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Natural purification capacity of tidal flats for organic matters and nutrients: A mesocosm study

Taewoo Kim[a,1], Junsung Noh[a,1], Bong-Oh Kwon[b], Changkeun Lee[a], Beomgi Kim[a], Inha Kwon[a], Seongjin Hong[c], Gap Soo Chang[d], Won Keun Chang[e], Jungho Nam[e], Jong Seong Khim[a,*]

[a] School of Earth and Environmental Sciences & Research Institute of Oceanography, Seoul National University, Seoul 08826, Republic of Korea
[b] Department of Marine Biotechnology, Kunsan National University, Kunsan 54150, Republic of Korea
[c] Department of Ocean Environmental Sciences, Chungnam National University, Daejeon 34134, Republic of Korea
[d] Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, SK S7N 5E2, Canada
[e] Korea Maritime Institute, Busan 49111, Republic of Korea

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ABSTRACT

The regulating services by natural tidal flats to purify organic pollutants are increasingly recognized, but a quantitative assessment is very limited. We developed a mesocosm system to determine removal efficiency of organic matters and nutrients by simulating a natural tidal condition. The tidal flat sediments significantly removed waterborne organic pollutants to background levels in ~2 and 6–7 days for COD and TP, respectively. This rapid removal of organic matters by natural sediments could be attributed to the microbe community degrading the corresponding pollutants. Temporal trend and degree of removal rates for COD and TP were similar between the bare tidal flat and the salt marsh. Meantime, the salt marsh environment removed waterborne DIP much quickly and also efficiently, implying a high affinity of halophytes on dissolved organic matters. Of note, sedimentary organic sink prevailed in defaunated condition under the smaller bioturbation effect. A mini-review on the purification capacity of natural and/or constructed coastal wetlands generally supported a high efficiency of vegetation to remove various sources of organic matters.

1. Introduction

Marine environments are currently experiencing intense pressure from anthropogenic driving forces due to high settlements along coastlines. Accordingly, increasing shortage of space and resources on land would cause the socio-economic demands for overexploitation to expand (Atkins et al., 2011; Borja and Dauer, 2008). Especially, tidal flat, where is the closest from the land, is one severely polluted region by discharge of various industrial and domestic effluents. Since marine sediment has been suggested as a final sink for organic pollutants, their continuing inputs to coastal areas can produce a wide range of deleterious effects on various marine lives. Such anthropogenic impacts include coastal eutrophication, harmful algal blooms, and declining aquaculture production and fisheries (Lee et al., 2018a; Hong et al., 2010). Thus, the role and function of tidal flat or salt marsh in the marine environment have been the subjects of recent intensive research in aspect of tidal flat's pollution control (Koo et al., 2011; Winberg et al., 2007; Yamochi, 2008).

Tidal flat is recognized as active buffer zone in the transport of nutrients and organic compounds between land and sea (Levin et al., 2001). Population growth, urbanization, and industrialization would augment organic matter and nutrient loads to the tidal flats. Imbalance between the pollutant loads and natural purification capacity in tidal flats could change the role of coastal sediments from a source of nutrients to a purifier. The role of sediments in organic matter and nutrient cycling has been highlighted primarily from the standpoint of carbon and nutrient turnover (Hu et al., 2006). For example, the role of sediment microbes to degrade organic matters has been known to contribute the overall purification function of tidal flats (Yagi and Terai, 2001). Several studies relating to the tidal flat restoration or artificial construction have also confirmed the ability of tidal flats to purify land-driven pollutants and nutrients (Hou et al., 2003; Lee et al., 1998). The results rekindled recent interest in restoration and protection of the tidal flat of Tokyo-Yokohama Bay in Japan (Hong et al., 2010) and the Atlantic and Pacific coasts as well as one along the Gulf of Mexico in USA (Turner et al., 2004). After restoration and protection

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[*] Corresponding author.
E-mail address: jskocean@snu.ac.kr (J.S. Khim).
[1] These authors contributed equally to this work.

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of these tidal flats, some positive effects on increasing the distribution of living organisms and root biomass were documented (Furukawa, 2013).

Since the early 1980s, the Korean Ministry of Oceans and Fisheries have designated the so called "special management area (SMA)" to protect the marine environment and ecosystem under significant risk by environmental deteriotation (MMAF, 2002). The SMA includes terrestrial areas that primarily contribute to marine pollution. Five coastal areas in Korea have been designated as SMAs to date, and Masan Bay was the first designated SMA in 1982 (Lee et al., 2016). To improve the water quality in SMAs, the Korean government has launched the Total Pollution Load Management System (TPLMS) and first applied it to Masan Bay in 2008. TPLMS contributed to the reduction of nutrients by sewer system improvement, technical upgrading of the two wastewater treatment plants (WWTPs), and an intensive river clean-up (Chang et al., 2012). However, despite substantial efforts, the concentrations of chemical oxygen demand (COD) and total phosphorus (TP), which are the water quality targets, have remained unchanged (Park et al., 2018). This issue drove the Korean government to implement various actions for enhancing the water-quality elements from prevention to post-treatment. Bongam tidal flat, situtated in Masan Bay SMA, has received increasing public attention as it is the only tidal flat located in a trading port and has been damaged by the construction of industrial and housing complexes since the 1960s. Significant efforts have been recently devoted to restore the deteriorated Bongam tidal flat from industrialization and urbanization (Lee et al., 2020).

In the present study, we designed an enclosed experimental ecosystem (viz., mesocosm) to evaluate the purification capacity of tidal flat sediments for waterborne organic matters and nutrients. Mesocosm has been suggested to have the potential to serve as a powerful tool for testing and expanding our understanding of the mechanisms that drive ecological dynamics in the coastal zone. The present study specifcally aimed to 1) evaluate the purification capacity of a tidal flat under extreme nutrient exposure, 2) compare removal rate of organic matters and nutrients between bare tidal flat and salt marsh, and 3) provide natural purification capacity of the Bongam tidal flat of Korea, along with a mini-review.

2. Materials and methods

2.1. Study design and development of mesocosm system

A mesocosm system was developed to simulate and control the tidal cycle of the intertidal area. A system consisted of three compartments; 1) one aquarium with sloped bare tidal flat and salt marsh bed, 2) the other aquarium serving as a reservoir of water during the tidal cycle, and 3) pump which controls the water transfer rate between two aquariums. From the aquarium containing the influent, the water is transferred to a sedimentary aquarium for 4 h and stays there for 2 h. The water was then transferred to the reservoir aquarium for 4 h. The two aquariums were mounted in a thermal water bath, where the temperature was maintained at 18 °C using a temperature control system (Table S1).

