with following gap of ca. 10 years (Lee et al., inpress).

3. Long-term ecological change

As indicated earlier and elsewhere, the study of tidal flat ecology in Korea has short scientific history being limited to relatively narrow spectrum, compared to the scientific efforts highlighted in the European countries (Koh and Khim, 2014), particularly when counting the international publications. For example, several pioneering works relating to the tidal flat biology conducted by the Korean scientists had not been introduced until the late 1980s (Koh and Shin, 1988). Fortunately, the Saemangeum benthic flora (Oh and Koh, 1995) and fauna (An and Koh, 1992) in the year of 1988 (Fig. 1A), say before the Saemangeum project launched, have been documented, in which benthic assemblages would represent the native tidal flat assemblages in the given area.

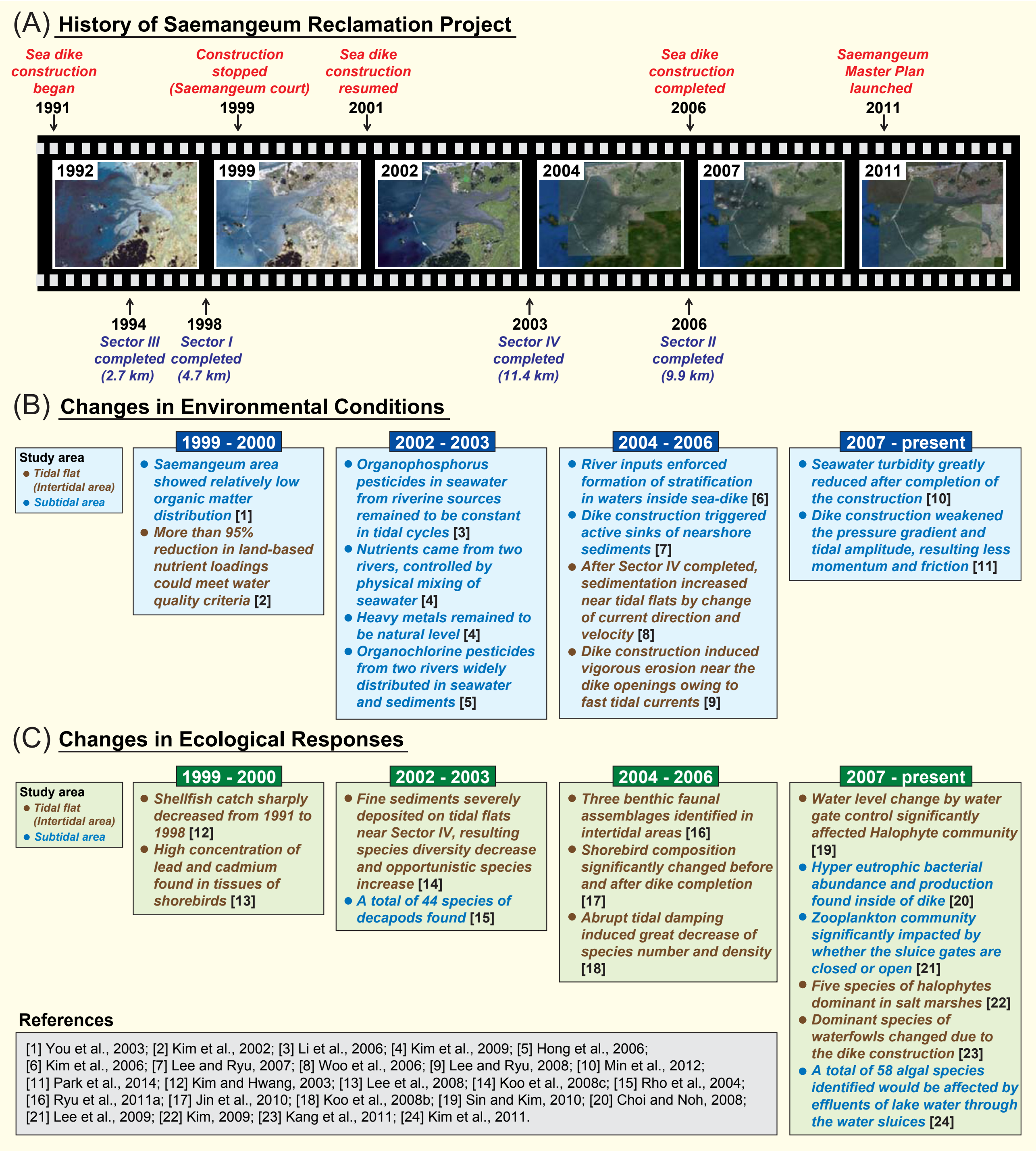
Later, the benthic assemblages of the Saemangeum were extensively studied during the periods of embankment (2003–05), which enabled us to compare long-term biological change for the Saemangeum MPB (Fig. 3) and MZB (Fig. 4). In particular, the 2003–05 surveys were conducted at the time of >80% of dike completion, thus the possible impact by the dikes (allocated by the sectors I–IV, see Fig. 1B) on the nearby benthic assemblages could be comparatively analyzed (Fig. 1B). Finally, to better understand the long-term biological changes in the assemblages of the Saemangeum flora and fauna, the dominant benthos species recorded in the earlier publications (refer to a set of 10 papers, see Fig. 5) were extracted and reanalyzed to support the discussion of long-term biological changes against the key events in the Saemangeum area.

3.1. Benthic floral assemblages and distribution

Among the several transects investigated in 1988, the Gyehwa showed the greatest species diversity with a total of 232 diatom taxa (Table 2). The dominants in the Gyehwa were *Achnanthes hauckiana*, *Paralia sulcata*, *Amphora coffeaeformis*, *Dimeregramma minor*, and *Opephora martyi*, in the order, encompassing ~40% of the total MPB abundance in the given area. In the meantime, the distinct microalgal zoning along transect was identified with two clustered groups, namely the upper and the lower intertidal assemblages (Fig. 3A). The dominant MPB found in the upper intertidal zone were *A. coffeaeformis*, *P. sulcata*, *Cymatosira belgica*, *Achnanthes hauckianum*, and *Navicula* sp. 1 with relative abundances of 14, 13, 6, 5, and 4%, respectively. Meanwhile those in the lower intertidal zone were *Achnanthes hauckanum*, *D. minor*, *O. martyi*, *Cocconeis* sp. 1, and finally *D. minor* var. *nana* with relative abundances of 16%, 11%, 7%, 6%, and 3%, respectively. In particular, it would be noteworthy in that the top five dominant species in the lower intertidal zone were all araphid and monoraphid taxa which are usually adnate to substratum such as macrophytes and/or sand grains (Round et al., 1990; Cox, 2006). Indeed the sediments in the lower intertidal zone, in the year of 1988, appeared to consist of mostly sand grains with lesser compositions of silt and clay.