Two separate experiments were designed and conducted depending on the topic. First experiment aimed to evaluate the purification capacity of organic matters and nutrients by the bare tidal flats. Three treatments (low, medium, and high groups) with varying initial waterborne concentrations of organic matters and nutrients were tested (Fig. 1a). The concentration gradients of organic pollutants were adjusted by having the sediment spiked with the standard materials (Glucose; KH_2PO_4, Sigma Aldrich). Of note, the initial COD concentrations in the low, medium, and high treatments were set to ~10, 15, and 40 mg L^{-1}, respectively. TPs in the corresponding treatments were set to ~0.1, 0.2, and 0.25 mg L^{-1}. Of note, the initial COD and TP given in the low treatment were about twice greater than those measured in influent water flowing into Bongam tidal flat in Masan Bay (Fig. S1). Seawater sampling was carried out daily during 14 days of experiment to monitor the water quality (COD and TP).

Second experiment utilized the organic enriched sediments collected from study area, in order to address the purification capacity of tidal flats (Fig. 1b). In particular, we focused on the evaluation of natural purification in absence of faunal activities (viz., bioturbation) and under vegetated environment. Two treatments were tested; one for the defaunated sediment, simulating the bare tidal flat, and the other for the vegetated one, modifying salt marsh system. Of note, eight *Phragmites australis* plants covering one-third of the sloped sediment area (0.2 m^2) were transplanted to modify the natural vegetated density in the upper intertidal flat of study area. During the 6 days of experiment, both seawater and sediment samples were collected twice every day, considering tidal cycle (viz., inflow and outflow) and general water and sediment qualities are monitored, as described below.

2.2. Sampling and data analyses

Sediments and seawater samples collected from mesocosm treatments (Fig. 1) were analyzed following the standard methods described elsewhere (APHA-AWWA-WPCF, 1981; Lee et al., 2019). First, sediment samples were analyzed for total organic carbon (TOC), TP, and total nitrogen (TN). The sediment was decalcified with 10% hydrochloric acid (HCl), washed twice with deionized water, and freeze-dried for TOC determination. The TOC and TN were measured using an Elemental Analyzer-Isotope Ratio Mass Spectrometer (EA-IRMS) (Elementar, Gmbh, Hanau, Germany). The water samples were analyzed for various parameters, including, COD_{Cr}, TP, and dissolved inorganic phosphorus (DIP).

t-test was carried out to determine the significant difference between the mesocosm experiments using Sigma Plot (Version 10.0, Chicago, IL).

3. Results and discussion

3.1. Purification under waterborne organic matters and nutrients in tidal flat

Three concentration gradients in the mesocosm were designed to determine how much organic matters and/or nutrients can be purified in seawater and sediment under extreme concentration exposures (Fig. 2). The initial concentration of COD was 10.3 mg L^{-1}, 15.6 mg L^{-1}, and 39.7 mg L^{-1}, respectively, and total phosphorus was set to 0.09 mg L^{-1}, 0.21 mg L^{-1}, and 0.26 mg L^{-1}. A day after the exposure (D + 1), the removal rates of COD were obtained to be 7.7 and 8.4% in the low and medium groups, respectively, while the high group exhibited much larger removal rate of 48.1%. The COD concentration in the low group tended to decrease continuously, and on 13th day (D + 13), the lowest concentration was detected. In the medium and high groups, there was a significant tendency of COD decrease from D + 1 to D + 2. After that, the saturation state began to occur until D + 14 in both groups. The lowest concentration was detected in the medium group at D + 14 and in the high group at D + 13. The initial concentration of COD was halved after 1–2 days in the high group (purification half-life, PHL). Consequently, it was confirmed that 47.2, 71.2, and 77.7% of COD were removed during 14 days in the low, medium, and high groups, respectively. TP showed a similar tendency as COD. At the low group, the concentration steadily decreased, and the saturation was reached on D + 3 (0.04 mg L^{-1}). The medium group showed the greatest reduction on D + 2 and the saturated state after D + 4 (PHL = 5 days). The greatest decrease was observed on D + 1 in the high group, and the concentration tended to remain constant from 0.07 ± 0.02 mg L^{-1} after D + 6 (PHL = 7 days). The removal rate in TP was determined to 52.4%, 64.7%, and 71.7% in low, medium, and high groups, respectively. Organic matters and nutrients which were targeted in this study, initially decreased rapidly and remained constant

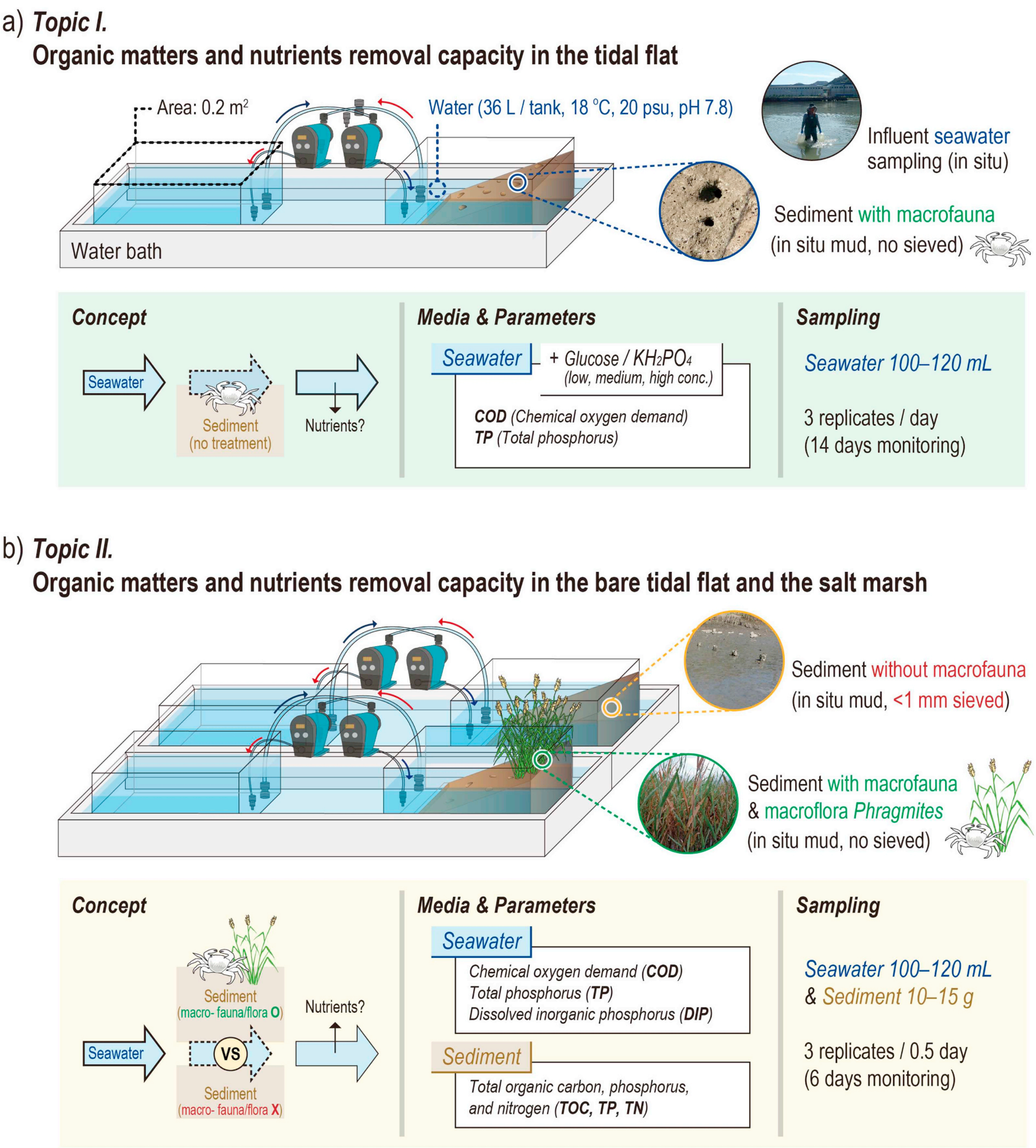

Fig. 1. Overview of workflow and experimental design for the evaluation of purification capacity in bare intertidal flat and salt marsh by use of mesocosm experiments.

over time. In particular, such a trend was clearly identified when the exposure concentration was high.

The core of the tidal flat's purification capacity is the ability of microorganisms to remove organic matters and nutrients introduced into tidal flats. Tidal flats provide sedimentary layers with oxygen through disturbance, submergence, and exposure of the surface sediments from water, enabling the more effective aerobic decomposition process. The decomposition of land-based organic matters thus becomes very active in the tidal flats (Howes et al., 1984; Jørgensen, 1977). Bioturbation of sediments through marine organism movements increases oxygen content in sediment-water interface. It could cause an increase in the purification of nutrients such as denitrification (Harada et al., 2014; Allen and Vaughn, 2009). And also, there are many studies on the removal of nutrients by microorganisms, and effective microbes (EM) have been developed for purifying the water quality. Lee et al., 2018 reported that Verrucomicrobiaceae and Planctomycetia, which are known to dominate in sludge and influent from treatment halophytes, showed relatively high abundance in Masan Bay (ElNaker et al., 2018). Verrucomicrobiaceae can be shown to grow and degrade nutrients at the early stage of exposure to high concentrations of nutrients according to this study. And also, it is well known that Planctomycetia plays an important role in the biogeochemical cycle in the marine environment, and rapidly uptake and degrade the nutrients (Zhang et al., 2019). The reduction of organic matters and nutrients at the initial stage can result in the deposition of organic particles present in the influent to the sediment during the exposure time and the use of microorganisms in the organic particles and nutrients. However, the amount of organic matters and nutrients that microbes can uptake is

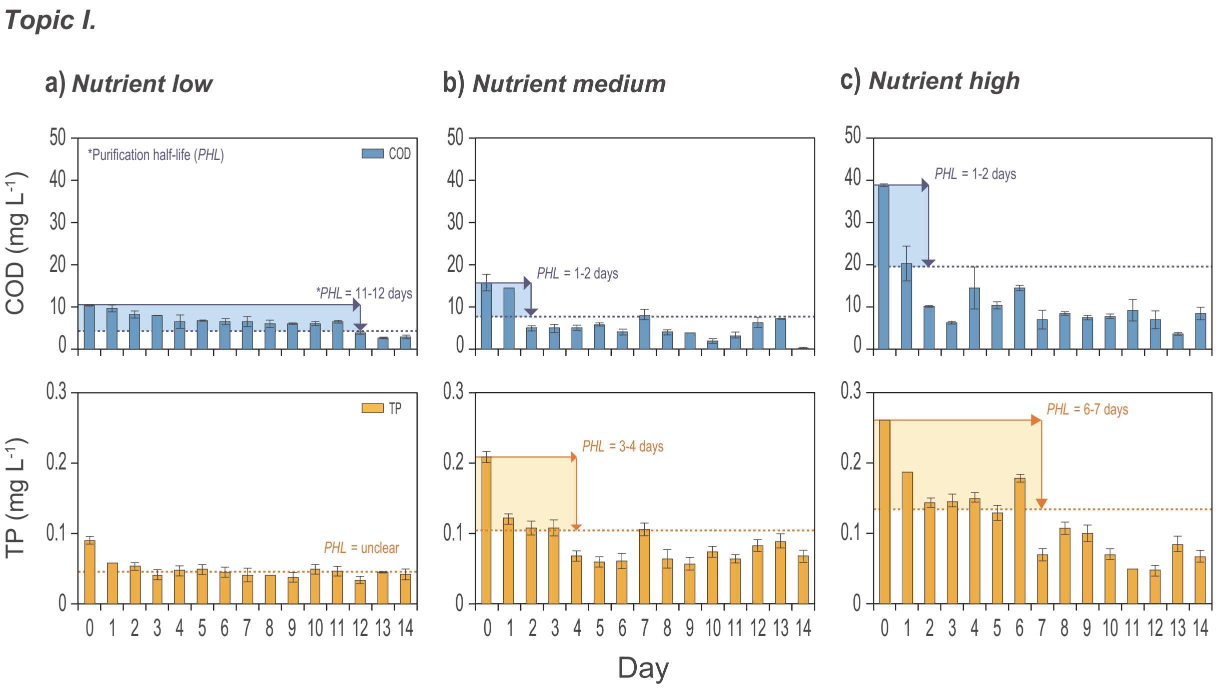

Fig. 2. Comparisons of purification capacity in water quality (COD and TP) depending on the gradients of initial concentrations of organic pollutants given by three groups; low, medium, and high. After initial waterborne exposure of organic matters and nutrients, concentrations of target water quality were daily monitored during the 14 days of experiments. Line over bars indicates the purification half-life (PHL) of organic matters and nutrients. Refer to the background concentrations in collected sediment from Bongam tidal flat and Masan Bay in Fig. S1.

limited, and if organic matters and nutrients are adsorbed at non-biological adsorption sites, microbes can no longer use them. In addition, change in the chemical composition in the sediment-water mixture due to microbes eventually leads to the equilibrium of organic matter and nutrient degradation (Kahl et al., 1993; Zhang and Huang, 2011).