In 2003, a transect survey comparable to that of 1988 (Fig. 1) has been conducted in the Gyehwa tidal flat, showing a total of 194 species, slightly reduced from the 232 species identified from the study of 1988 (Table 2). The dominants in the second survey were similar but not identical compared to those in the earlier study, encompassing *Amphora subholsatica*, *Amphora borealis*, *Fogedia coreana*, *Amphora* aff. *spartinetensis*, and *Navicula* cf. *flagellifera* with collective abundance of ~40% of the total MPB in the Gyehwa (Park, 2011; Park and Koh, 2012; Park et al., 2013). Similar to the previous study in the year of 1988, the whole transect in the year of 2003 again showed a distinct two assemblage zones with similar subportion in space (Fig. 3B). The dominant species of the upper intertidal zone were *A. subholsatica*, *A. borealis*, *Paralia fenestrata*, *Navicula* sp. 4, and *Navicula* cf. *flagellifera* with relative abundances of 20, 12, 6, 5, and 5%, respectively. Meanwhile those in the lower intertidal zone encompassed *F. coreana*, *Navicula* cf. *bipustulata*, *A. borealis*, *Fogedia densa*, and finally *Fogedia elliptica* with relative abundances of 21, 7, 6, 6, and 5%, respectively. It is noteworthy that araphid and monoraphid diatoms dominated in 1988 seemed not to be common in 2003, with relative abundance of maximum 5% in the lower intertidal zone of the Gyehwa.

When superficially observed, there was little overlapping in the dominant species or groups between two surveys (1988 vs. 2003), thus the taxonomic revision in the identification of the diatom species has been included for better treating the species compositional analysis, as part of meta-data analysis herein. At first, *A. coffeaeformis* sensu Oh and Koh 1995 appeared to be identical to *A. borealis* from the Gyehwa tidal flat in the year of 2003 considering its size range and striae density. In fact *A. borealis* has been often misidentified as *A. coffeaeformis* (Levkov, 2009). Another group of species interested was *P. sulcata*; although *P. sulcata* had been considered to be the only extant species of the corresponding genus until very recently, it has been shown that there also exist other extant species of the *Paralia* in the Northeast Asia (Sawai et al., 2005). Through careful examination of the *Paralia* species from the Gyehwa tidal flat in the year of 1988 and 2003, we confirmed the species as *P. fenestrata* based on its size range as well as the observations of LM/SEM. Thus the top two dominant diatoms in the upper intertidal



(B) Changes in Environmental Conditions

Study area
- ● Tidal flat (Intertidal area)
- ● Subtidal area

1999 - 2000
- ● Saemangeum area showed relatively low organic matter distribution [1]
- ● More than 95% reduction in land-based nutrient loadings could meet water quality criteria [2]

2002 - 2003
- ● Organophosphorus pesticides in seawater from riverine sources remained to be constant in tidal cycles [3]
- ● Nutrients came from two rivers, controlled by physical mixing of seawater [4]
- ● Heavy metals remained to be natural level [4]
- ● Organochlorine pesticides from two rivers widely distributed in seawater and sediments [5]

2004 - 2006
- ● River inputs enforced formation of stratification in waters inside sea-dike [6]
- ● Dike construction triggered active sinks of nearshore sediments [7]
- ● After Sector IV completed, sedimentation increased near tidal flats by change of current direction and velocity [8]
- ● Dike construction induced vigorous erosion near the dike openings owing to fast tidal currents [9]

2007 - present
- ● Seawater turbidity greatly reduced after completion of the construction [10]
- ● Dike construction weakened the pressure gradient and tidal amplitude, resulting less momentum and friction [11]

(C) Changes in Ecological Responses

Study area
- ● Tidal flat (Intertidal area)
- ● Subtidal area

1999 - 2000
- ● Shellfish catch sharply decreased from 1991 to 1998 [12]
- ● High concentration of lead and cadmium found in tissues of shorebirds [13]

2002 - 2003
- ● Fine sediments severely deposited on tidal flats near Sector IV, resulting species diversity decrease and opportunistic species increase [14]
- ● A total of 44 species of decapods found [15]

2004 - 2006
- ● Three benthic faunal assemblages identified in intertidal areas [16]
- ● Shorebird composition significantly changed before and after dike completion [17]
- ● Abrupt tidal damping induced great decrease of species number and density [18]

2007 - present
- ● Water level change by water gate control significantly affected Halophyte community [19]
- ● Hyper eutrophic bacterial abundance and production found inside of dike [20]
- ● Zooplankton community significantly impacted by whether the sluice gates are closed or open [21]
- ● Five species of halophytes dominant in salt marshes [22]
- ● Dominant species of waterfowls changed due to the dike construction [23]
- ● A total of 58 algal species identified would be affected by effluents of lake water through the water sluices [24]