3.2. Comparison of purification capacity between bare and vegetated sediment

We investigated whether the presence of halophytes can enhance the purification of organic matters and nutrients in the water (Fig. 3 and Table 1). The experiments were conducted in the same environmental condition after sieving to minimize the influence of bioturbation. *P. australis* were selected and transplanted into the mesocosm for comparison with bare tidal flat. COD, TP, and DIP were parameters indicating water purification parameters. Whilst OM, TOC, and TN were for sediment purification (Fig. 4). During the experiment periods, water and sediment samples were collected and analyzed. In the bare tidal flat, on average, 5.20, 0.20, and 0.02 mg L^{-1} of removal capacity in COD, TP, and DIP were obtained, respectively, from the renewal treatments (i.e., total of 11 samples at 12 h intervals for 6 days). Same orders, for the salt marsh, 6.50, 0.17, and 0.14 mg L^{-1} of removal in COD, TP, and DIP were obtained, respectively. Based on accumulated amounts of DIP and COD indicated greater capacity in salt marsh treatments compared to the that of bare tidal flat. Remarkably, 7 times efficiency observed for DIP in salt marsh sediments (0.14 mg L^{-1}) than bare tidal flats (0.02 mg L^{-1}). Despite greater removal capacity of both DIP and COD in salt marsh experiments, similar accumulated removal capacities were observed in TP treatments (Fig. 3). On the other hand, OM, TOC, and TN showed reversal trends compared to the water parameters, at the end of experiments, the amounts of sediment parameters increased in all treatments (Fig. 4). For COD, TP, and DIP in the bare tidal flat treatments, on average, 3.40, 3.50, and 0.47 mg L^{-1} of accumulation capacity were obtained, respectively, whilst 1.40, 1.80, and 0.39 mg L^{-1} of accumulation capacity were obtained in salt marsh, respectively. Accumulation capacities for OM and TOC in bare tidal flat treatments indicated approximately over doubled compared to that of salt marsh treatments. There was no distinctive trend between bare tidal flat and salt marsh for TN. Altogether, these results suggest that organic matters and nutrients in the form of particles can be decomposed and removed more efficiently than those in the dissolved state after the accumulation of organic matters.

Organic matters and nutrients are mainly removed by adsorption and sedimentation, as well as intake by environmental organisms (Imfeld et al., 2009). It is also reported that iron (Fe) and aluminum (Al) present in the tidal flat promote the precipitation of phosphorus. Phosphorus is known to react rapidly with inorganic components such as Al, Fe, and Ca, as well as sediments (Nichols, 1983). The concentrations of COD and TP can decrease due to sedimentation and the microbial response to organic matters and nutrients after the influent flowed into the aquarium, but no significant difference in removal rate of COD and TP was found between the bare tidal flat and salt marsh in this study. Previous studies have emphasized the role of vegetation in the fate of phosphorus in tidal flat or wetland (Fisher and Acreman, 2004). The presence of vegetation distributes the flow velocity of water, which encourages sedimentation of suspended particles. Halophytes assimilate phosphorus to meet their nutritional requirements. And also, since the activity of microbial is more active than the bare tidal flat, decomposition of precipitated organic matter occurs a lot (Dai et al., 2009; Duarte et al., 2009). In addition, halophytes can influence the redox potential, which is an important determinant of the exchange of phosphorus between the sediment and water column (Chen and Barko, 1988). Especially, *P. australis* is one of the most distributed plants in marine ecosystem over the world including South Korea (Park et al., 2013). Many previous studies have identified what *P. australis* plays in the marine environment, and one of them has reported its purification ability. *P. australis* could incorporate nitrogen and phosphorus into its tissues and promote phosphorus absorption onto the tidal flat by the release of oxygen from the roots (Wathugala et al., 1987). Therefore, *P. australis* in the salt marsh can make result in a relatively high removal

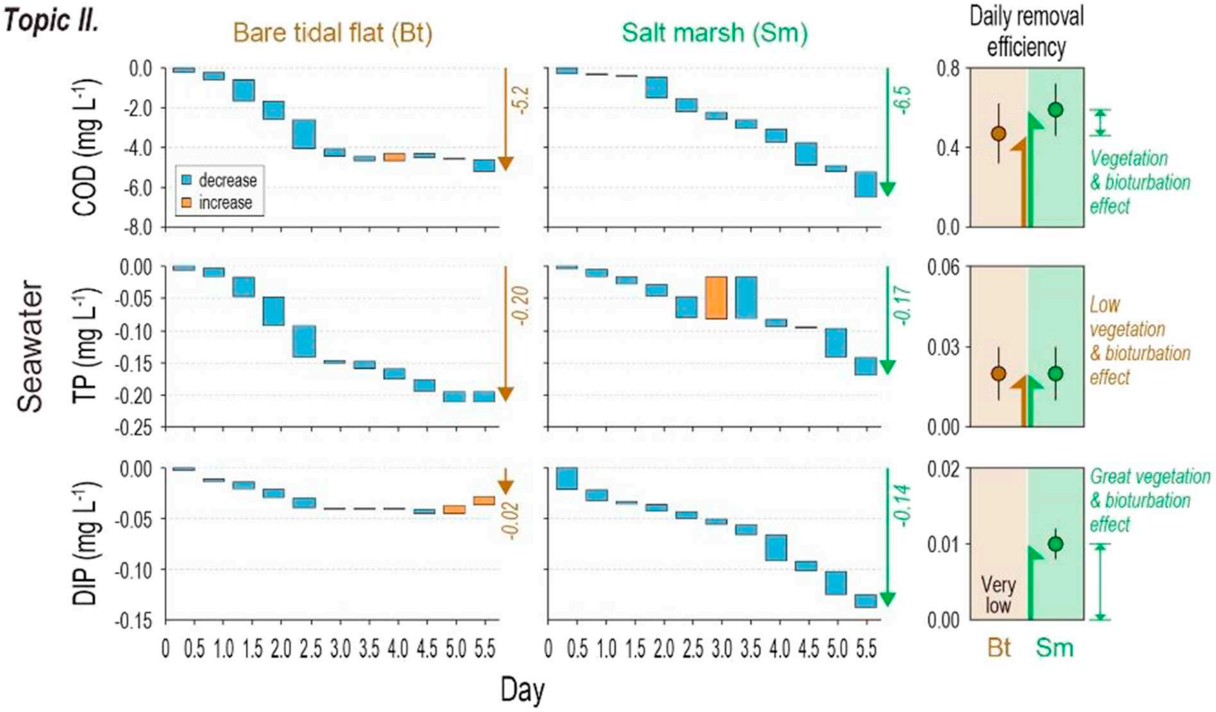

Fig. 3. Comparison of the purification capacity of COD, TP, and DIP in seawaters of the bare tidal flat and the salt marsh by use of mesocosm experiments. Values indicate the changes in concentrations of COD, TP, and DIP; set 0 at Day 0. The physico-chemical properties of inflow water and sediment are given (Table S1). Actual concentraions of COD, TP, and DIP measured in seawaters of the bare tidal falt (Table S2) and the salt marsh (Table S3) are further provided.

efficiency of DIP compared to the bare tidal flat (Tables S2 and S3).

3.3. Purification capacity in Bongam tidal flat, Masan Bay

Removal efficiency of COD in the salt marsh and the bare tidal flat was determined to be 7.9% and 22.5%, and that of TP was 6.4% and 20.2%, respectively. In order to quantitatively evaluate the purification performance of the Bongam tidal flat, we calculated the removal amount of COD and TP by considering the average water quality in Masan Bay (3.50 mg L^{-1} for COD and 0.13 mg L^{-1} for TP), the width of the mesocosm (0.2 m^2), the volume of inflow (36 L), and the exposure time (6 h) during the experiment period of 14 days (Table 2). The removal of COD and TP was expressed in g m^{-2} h^{-1} according to the equation below and converted to the amount during the day (Eq. 1):

$$\text{Purification capacity} = CRV/ST \tag{1}$$

where C is the mean concentration of COD or TP in Masan Bay (mg L^{-1}), R is the removal efficiency (%), V is the volume of water inflow (L), S is the width of the sediment (m^2), and T is the exposure time (h). The purification capacity of the Bongam tidal flat in Masan Bay determined from the equation was 0.1–0.3 g m^{-2} day^{-1} for COD and 0.002–0.007 g m^{-2} day^{-1} for TP. Applying this to the entire area of the Bongam tidal flat, the removal amount of COD and TP was estimated to be 20–57 kg day^{-1} and 0.5–1.5 kg day^{-1}, respectively (Table 2). The values are smaller than the removal amount of organic matters and nutrients in Saemangeum tidal land reported by You and Kim (1999). However, in terms of efficiency, the removal rate of the Bongam tidal flat in this study is greater. In the case of the Saemangeum tidal flat, the area is 400 km^2, while the Bongam has a total tidal flat area of ~0.2 km^2, which is considerably small compared to the Saemangeum (Lee et al., 2020; Ryu et al., 2011). Therefore, it should be advised that even if the purification rates between the tidal flats do not vary greatly, there could be a large difference in the actual purification amounts between tidal flats. Of note, we provided the estimated purification capacities of COD and TP for the Korean tidal flats during the past 30 years (Table S4).

3.4. Comparison to other mesocosm studies for purification capacity of tidal flats

Previous mesocosm studies have mainly designed the experiments to replicate wetlands with relatively few experiments for bare tidal flat

Table 1
Purification capacity of bare tidal flat versus salt marsh in experimental scale studies.

Compounds	Experimental set	Removal rate (%) in each experiment[a]											Average (%)
		1	2	3	4	5	6	7	8	9	10	11	
COD	Bare tidal flat	7.3	10.2	28.7	18.8	22.5	13.9	11.6	−16.7	7.5	2.1	19.4	11.4
	Salt marsh	8.1	1.4	2.2	31.9	18.0	9.6	12.2	17.1	31.9	8.3	36.3	16.1
TP	Bare tidal flat	6.3	9.3	20.3	23.8	22.0	3.5	11.1	9.0	10.1	14.5	−24.1	9.6
	Salt marsh	6.4	12.2	11.3	16.6	23.3	−31.6	27.4	9.6	0.9	11.3	26.6	10.4
DIP	Bare tidal flat	4.1	5.8	8.6	7.7	11.5	1.1	2.2	2.2	5.1	−21.1	−14.6	1.2
	Salt marsh	5.1	5.2	9.1	7.1	8.2	4.4	1.4	4.4	18.9	5.1	14.9	7.6

Equation: $100 - (C_e \div C_i) \times 100 = \textit{removal}$ rate (%).

[a] C_e: Initial concentration of COD, TP and DIP; C_i: the concentration of COD, TP and DIP after exposure 6 h.

Fig. 4. Comparison of the burial amounts of OM, TOC, and TN in sediments of the bare tidal flat and the salt marsh by use of mesocosm experiments. Values indicate the changes in concentrations of OM, TOC, and TN; set 0 at Day 0. The physico-chemical properties of inflow water and sediment are given (Table S1). Actual concentrations of OM, TOC, and TN measured in sediments of the bare tidal flat (Table S2) and the salt marsh (Table S3) are further provided.

Table 2
Evaluation on the purification capacity of the bare tidal flat in Bongam, Korea.

Target	Concentration (mg L^{-1})[a]	Removal rate (%)[b]	Removal amount (g m^{-2} day^{-1})[c]	Purification capacity[d] (kg day^{-1})
COD	3.5	7.9–22.5	0.1–0.3	20–57
TP	0.1	6.4–20.2	0.002–0.007	0.5–1.5

[a] Mean values in Bongam tidal flat (2018) from National Maritime Environmental Information Integration System (MEIS) (refer to Fig. S1).

[b] Removal efficiency in this study; values given as the 25th to 75th percentiles of the removal rates for COD and TP in the bare tidal flat (data from Table 1).

[c] Emersion time: 6 h; volume of seawater in experiment: 36 L, area of sediment in the mesocosm: 0.2 m^2; daily values convereted from hourly ones by multiplying 12 h, considering a diurnal tidal cycle.

[d] Applying area of 200,000 m^2 in Bongam tidal flat.