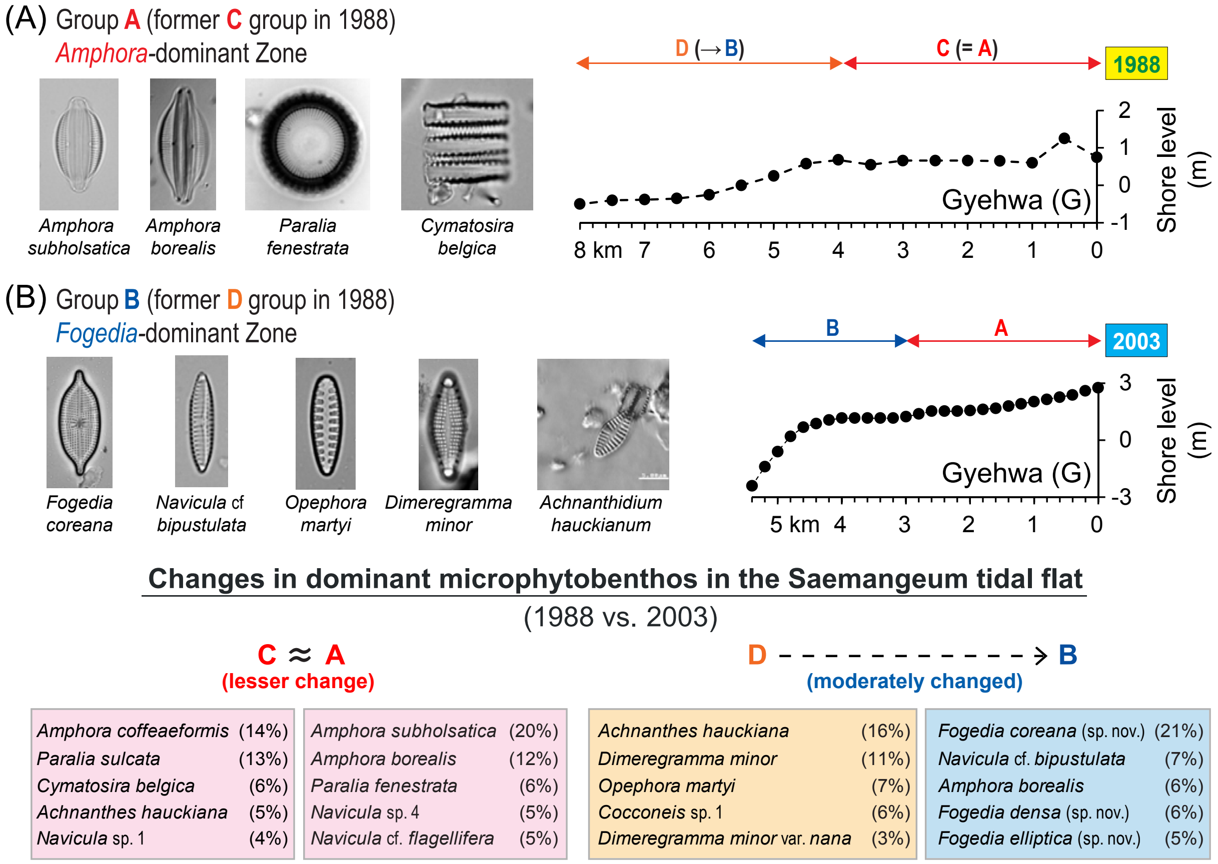
References

[1] You et al., 2003; [2] Kim et al., 2002; [3] Li et al., 2006; [4] Kim et al., 2009; [5] Hong et al., 2006; [6] Kim et al., 2006; [7] Lee and Ryu, 2007; [8] Woo et al., 2006; [9] Lee and Ryu, 2008; [10] Min et al., 2012; [11] Park et al., 2014; [12] Kim and Hwang, 2003; [13] Lee et al., 2008; [14] Koo et al., 2008c; [15] Rho et al., 2004; [16] Ryu et al., 2011a; [17] Jin et al., 2010; [18] Koo et al., 2008b; [19] Sin and Kim, 2010; [20] Choi and Noh, 2008; [21] Lee et al., 2009; [22] Kim, 2009; [23] Kang et al., 2011; [24] Kim et al., 2011.

Fig. 2. Brief summary for (A) the history of the Saemangeum reclamation project, (B) temporal changes in the environmental conditions, and (C) temporal changes in the ecological responses by the analysis of meta-data published in the earlier studies (references given).

zone of the Gyehwa transect in 1988, viz., '*A. coffeaeformis*' and '*P. sulcata*', belonged to the group of dominant species in the upper intertidal zone in 2003, as re-identified species of '*A. borealis*' and '*P. fenestrata*', respectively. In general, the species composition of MPB in the upper intertidal zone of the Gyehwa did not greatly differ from each other between two periods, indirectly reflecting the lesser dike effects on benthic floral assemblages in the given area.

Meanwhile, the lower intertidal zone of the Gyehwa tidal flat exhibited quite a bit change in the MPB assemblages in terms of dominant species and their abundances (Fig. 3 and Table 2). First, as noted above, the araphid and monoraphid diatoms such as the genera of *Achnanthes*, *Cocconeis*, *Dimeregramma*, and *Opephora* were predominant in the year of 1988 but never representative in 2003. The dominance of such adnate diatoms, in turn, could suggest the influences of the natural tidal dynamics in the typical tidal flat of the Gyehwa at the time of 1988. It should be noted that the completion of >80% of dikes at the time of 2003 survey would have hampered the tidal dynamics which was clearly supported from the increase of the mud contents of sediments in the given area from 24% in 1988 to 48% in 2003.



C (1988)		A (2003)		D (1988)		B (2003)	
Amphora coffeaeformis	(14%)	*Amphora subholsatica*	(20%)	*Achnanthes hauckiana*	(16%)	*Fogedia coreana* (sp. nov.)	(21%)
Paralia sulcata	(13%)	*Amphora borealis*	(12%)	*Dimeregramma minor*	(11%)	*Navicula* cf. *bipustulata*	(7%)
Cymatosira belgica	(6%)	*Paralia fenestrata*	(6%)	*Opephora martyi*	(7%)	*Amphora borealis*	(6%)
Achnanthes hauckiana	(5%)	*Navicula* sp. 4	(5%)	*Cocconeis* sp. 1	(6%)	*Fogedia densa* (sp. nov.)	(6%)
Navicula sp. 1	(4%)	*Navicula* cf. *flagellifera*	(5%)	*Dimeregramma minor* var. *nana*	(3%)	*Fogedia elliptica* (sp. nov.)	(5%)

Fig. 3. Long-term change (1988 vs. 2003) in dominant species and zonal distribution of microphytobenthos in the Gyehwa tidal flat of the Saemangeum area, the dominant species are given as plates in the two representative groups of flora assemblages (group A and B), of which relative abundances are given in the parenthesis.

Due to the lack of long-term studies on the benthic flora in the Saemangeum tidal flat over the past 20 years, the yearly change of MPB assemblages could not be fully analyzed at this time. However, the apparent change of the dominant taxa during or after the couple of site-specific events, say the construction of series of dikes III, I, IV, and II in timely manner, might indicate the change of environmental conditions in the corresponding periods. For example, in 2003, such environmental changes in tidal energy followed by the modified sedimentary process in the Gyehwa area might have favored the motile biraphid naviculoid diatoms such as *Fogedia* and *Navicula* species (Table 2). Thus the long-term environmental change such as the altered geophysical settings of the Gyehwa area by the embankment has resulted in the corresponding ecological changes in benthic floral assemblages in the given area.

3.2. Benthic faunal assemblages and distribution

Similar to the identified zoning in benthic floral assemblages, the distinct 2 or 3 clustered groups of MZB have been observed in the Saemangeum tidal flat both in the surveys of 1988 and 2004–05 (Fig. 4), which would be a typical pattern of faunal zonation in the Korean tidal flats (Frey et al., 1987; Koh and Shin, 1988; Ryu et al., 2011a). In 1988, three major faunal assemblages were identified along the tidal elevation from eight transects in the Saemangeum tidal flat (Fig. 1A), named as the *Perinereis*, *Macrophthalmus*, and *Bullacta-Mactra-Umbonium* zones (An and Koh, 1992). The two separately grouped zones of the *Perinereis* and *Macrophthalmus* at the upper tidal level in 1988 were found to be combined in 2004–05 survey, say the *Periserrula-Macrophthalmus* assemblage (station group A, see Fig. 4A). The group A species in the 2004–05 survey included five characteristic species; *Sinocorophium japonicum*, *Ilyoplax pingi*, *Perinereis linea*, *Paraleonnates uschakovi* and *Macrophthalmus japonicus*, with common occurrence along the three transects of the Gyehwa, Gwanghwal, and Sandong (Fig. 4). This group species occupied the upper most intertidal zone. The dominant species belonging to the *Bullacta-Mactra-Umbonium* assemblage recorded in 1988 have been slightly changed to comprise the *Umbonium-Meretrix* assemblage (group B, see Fig. 4B) in 2004–05 at the mid intertidal zone.

The forming boundary between group A and group B could be simply explained by two indicators, i.e., mud and/or organic contents (measured) and biogenic structure (observed). For example, the location exhibiting a sharp declines in mud and/or organic contents in bottom sediments consistently was found to be the boundary, in consistent manner, between two identified faunal assemblages along the three transects of the Saemangeum tidal flat. Meanwhile, the water content did not seem to be the factor controlling the benthic faunal assemblages although it was strongly related with shore level in the given area.