(Fig. 5). Among the studies conducted using in situ mesocosms, the average of maximum COD removal rate for vegetated one was reported to be 100%. On the other hand, the in-lab mesocosm experiments showed the removal rate of 74% for the bare tidal and 94% for the salt marsh on maximum (Fig. 5a), which are much different from the COD results in this study (29% and 36%, respectively). The different removal efficiency between in situ and in-lab experiments indicates the influence of various environmental and non-environmental factors. In the case of TP, the in situ mesocosm experiment showed 89% of the maximum removal rate, while 39% was obtained from the in-lab mesocosm. In this study, the bare tidal flat and salt marsh resulted in the removal rate of 23% and 27%, respectively, from in-lab experiments (Fig. 5b). The relatively low purification capacity of phosphorus in the tidal flat reflects that phosphorus is more stable than organic matters in environment (Suzumura and Ingall, 2004), which is in accordance with other studies reporting the higher removal efficiency of TP in the presence of vegetation than in bare condition (Fig. 5b). We note that previous studies on the role of vegetation in environmental purification were usually conducted in the fields of *P. australis* or transplanted mesocosms (Table S5). *P. australis* is one of the dominant halophytes in the tidal flats and wetlands, and it has been reported that these halophytes contribute to the purification by up taking phosphorous or nitrogen (Romero et al., 1999).

To conclude, recent reconsideration of marine ecosystem services has led a growing interest in the restoration or construction of tidal flat and wetland as a countermeasure for land-driven pollution (Kimura et al., 2002). The purification capacity of tidal flats has been confirmed through mesocosm experiments and emphasizes the importance of not only the purification capacity but also other values such as aesthetic and economic values in tidal flat (Kim, 2013). This study focused on the purification capacity of organic pollution by in situ sediments under conditions of bare intertidal flat and salt marsh. There are many international studies focusing on the purification of organic matters and nutrients from artificial wetlands rather than natural tidal flats. Also, Meuleman et al. (2003) and Austin and Lohan (2005) suggested a vertical-flow constructed wetland model for the treatment of wastewater. There are several other models, such as the reed-bed treatment system and gravel-bed wetland mesocosm. Since the mechanism of purification that occurs in the tidal flat is diverse, the shape and results of mesocosm might differ depending on which mechanism was focused on in each study (Hasanudin et al., 2004). For example, it is suggested to use an approach for microbial communities in the sediment to accurately identify the purification mechanisms in the tidal flat ecosystem (Jones et al., 2005; Kim et al., 2012). In particular, ignoring the microbial community may cause a biased and even erroneous identification of purification capacity in the tidal flat. Thus, not only chemical data but also biological data are needed to quantitatively confirm the purification and its mechanism in the tidal flat. The difference of the natural purification results seems to be due to the design and function of the mesocosm. To understand and address the natural remediation capacity of tidal flats, it will be necessary to determine various mechanisms and functions being unsolved in the future.

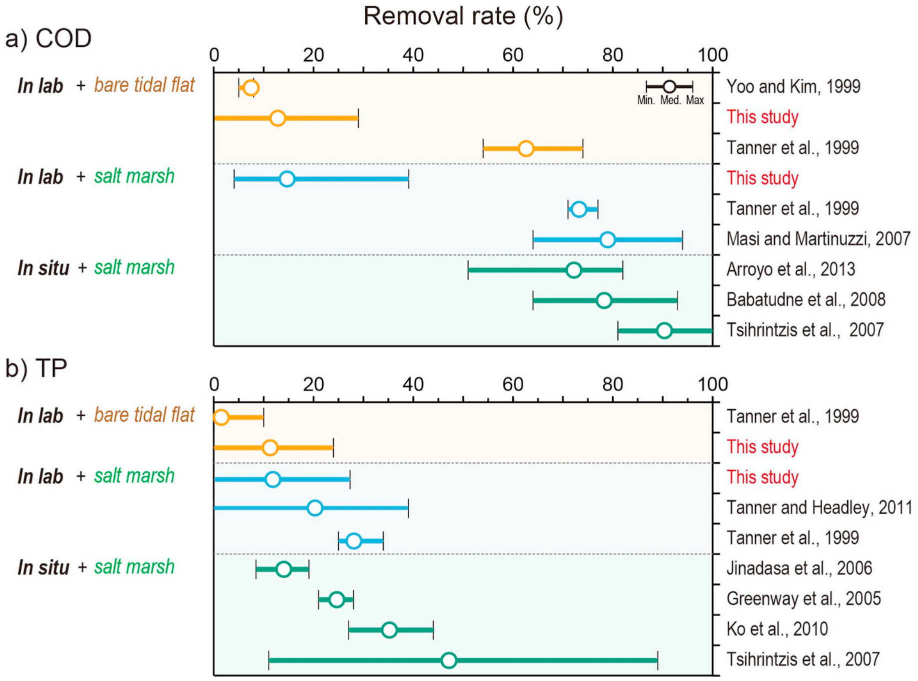

Fig. 5. Mini review on the studies evaluating removal efficiency of COD and TP by the tidal flats based on the in situ and laboratory mesocosm experiments, the present study included as for a comparison. Refer to the original meta-data provided in Table S5.

4. Conclusions

There has been significant and increasing interest in the purification capacity of organic matters and nutrients in the natural tidal flat. Nowadays, artificial tidal flat and constructed wetland are considered an effective option to control the non-point sources of organic pollutants from the land. As part of the present study, we reported the purification capacity of a tidal flat in the extreme nutrient exposure and identified the removal effiency between the bare tidal flat and the salt marsh with the expectation of how much organics can be removed in Bongam tidal flat. Further, we summarized the results of in situ and lab-mesocosm studies, including the data from present work. The mini-review confirmed great variations in purification capacity cross habitats and region, indicating the various mechanisms of purifying target materials. Ecosystem services and functions (viz., aesthetic, purification) provided by the tidal flat should be recognized following the adaptive management and restoration. Finally, further work is necessary to develop enhanced mesocosm systems and address more profound mechanisms of natural purification capacity and pathways in the tidal flats.

CRediT authorship contribution statement

Taewoo Kim: Conceptualization, Formal analysis, Investigation, Visualization, Writing - original draft.**Junsung Noh:**Conceptualization, Visualization, Writing - original draft, Writing - review & editing.**Bong-Oh Kwon:**Formal analysis, Investigation.**Changkeun Lee:**Investigation.**Beomgi Kim:**Formal analysis.**Inha Kwon:**Investigation.**Seongjin Hong:**Project administration.**Gap Soo Chang:**Project administration, Writing - review & editing.**Won Keun Chang:**Resources, Writing - review & editing.**Jungho Nam:**Resources, Writing - review & editing.**Jong Seong Khim:**Conceptualization, Writing - review & editing, Project administration, Funding acquisition, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2020.111046.

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<Supplementary Materials>

Natural purification capacity of tidal flats for organic matters and nutrients: A mesocosm study

Taewoo Kim, Junsung Noh, Bong-Oh Kwon, Changkeun Lee, Beomgi Kim, Inha Kwon,
Seongjin Hong, Gap Soo Chang, Won Keun Chang, Jungho Nam, Jong Seong Khim*

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*Corresponding author.

E-mail address: jskocean@snu.ac.kr (J.S. Khim).

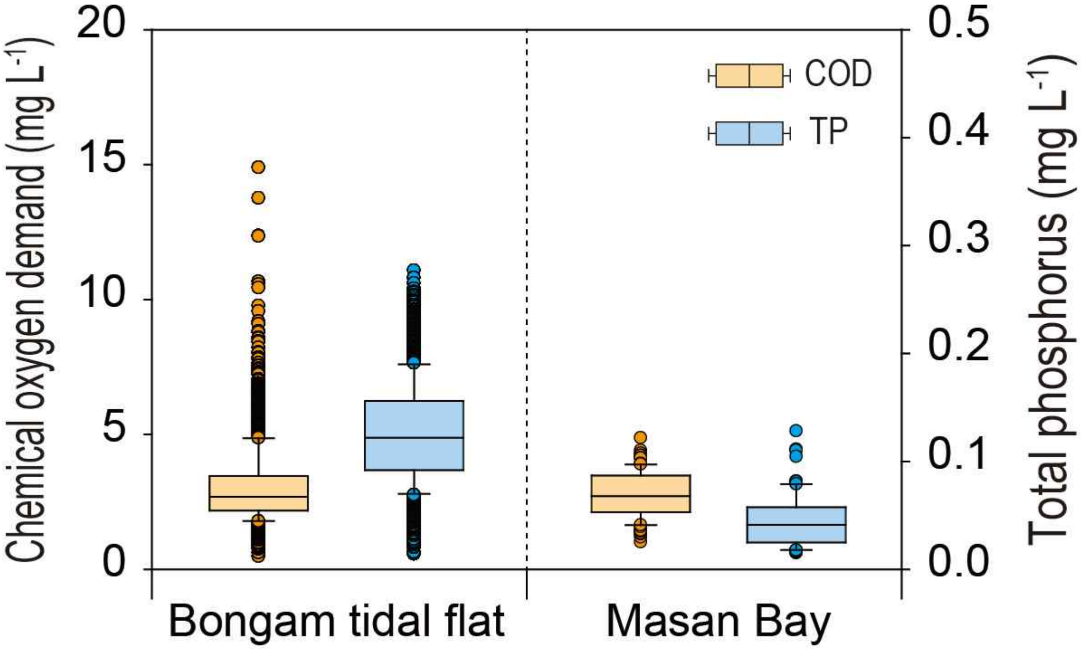

Fig. S1. Concentrations of chemical oxygen demand (COD) and total phosphorus (TP) measured in seawater of the Bongam tidal flat and Masan Bay from January to August, 2018. The data from MEIS (http://www.meis.go.kr).

Supplementary Tables

Table S1. Physico-chemical properties of seawater (inflow) and sediment measured at the mesocosm treatments for the bare tidal flat and the salt marsh.

Sample	Variables	Bare tidal flat		Salt marsh	
		Mean	SD	Mean	SD
Seawater	Temperature (°C)	18	1.4	17	1.4
	pH	7.8	0.1	7.9	0.2
	Dissolved oxygen (mg L^{-1})	7.9	1.5	7.5	1.1
	Salinity (psu)	20	2.2	20	2.9
Sediment	Temperature (°C)	18	1.1	18	1.2

Table S2. Average influent and effluent concentrations (mg L^{-1}) of COD, TP, and DIP in seawater, and contents (%) of OM, TOC, and TN in sediment from the bare tidal flat.

Sample	Target		0.5 d	1.0 d	1.5 d	2.0 d	2.5 d	3.0 d	3.5 d	4.0 d	4.5 d	5.0 d	5.5 d	Total	Mean
Seawater	COD	Influent	2.74	3.83	3.84	5.10	6.32	2.44	2.16	1.98	2.67	2.34	2.99	36.41	3.31
		Effluent	2.54	3.44	2.74	4.14	4.90	2.10	1.91	2.31	2.47	2.29	2.41	31.25	2.84
		Difference	-0.20	-0.39	-1.10	-0.96	-1.42	-0.34	-0.25	0.33	-0.20	-0.05	-0.58	-5.16	-0.47
	TP	Influent	0.13	0.15	0.15	0.18	0.22	0.15	0.09	0.20	0.20	0.11	0.07	1.65	0.15
		Effluent	0.12	0.13	0.12	0.14	0.17	0.15	0.08	0.19	0.18	0.09	0.09	1.46	0.13
		Difference	-0.01	-0.01	-0.03	-0.04	-0.05	-0.01	-0.01	-0.02	-0.02	-0.02	0.02	-0.20	-0.02
	DIP	Influent	0.05	0.06	0.07	0.13	0.08	0.04	0.00	0.04	0.06	0.04	0.05	0.63	0.06
		Effluent	0.05	0.06	0.07	0.12	0.07	0.04	0.00	0.04	0.06	0.05	0.06	0.61	0.06
		Difference	0.00	0.00	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	0.01	0.01	-0.02	0.00
Sediment	OM	Influent	6.85	6.24	5.73	5.37	6.42	5.14	6.24	8.67	6.13	5.87	6.10	68.76	6.25
		Effluent	6.91	6.40	6.14	5.89	6.77	5.23	6.55	8.64	7.44	6.12	6.02	72.11	6.56
		Difference	0.06	0.16	0.41	0.52	0.35	0.09	0.31	-0.03	1.31	0.25	-0.08	3.35	0.30
	TOC	Influent	0.88	0.74	1.43	1.56	1.36	1.14	0.88	0.74	1.21	1.11	1.36	12.42	1.13
		Effluent	1.43	1.39	1.92	1.86	1.41	1.42	1.39	1.22	1.41	0.98	1.47	15.91	1.45
		Difference	0.55	0.65	0.49	0.30	0.05	0.28	0.51	0.48	0.20	-0.13	0.11	3.48	0.32
	TN	Influent	0.03	0.05	0.06	0.04	0.07	0.05	0.07	0.04	0.06	0.06	0.05	0.58	0.05
		Effluent	0.07	0.08	0.07	0.07	0.13	0.09	0.14	0.08	0.15	0.10	0.07	1.05	0.10
		Difference	0.04	0.03	0.01	0.03	0.06	0.04	0.07	0.04	0.09	0.04	0.02	0.47	0.04

Table S3. Average influent and effluent concentrations (mg L^{-1}) of COD, TP, and DIP in seawater, and contents (%) of OM, TOC, and TN in sediment from the salt marsh.