However, the assemblage group F identified in the mid-lower intertidal zone of the Sandong transect in 1988, comprising dominant species of *Protankyra bidentata*, *Solen corneus*, and *Owenia fusiformis*, has been replaced with alternative species group, say *Prionospio-Potamocorbula* assemblage (group C, see Fig. 4C), indicating complete change of MZB in the given area after 15 years. The newly formed group C species would have experienced a temporarily favored condition during the embankment of the sector IV,

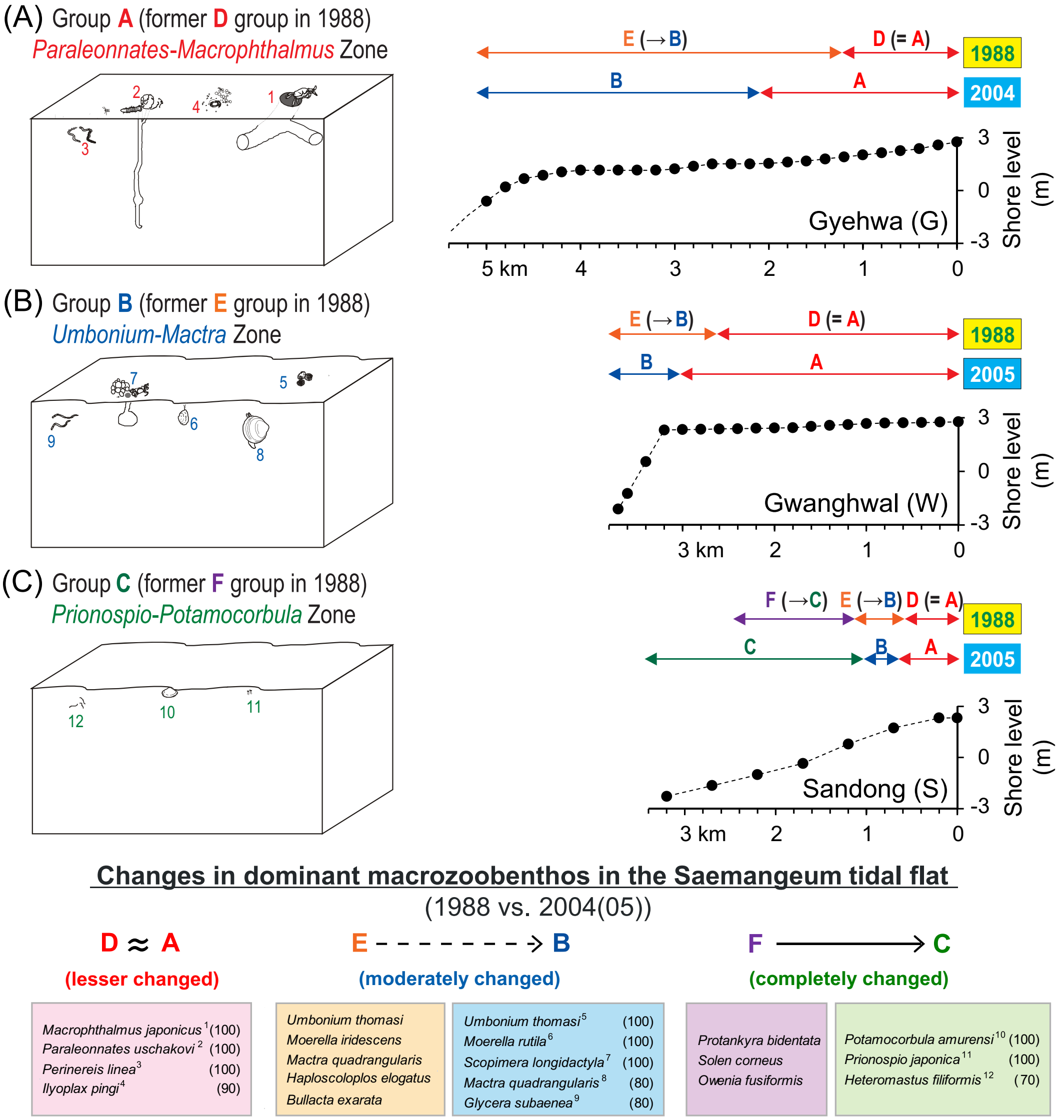


Fig. 4. Long-term change (1988 vs. 2004–05) in dominant species and zonal distribution of macrozoobenthos in the Gyehwa, Gwanghwal, and Sandong tidal flats of the Saemangeum area, the dominant species are illustrated in the three representative groups of fauna assemblages (group A, B, and C), of which relative abundances are given in the parenthesis.

situated nearby the Sandong transect. This assemblage showed relatively high degree of species diversity, abundance, and biomass compared to those in the other two assemblages in 2004–05 study. For example, the biomass of MZB collected in the Sandong transect was found to be approximately one order of magnitude greater than those recorded in the other assemblages.

Such effects could be explained by the fact that moderately nutrient-enriched condition might result in an increase of the species number, species density, and biomass above the level of normal environmental conditions (Dauer and Connor, 1980). In fact, the dike in the sector IV situated in close proximity to the Sandong transect was completed in 2003 (Fig. 1B), a year before the sampling in 2004–05 survey, there should be a reduction in tidal energy followed by the accumulation of finer sediments with higher organic content in the given area (Lee and Ryu, 2008). In anyhow, such rapid changes in physicochemical properties of bottom sediments could have resulted in dramatic changes in species composition and distribution, either promoting or deterring certain specific group of MZB in time and space.

In general, after the dike construction began in 1991, the varying dominant taxa have long been associated with the Saemangeum and sometimes reoccurred with cycling gap of couple years over the past 20 years, for example *Umbonium thomasi* in the intertidal zone and *Heteromastus filiformis* in the subtidal zone as top dominant species for many years (Fig. 5). However, the predominant occurrence of certain species, including newly ranked dominant ones, such as *Theora fragilis* in the lower intertidal zone and *Sternaspis scutata* in the subtidal zone in 2006–07, after completed the dikes, might indicate the accumulated environmental changes in the given area. Further, several species usually found in the organic enriched sediment (Pearson and Rosenberg, 1978) have long been recognized as set of dominant benthos, particularly the polychaete species, *H. filiformis*, occurring cross the intertidal and subtidal areas of the Saemangeum. It should be also noted that several opportunistic species were consistently found in the Saemangeum tidal flat over the past 20 years, reflecting the vulnerable benthic habitat environment through the period of the Saemangeum reclamation project, until recently (Fig. 5).

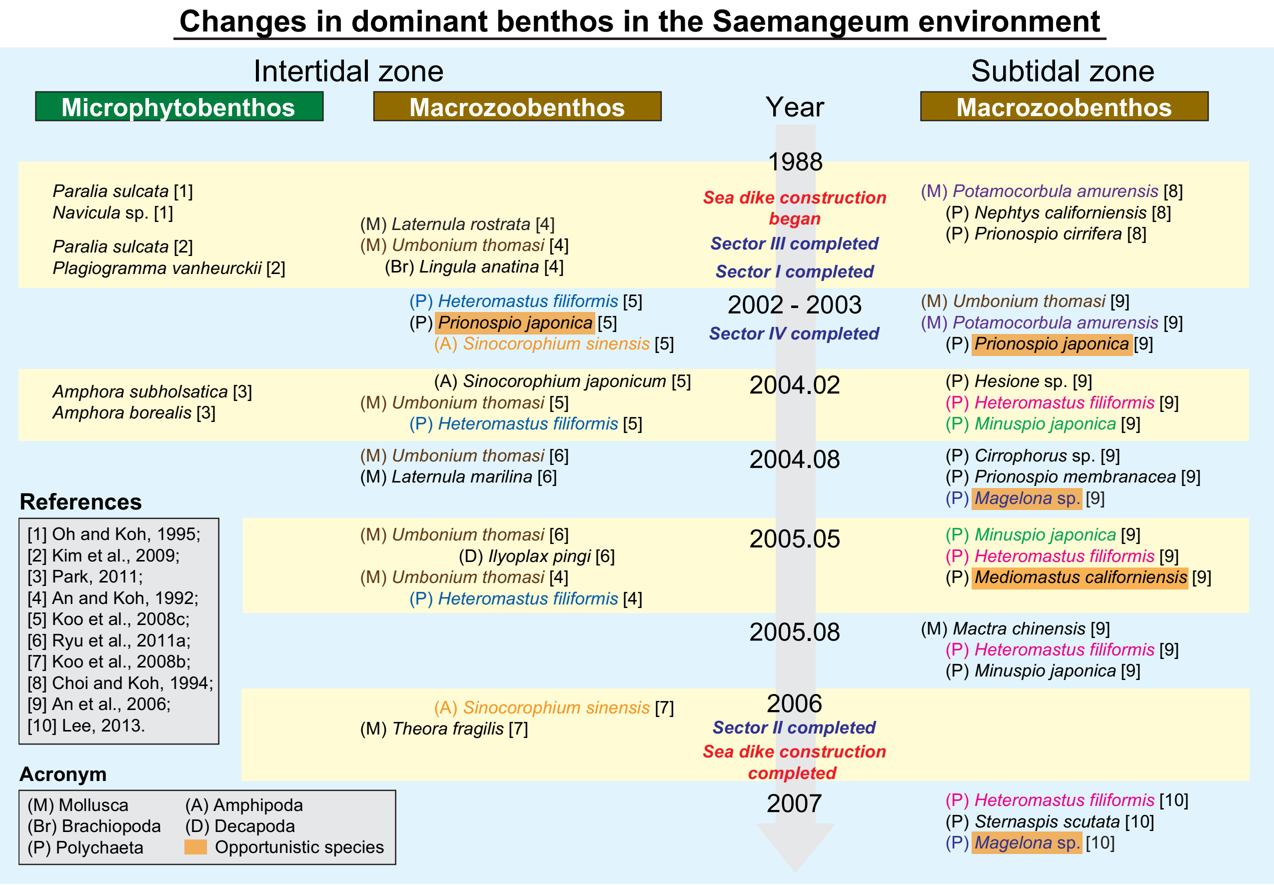


Fig. 5. The dominant microphytobenthos and macrozoobenthos found in the Saemangeum tidal flat since during the Saemangeum reclamation projects, over the past 15 years (references given), listed the spices belonging five taxonomic groups with highlight of the opportunistic species occurred in the intertidal and subtidal zones.

4. Short-term ecological responses

Comparative analysis targeting 15-year biological change revealed relatively weaker community change, for both MPB and MZB, in the upper intertidal zone of the Gyehwa, which could be explained by the lesser change in hydrodynamics along the transect to offshore. While, the faunal assemblage in the lower intertidal zone of the Sandong, as indicated by the species composition, faunal density, and biomass of dominant MZB, has been completely changed during the dike construction in 2004–05. One weakness in such long-term comparison presented in the above section would be a “snapshot” between two time periods, which may not consider the short-term temporal variation of benthic community structure. For this reason our focus has been also given to understand benthic community change with shorter time-resolution, say monthly to seasonal, in the Saemangeum tidal flat. Here we focused on characterizing the seasonal variations of both MPB and MZB in the Gyehwa, which formerly exhibited the greatest biodiversity encompassing both flora and fauna among the several transects of the Saemangeum surveyed in 1988 (Fig. 1A) and 2003–05 (Fig. 1B).

4.1. Spatio-temporal distribution of benthic chlorophylls

We scrutinized the year-round seasonal data (2003–04) obtained in the Gyehwa tidal flat through the series of our Saemangeum study in the 2000s in order to address spatio-temporal variations of the benthic chlorophylls (Chl a; used as an index of MPB biomass). Sampling was designed to find both spatial and temporal distributions of MPB biomass, with systematic grid sampling on a seasonal basis (see green box in Fig. 6) together with transect line sampling on a monthly basis (line G in Fig. 6). The total number of the monitoring locations was 64 (February, May, and November) and 82 (August), nearly covering the entire area of intertidal zone in the Gyehwa (ca. 5 × 5 km^2, 500 m intervals).

First, the concentrations of sediment Chl a varied greatly ranging from 1.3 to 93.1 mg m^{-2}, during the entire period spanning four seasons with large spatial variation reflecting the heterogeneity of MPB assemblages (Fig. 6). A notable increase of benthic algal biomass with much fluctuation over time was observed in the lower intertidal zone of the Gyehwa, particularly elevated in the winter, but general decrease of benthic algal biomass over the following seasons seemed to follow the natural temporal variation.

Interestingly, algal blooming of the dinoflagellates (*Gymnodinium* spp.) was observed in February (winter-early spring), without any solid evidence linking to the dike construction, which brought the elevated concentrations of sediment chlorophylls in the lower intertidal zone of the Gyehwa. Except for the blooming data in this area, overall sediment chlorophylls showed the positive correlation with the mud content in sediment, generally supporting the zonal distribution of MPB assemblages presented earlier (see Section 3.1).

Meantime, looking at the monthly distributions of sediment Chl a in the Gyehwa transect, large seasonal variation was also observed cross the seasons, for example Chl a in winter season (December, January, and February) greatly varied from 2.8 to 33.9 mg m^{-2}, on average, in line G. However it should be noted that such monthly variation fairly weakened approaching fall which in turn supported that the algal heterogeneity has been pronounced due to the winter blooming in the lower intertidal zone. The

Table 2
The comparative summary for the environments and the communities of benthic flora and fauna investigated in the Gyehwa tidal flat of the Saemangeum in 1988 and 2003–05 survey.