Sample	Target		0.5 d	1.0 d	1.5 d	2.0 d	2.5 d	3.0 d	3.5 d	4.0 d	4.5 d	5.0 d	5.5 d	Total	Mean
Seawater	COD	Influent	3.59	3.64	2.23	3.60	3.94	3.64	3.76	3.87	3.60	3.25	3.66	38.78	3.53
		Effluent	3.30	3.59	2.18	2.45	3.23	3.29	3.30	3.21	2.45	2.98	2.33	32.31	2.94
		Difference	-0.29	-0.05	-0.05	-1.15	-0.71	-0.35	-0.46	-0.66	-1.15	-0.27	-1.33	-6.47	-0.59
	TP	Influent	0.08	0.09	0.09	0.14	0.14	0.20	0.23	0.13	0.15	0.42	0.10	1.76	0.16
		Effluent	0.07	0.08	0.08	0.11	0.10	0.26	0.17	0.12	0.15	0.37	0.08	1.59	0.14
		Difference	0.00	-0.01	-0.01	-0.02	-0.03	0.06	-0.06	-0.01	0.00	-0.05	-0.03	-0.17	-0.02
	DIP	Influent	0.07	0.05	0.03	0.10	0.07	0.12	0.09	0.13	0.05	0.06	0.08	0.85	0.08
		Effluent	0.04	0.04	0.03	0.09	0.06	0.12	0.08	0.10	0.04	0.04	0.07	0.71	0.06
		Difference	-0.02	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	-0.03	-0.01	-0.02	-0.01	-0.14	-0.01
Sediment	OM	Influent	6.57	7.03	6.40	6.43	5.91	5.97	5.19	5.93	6.02	5.13	6.93	67.51	6.14
		Effluent	7.20	7.54	6.76	6.35	5.97	6.38	5.93	5.72	6.21	5.14	5.71	68.90	6.26
		Difference	0.63	0.51	0.36	-0.07	0.06	0.41	0.73	-0.21	0.19	0.01	-1.22	1.40	0.13
	TOC	Influent	0.88	0.74	1.11	1.33	0.98	1.14	1.75	0.99	1.65	1.41	1.21	13.20	1.20
		Effluent	1.39	0.98	1.42	1.41	1.00	1.24	1.75	1.14	1.77	1.56	1.34	15.00	1.36
		Difference	0.51	0.24	0.31	0.08	0.02	0.10	0.00	0.15	0.12	0.15	0.13	1.80	0.16
	TN	Influent	0.07	0.11	0.06	0.05	0.11	0.03	0.07	0.05	0.04	0.04	0.05	0.68	0.06
		Effluent	0.14	0.14	0.07	0.07	0.14	0.07	0.11	0.08	0.09	0.07	0.09	1.07	0.10
		Difference	0.07	0.03	0.01	0.02	0.03	0.04	0.04	0.03	0.05	0.03	0.04	0.39	0.04

Table S4. Purification capacity of COD and TP in the tidal flats, by region, along the west-south coast of Korea from the 1990s to 2010s.

Year	Region	Concentration (mg L^{-1})[a]		Area of tidal flat (km^2)[b]	Purification capacity (ton d^{-1})[c]	
		COD	TP		COD	TP
1990s	Incheon-Gyeonggi	1.5	-	857	37 – 104	-
	Chungnam	1.3	-	288	11 – 30	-
	Jeonbuk	1.5	-	323	14 – 39	-
	Jeonnam	1.2	-	900	31 – 87	-
	All	1.4	-	2368	94 – 230	-
2000s	Incheon-Gyeonggi	1.6	0.08	524	24 – 68	0.9 – 2.9
	Chungnam	1.2	0.05	287	10 – 28	0.3 – 1.0
	Jeonbuk	1.6	0.07	77	3.5 – 10	0.1 – 0.4
	Jeonnam	1.3	0.06	818	25 – 71	1.0 – 3.2
	All	1.4	0.06	1706	68 – 193	2.6 – 8.1
2010s	Incheon-Gyeonggi	1.7	0.06	659	32 – 91	0.8 – 2.7
	Chungnam	1.4	0.03	318	13 – 36	0.2 – 0.8
	Jeonbuk	1.8	0.04	64	1.5 – 9.3	0.1 – 0.2
	Jeonnam	1.3	0.04	674	25 – 71	0.7 – 2.1
	All	1.6	0.04	1715	78 – 220	1.7 – 5.3

[a] COD and TP given by meta-analysis from the Marine Environment Information System (MEIS, http://www.meis.go.kr).

[b] Data from Yim et al., 2018.

[c] Calculated using the removal rate obtained from the present study; set removal period of ~12 h for a day considering diurnal tide cycle.

Table S5. Mini-review for in situ and lab-mesocosm studies for evaluating the purification capacity of COD and TP in the bare tidal flat and the salt marsh.

Target	Mesocosm	Habitat	Vegetation	Removal rate (%)		Reference
				Min.	Max.	
COD	Laboratory	Bare tidal flat	-	5	7	Yoo and Kim, 1999
			-	<0	29	***This study***
			-	54	74	Tanner et al., 1999
		Salt marsh	*Phragmites australis*	1	36	***This study***
			Schoenoplectus tabernaemontani	71	77	Tanner et al., 1999
			Phragmites australis	64	94	Masi and Martinuzzi, 2007
	In situ	Salt marsh	*Iris pseudacorus*	51	82	Arroyo et al., 2013
			Phragmites australis	64	93	Babatunde et al., 2008
			Phragmites australis & *Arundo donax*	81	100	Tsihrintzis et al., 2007
TP	Laboratory	Bare tidal flat	-	<0	10	Tanner et al., 1999
			-	<0	23	***This study***
		Salt marsh	*Phragmites australis*	<0	27	***This study***
			Schoenoplectus tabernaemontani	<0	<0	Tanner and Headley, 2011
			Juncus edgariae	<0	1	
			Cyperus ustulatus	<0	27	
			Carex virgata,	<0	39	
			Schoenoplectus tabernaemontani	25	34	Tanner et al., 1999
	In situ	Salt marsh	*Typha angustifolia*	8	15	Jinadasa et al., 2006
			Scirpus grassus	8	19	
			Phragmites australis	21	28	Greenway, 2005
			Mixed vegetation (>14 species)	27	49	Ko et al., 2010
			Phragmites australis & *Arundo donax*	11	89	Tsihrintzis et al., 2007

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