Parameter	1988 survey		2003–05 survey	
Environment				
Shore level (cm + MSL)	−50–120		−60–276	
Mud content (%, Mean ± SD (range))	24 ± 20	(4–56)	48 ± 18	(26–98)
LOI (%, Mean ± SD (range))	1.6 ± 0.6	(1.0–2.9)	1.5 ± 0.4	(1.2–3.0)
Benthic community				
1. Microphytobenthos[b]				
Number of species	232		194	
Mean density (10^4 cells cm^{-2})	75.7		3.9	
Density dominant flora (10^4 cells cm^{-2})	*A. haukiana*	7.4 (10%)	*A. subholsatica*	(11%)
	P. sulcata	6.9 (9%)	*A. borealis*	(9%)
	A. cofeaeformis	6.1 (8%)	*F. coreana*	(8%)
	D. minor	4.4 (6%)	*A. aff. spartinetensis*	(4%)
	O. martyi	3.0 (4%)	*N. cf. flagellifera*	(4%)
2. Macrozoobenthos[c]				
Number of species	38		51.0	
Mean density (indiv. m^{-2})	19 023 (1 374)[a]		426	
Mean biomass (g AFDW m^{-2})			3.9	
Fauna taxa composition				
Number of species				
Polychaeta	18	(47%)	17	(33%)
Mollusca	13	(34%)	15	(29%)
Crustacea	6	(16%)	14	(28%)
Brachiopoda	1	(3%)	1	(2%)
Others	0	(0%)	4	(8%)
Density				
Polychaeta	272	(1%)	213	(23%)
Mollusca	18 331	(96%)	421	(45%)
Crustacea	40	(0.2%)	261	(28%)
Brachiopoda	380	(2%)	41	(4%)
Others	0	(0%)	9	(1%)
Biomass (AFDW)				
Polychaeta			0.8	(10%)
Mollusca			4.5	(52%)
Crustacea			1.1	(12%)
Brachiopoda			2.1	(25%)
Others			0.1	(1%)
Density dominant fauna (indiv. m^{-2})	*U. thomasi*	17 649 (96%)	*U. thomasi*	125 (29%)
	L. unguis	380 (2%)	*I. pingi*	56 (13%)
	N. festivus	253 (1%)	*M. rutila*	37 (9%)
	L. cf. limicola	193 (1%)	*S. japonicum*	25 (6%)
	M. iridescens	96 (1%)	*G. subaenea*	24 (6%)
Biomass dominant fauna (g AFDW m^{-2})			*L. unguis*	0.9 (24%)
			M. petechialis	0.8 (20%)
			U. thomasi	0.4 (10%)
			M. quadrangularis	0.3 (9%)
			C. sinensis	0.2 (6%)

[a] Excluded *U. thomasi*.

[b] Full name for floral species (in order of appearance): *Achnanthes hauckiana* (*A. hauckiana*), *Paralia sulcata* (*P. sulcata*), *Amphora coffeaeformis* (*A. coffeaeformis*), *Dimeregramma minor* (*D. minor*), *Opephora martyi* (*O. martyi*), *Amphora subholsatica* (*A. subholsatica*), *Amphora borealis* (*A. borealis*), *Fogedia coreana* (*F. coreana*), *Amphora* aff. *Spartinetensis* (*A.* aff. *Spartinetensis*), and *Navicula* cf. *flagellifera* (*N.* cf. *flagellifera*).

[c] Full name for faunal species (in order of appearance): *Umbonium thomasi* (*U. thomasi*), *Lingula unguis* (*L. unguis*), *Nassarius festivus* (*N. festivus*), *Laternula rostrata* (*L. rostrata*), *Moerella iridescens* (*M. iridescens*), *Ilyoplax pingi* (*I. pingi*), *Moerella rutila* (*M. rutila*), *Sinocorophium japonicum* (*S. japonicum*), *Glycera subaenea* (*G. subaenea*), *Meretrix petechialis* (*M. petechialis*), *Mactra quadrangularis* (*M. quadrangularis*), *Cyclina sinensis* (*C. sinensis*).

increased benthic algal biomass in the muddy bottom of the mid intertidal zone and reduced biomass in the lower sand area (i.e., northwest locations) simply indicated the shore-level associated benthic algal distribution in the given transect.

In anyhow, the single parameter only could not seem to explain the spatio-temporal distributions of benthic algal biomass in the intertidal zone apparently due to the combined effects of physical and biological components in the field. The characteristics of winter blooming observed in the Gyehwa area have been reported in the previous reports in the similar environments of tidal flats, for example, in the Ariake Sea, Japan (Koh et al., 2007), the Peel-Harvey Estuary, Australia (Lukatelich and Mc Comb, 1986), and the Tagus Estuary, Portugal (Brito et al., 2013). In general, those winter blooming was associated with high nutrients, increasing insolation, differences in day-length, and temperature effects etc., but those effects could not be clearly seen in the Gyehwa case. At present, it may not be appropriate to directly link the benthic algal assemblages or distribution into the effects of dikes (sectors I and II) off the Gyehwa in 2004, thus the site-specific algal blooming including MPB remains in question for biological feedback when addressing the impact of the embankment in the given area.

4.2. Community structure of macrozoobenthos

Earlier, we found the long-term biological change in MZB assemblages between 1988 and 2004–05, by emphasizing the changes of several environmental parameters (Table 2). Looking closer the very variations, we reanalyzed the seasonal distributions of several geochemical parameters including mud content, organic content, water content, and shore level, of which levels and distributions would be associated with MZB distribution over time (Fig. 7). As being obvious the lesser degree of the environmental changes over seasons in 2004–05, particularly compared to that observed in the 15 year-difference, the benthic environment, at least sedimentary geochemical components, did not seem to undergo significant changing over the shorter time periods (viz., monthly to seasonal). Only exception was slight increase of mud content in the lower intertidal zone during the winter by ~15%, on average (Fig. 7A).

Meantime, with not being surprised, great spatial variations were found for all measured environmental parameters, reflecting their gradients to the shore level, in other words the duration of exposed time in the tidal flat. In particular, the species composition of MZB cross the entire area of the Gyehwa exhibited a close relation to mud content and such relationship seemed to be fairly consistent over time. For example, the mud-favoring species, such as *P. linea*, *P. uschakovi*, *M. japonicus*, and *I. pingi* were primarily found in the upper intertidal zone in consistent manner. Next, the sand-favoring species, *Aricidea pacifica, Mactra quadrangularis*, *Monoculodes koreanus*, and *Nephtys polybranchia* mainly occurred in the lower intertidal zone of the Gyehwa. Meanwhile, several species, *Lingula unguis, Lumbrineris nipponica, Spio filicornis* and *U. thomasi*, dominated in the intermediate positions between muddy and sandy bottoms, with apparent characteristics of high biomass. The spatial distributions and gradients for both parameters of mud content and organic matter (Fig. 7B) seemed to be influenced by the geomorphology of tidal channels together with shore level shaping in the Gyehwa tidal flat, as supported by their significant correlations. However, the organic content seemed not to be as sensitive as the mud content for identification of spatial distributions of MZB, considering the narrow range of organic content (1.25–1.66%) for the median of species occurrence in the given area (Ryu et al., 2011b).

For this reason, the cluster analysis indicated three representative assemblages of MZB from the upper to the lower intertidal

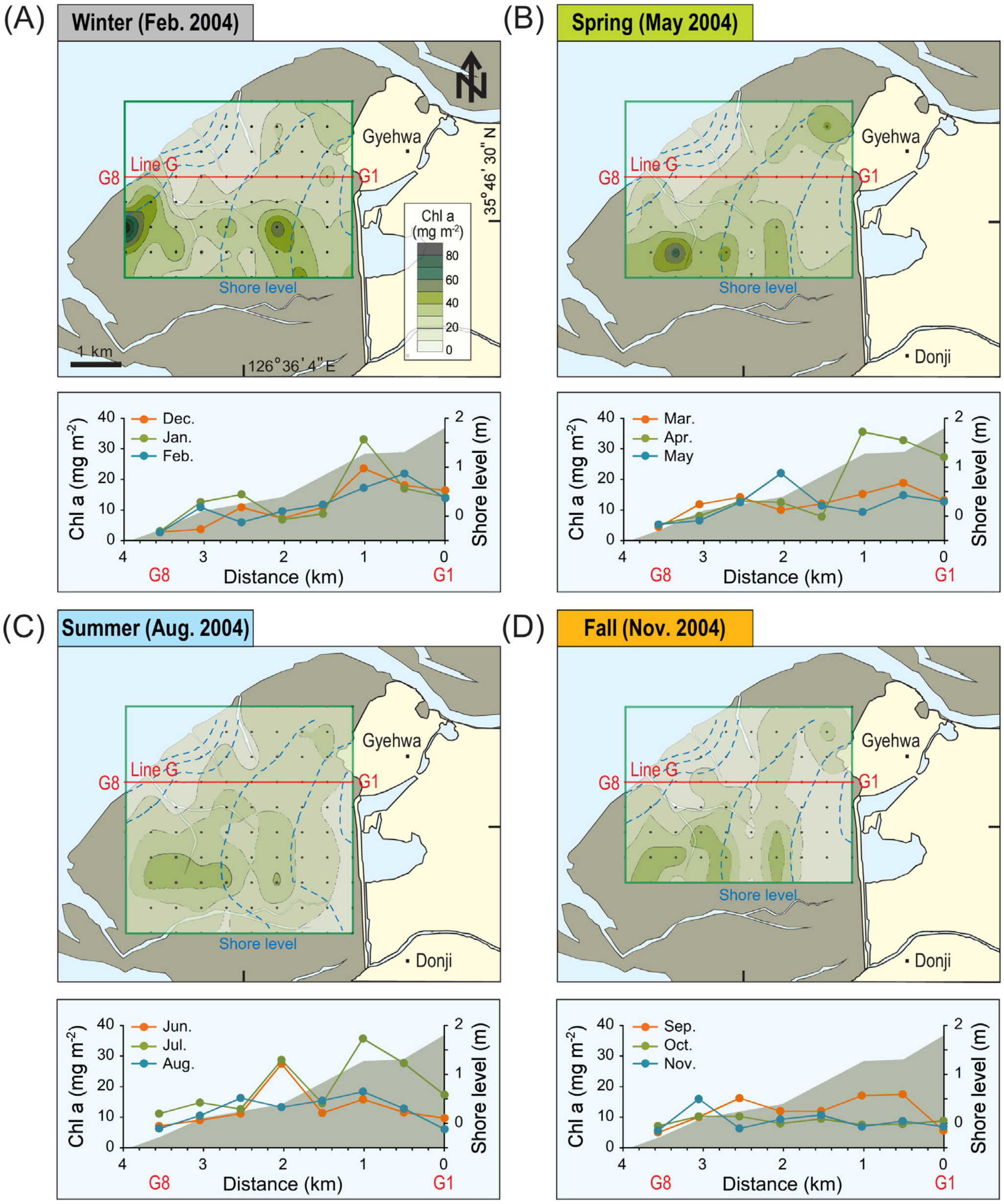


Fig. 6. Spatio-temporal distributions of benthic chlorophylls in the Gyehwa tidal flat of the Saemangeum, with seasonal distributions in two dimensional grid samplings and monthly distribution on the transect sampling (line G) from the year-round survey in 2004. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

zone of the Gyehwa (Fig. 7D), which could be expected by the clear gradients of shore level, mud content, and organic matter content. The lack of variations in mud and organic contents with similar degree of gradients over four seasons together with the lesser change of benthic faunal assemblages indicated relatively stable environmental conditions during the period of 2004–05 survey, in general. However, it should be noteworthy in that the slight change in species composition within the major corresponding groups seemed to increase approaching winter season. For example group B', separately allocated in the lower intertidal zone from the original group B, occurred in fall and winter at one location with high density increase of *Prionospio japonica*. Also, two locations of the group A″, formerly belonging to the group A, having no *P. uschakovi* and *M. japonicus*, were found in the most upper intertidal area in winter only. Such modified community structure, though slight but somehow impactful for certain species, would be combined effects of the numerous environmental parameters being naturally and/or eventually changed. At this time, the BIO-ENV analysis indicated that the combination of shore level and mud content best matched the faunal distribution in all seasons, thus possible topographical and/or geomorphological changes of tidal flats might influence the seasonal to year-round biological changes in the given area and time. Overall, the MZB did not seem to be as sensitive as the MPB in terms of short-term benthic community response, considering the lack of faunal changes in species composition over the full seasons covered by the year of 2004–05 survey (Figs. 6 and 7).

5. Outlook for further research and management

Since the original Saemangeum project launched in 1991, the social and institutional situation has long been changed during the past two decades and a totally different plan came out at present

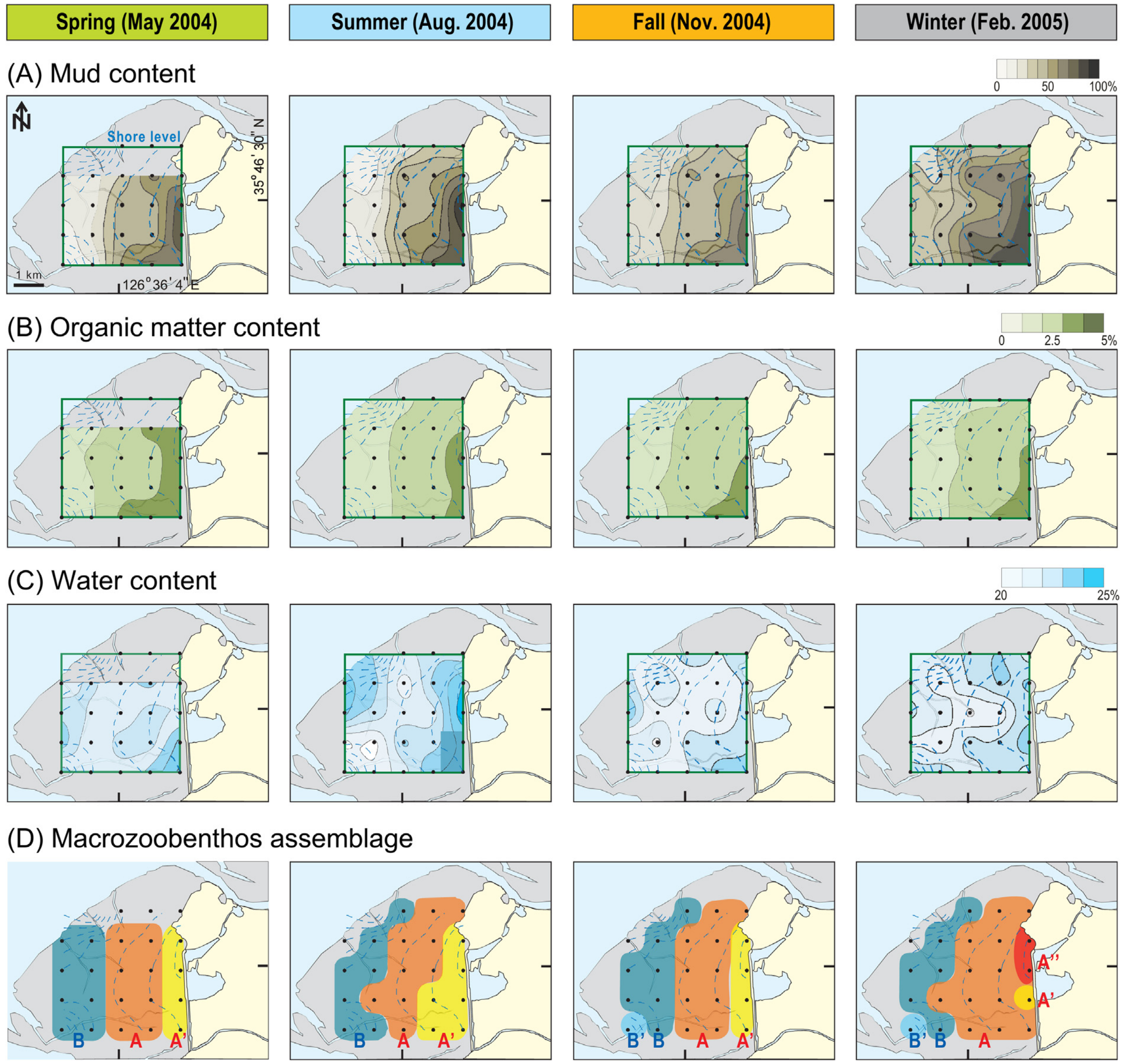


Fig. 7. Spatio-temporal distributions of (A) mud content, (B) organic matter content (loss on ignition), (C) water content in surface sediment, and (D) macrozoobenthos assemblage (grouped by cluster analysis) in two dimensional grid samplings in the Gyehwa tidal flat of the Saemangeum from the year-round survey in 2004–05.

(Table 3). Recently, the SAPSP (a new law supporting the project) was legislated in 2007 and the policy revision made in 2011 now supports the sustainable development of the Saemangeum by emphasizing the industrial and urban uses (now 70%), together with agricultural uses (reduced to 30% now, originally 100%) (Table 1). More recently, the Saemangeum Development Agency was established in 2013 to efficiently implement the SMP (Table 3). The SMP set the new plan for developing the inside of dike and Saemangeum New Port by 70% completion until 2020, with increasing budget of 12.3 billion USD.

Although the future of the Saemangeum seems to be full of bright hope in the governmental side, the Saemangeum issues seem to follow the bad example of the Lake Shihwa (Lee et al., inpress), particularly considering the historical debates on every aspect of environment, community, and management processes from the beginning to the present. One positive aspect would be the policy shift concerning pollution issues both inside (same as the Lake Shihwa) and outside of the dike. A total of ~2.8 billion USD has been allocated to invest water quality improvement in the lake Saemangeum, more targeting watershed environment by 2020. However, it would be a challenge to meet the goal of water quality (grade IV–III) considering the past experiences related with the similar cases including the Lake Shihwa (Lee et al., inpress). Recently, one model case for the partial improvement of water quality from the severely polluted region of the Masan Bay, Korea suggested the total pollution load management system as a promising water quality management tool in Korea (Chang et al., 2012). In anyhow, if not carefully treated at all, it is highly probable that the Saemangeum would follow the Lake Shihwa case that the government finally abandoned the original desalination plan of the lake after spending a lot of money. This is why the Saemangeum project should have been canceled earlier at least when nationwide citizen's campaign for breaking off the Saemangeum project prevailed in the early 2000s, by timely recognition of such “unthinkable” governmental policy in Europe.

In this study, we tried to best deliver the long-term environmental and ecological changes against the corresponding years of the Saemangeum project over the past 20 years, though limited

Table 3
Comparative description on the reclamation project of the Saemangeum area at the early stage and present.

Category	At early stage (as of 1991)	At present (as of 2013)
Legislation	Agricultural Community Modernization Promotion Act, Public Waters Reclamation Act	Special Act on Promotion of the Saemangeum Project (2007)
Organization(s)	Ministry of Agriculture and Forestry, Korea Development Institute	Office of the Prime Minister, Saemangeum Development Agency (2013)
Objective(s)	Reclaimed agriculture land, water resources, welfare for farming and fishing village	Converted to Saemangeum Master Plan (2011)
Target regions	19 towns, 3 counties (Buan, Gimje, Okgu) in Jeollabuk-do province	Same as left
Area for reclamation	283 km^2 (agricultural land) & 118 km^2 (lake, additional)	86 km^2 (agricultural land) & 197 km^2 (industrial area etc.)
Facilities	32.8 km of sea-dike, 2 sea-dike sluices (470 m)	Listed Saemangeum dike in "Guinness World Records" as the longest man-made sea barrier (33.9 km)
Project period	1991–98: construction of sea-dike 1999–04: development for inside of dike	2006: Saemangeum sea-dike completed 2011–20: development for inside of dike and Saemangeum New Port (aimed 70% completion)
Investment (as year of)	Planned total: 1.2 billion USD spent in 1991–06: 3.4 billion USD	Planned total: 21.2 billion USD • Land development (~50%), infrastructure (~30%), others (~20%) 1st period in 2011–20: 12.3 billion USD 2nd period after 2021: rest of planned (ca. 8.9 billion USD)

data presented and/or supported. In fact, a long-term monitoring program led by the government has been conducted during the past 20 years but on an irregular basis (Table 1). In 2000s, such efforts has been continuing but limited to outer areas of the Saemangeum dikes, thus the environmental impacts in the tidal areas have long been out of concerns after completion of dike construction (Koh, 2014). Besides, the monitoring program mainly considered the physical environment not being much linked to the ecosystem health, accordingly the solid linkage of ecological changes due to the physical and sedimentological alterations could not be well addressed (Park et al., 2014). Of note, a limitation in ecosystem study also resulted in difficulties in interpreting such cause–effect association as the biological components targeted in the monitoring program have not been documented in a periodic or consistent manner.

In anyhow, the set of ecological data from the intensive investigations by our group before (1988) and during the dike construction (2003–05) generally supported the sound before-after analysis in terms of long-term ecological responses in relation to the embankment (An and Koh, 1992; Ryu et al., 2011a). In this year, a 10-year interdisciplinary monitoring and modeling study on the Saemangeum coastal area was newly launched, of which project targets were water quality and ecosystem health. This particular monitoring program aimed to estimate pollutant loadings from watershed, and to minimize environmental impact of the Saemangeum development and land use on marine ecosystems. In order not to repeat the Lake Shihwa case that totally wasted great amounts of environmental, social, and economic costs, the Saemangeum management needs to focus primarily on the ecosystem and science based policy, not being undervalued as political engine.

The Saemangeum and Lake Shihwa projects would be two representative examples, say the worst, of massive landfilling action to inevitably destroy the natural and productive ecosystem of the tidal flats in the past. Currently, the similar projects with different name of construction projects are still planned to build tens of kilometer tidal barrages, for example three tidal power plants in the Gyeonggi Bay and Garorim Bay, Korea. Such irreversible projects are never permitted again by the development-oriented policy, otherwise the environmental and socio-ecological costs will be delivered to the future generations by repeating the same mistakes. The future direction toward conservation shifting from the former developmentalism such as grand reclamation projects might be demanding high amount of economic costs. However, the accumulated efforts toward wetland protection collectively given by various stakeholders including environmental groups, religious groups, academic experts, and journalists would be a promising and worth of investment for the future generation (Koh, 2014).

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