Journal of Ecology and Environment

RESEARCH Open Access

Estimation of carbon storage in coastal wetlands and comparison of different management schemes in South Korea

Chaeho Byun†, Shi-Hoon Lee† and Hojeong Kang*

Abstract

Background: Organic carbon stored in coastal wetlands, which comprises the major part of oceanic "blue carbon," is a subject of growing interest and concern. In this study, organic carbon storage in coastal wetlands and its economic value were estimated using the raw data of 25 studies related to soil carbon storage. Data were collected from three tidal flats (one protected and two developed areas) and two estuarine salt marshes (one protected and one restored area). Bulk density, soil organic matter content, and standing biomass of vegetation were all considered, with Monte Carlo simulation applied to estimate the uncertainty.

Results: Mean carbon storage in two salt marshes ranged between 14.6 and 25.5 kg C m^{-2}. Mean carbon storage in tidal flats ranged from 18.2 to 28.6 kg C m^{-2}, with variability possibly related to soil texture. The economic value of stored carbon was estimated by comparison with the price of carbon in the emission trading market. The value of US $6600 ha^{-1} is ~ 45% of previously estimated ecosystem services from fishery production and water purification functions in coastal areas.

Conclusions: Although our study sites do not cover all types of large marine ecosystem, this study highlights the substantial contribution of coastal wetlands as carbon sinks and the importance of conserving these habitats to maximize their ecosystem services.

Keywords: Blue carbon, Tidal flat, Salt marsh, Soil organic matter, Ecosystem services

Background

Coastal wetlands are highly productive transient zones located between terrestrial and marine ecosystems (Mitsch and Gosselink 2015). Depending on the climate and hydrological conditions, coastal wetlands can be grouped into several categories including mangroves, seagrasses, tidal salt marshes, or mud flats. Important factor that has recently drawn much attention is the potential for carbon storage in coastal ecosystems (Choi and Wang 2004; Hopkinson et al. 2012; Mitsch et al. 2013). These ecosystems cover only 2.5% of total land surface of the world, but their net global carbon storage is estimated to be 25 Pg (Duarte et al. 2013). It is estimated that carbon accumulation rate per unit area is 30–50 times higher in coastal wetlands than in forest ecosystems (Bridgham et al. 2006; Mcleod et al. 2011; Ouyang and Lee 2013), highlighting their importance with respect to the global carbon cycle (Howard et al. 2017; Jain 2008). Carbon stored in vegetation and soils of coastal wetlands represents the majority of "blue carbon" (Herr et al. 2012; Howard et al. 2014), which is defined as the carbon stored in marine ecosystems (Nellemann and Corcoran 2009). Several global-scale estimates of carbon sequestration and storage in coastal wetlands have been reported. Chmura et al. (2003) reported an annual carbon sequestration rate of ~ 44.6 Tg C for soils in mangroves and salt marshes, while Kennedy et al. (2010) reported a value of ~ 48–112 Tg for seagrass. Comparable values were also reported by other researchers (Duarte et al. 2013; Duarte et al. 2005; Murray et al. 2011; Ouyang and Lee 2013). Two mechanisms underlie the high carbon storage capacity of coastal wetlands. Firstly, primary production rates are extremely high (Madrid et al. 2012), ranging from 2.96 to 6.75 kg

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m^{-2} $year^{-1}$. This value is much higher than typical net primary production of terrestrial ecosystems, which ranges from 1.12 to 2.55 kg^{-2} m^{-2} $year^{-1}$ in Brookhaven Forest (Woodwell and Whittaker 1968) and 0.847 kg m^{-2} $year^{-1}$ in the South East Asian tropical region (Potter et al. 2012). Secondly, the decomposition rate of organic matter is slow due to low oxygen availability and salinity, resulting in the accumulation of organic matter in sediments (Pendleton et al. 2012).

The extent of coastal wetlands has been reduced significantly by coastal development, including reclamation projects. Environmental problems such as eutrophication, ocean deoxygenation, harmful algae bloom, sea level rise, and invasive species also pose threats to the integrity of coastal ecosystems (Cahoon et al. 2006; Deegan et al. 2012; Heisler et al. 2008; Keeling et al. 2009; Williams and Grosholz 2008). Pendleton et al. (2012) reported that 1.7% of coastal wetlands are being destroyed worldwide each year, resulting in the release of 0.45 Pg CO_2 $year^{-1}$ into the atmosphere. This is equivalent to 13.6% of the annual CO_2 emissions caused by deforestation and land use change and is comparable to the amount released per year in the UK by fossil fuel combustion (Le Quéré et al. 2015; Pendleton et al. 2012). The global financial cost incurred by the destruction of coastal wetlands was estimated to be US $18.5 billion (Pendleton et al. 2012). The protection and restoration of coastal wetlands as sustainable carbon sinks is widely considered as one of the tools of carbon capture and storage (CCS) (Irving et al. 2011).

Despite the current interest in carbon storage in coastal wetlands, there are still large gaps in our knowledge. There are few studies about estimates of carbon storage conducted in salt marshes and in temperate-zone mud flats particularly in Africa and Asia. There are also few studies about below-ground production and carbon storage in soils and carbon storage capacity of natural and restored wetlands comparing different management schemes.

Previous estimates of carbon storage derive largely from mangroves and seagrasses in the USA or Europe, with fewer studies conducted in salt marshes (Fourqurean et al. 2012; Ouyang and Lee 2013). Carbon storage in temperate-zone mud flats has rarely been studied even though the number of publications dealing with carbon estimation in coastal wetlands increased from 30 in 2005 to 110 in 2012 (Duarte et al. 2013). Many studies have focused on net primary production of above-ground biomass, while below-ground production and carbon storage in soils may also be substantial (Clark et al. 2001). In addition to variability among different wetland types, the lack of data from Africa and Asia is another important source of uncertainty in estimation of global carbon storage in coastal wetlands (Grimsditch et al. 2013; Howard et al. 2014). Our understanding of the relative carbon storage capacity of natural and restored wetlands is also very limited. Surface vegetation in natural and restored wetlands may show similar rates of primary productivity, but the long-term fate of carbon sequestered in soils is still poorly known. The efficiency of restoration methods in terms of carbon storage has also been tested (Irving et al. 2011; Madrid et al. 2012), but these studies focused only on emergent or submerged vegetation without considering soil organic carbon. The effects of management scheme and human intervention on carbon storage were not clearly understood (Armentano and Menges 1986; Bauer et al. 2013; Howard et al. 2014).

In this study, blue carbon sequestration in coastal wetlands was estimated by quantifying the absolute amount and density of carbon stored in wetlands along the southwest coast of South Korea as a case study. Data were collected based on literature review which includes 25 studies (including more than 25 study sites) in mud flats and salt marshes (Fig. 1), and carbon storage in soils was quantified along with uncertainties involved in the estimation. The inclusion of "restored," "highly protected," and "unmanaged" coastal wetlands allowed assessment of the effects of management scheme on carbon storage. Monetary values for carbon stored in these wetlands were compared with existing data for ecosystem services. There is growing evidence and consensus that promoting the conservation, restoration, and sustainable use of coastal ecosystems has great potential as an effective tool in global carbon management. Scientific understanding of carbon sequestration and potential emissions from coastal ecosystems is now sufficient to develop effective carbon management, policy, and conservation incentives for coastal blue carbon.

Results

Carbon storage in estuarine salt marsh

Figure 2a, b, c, and d show the results of Monte Carlo simulation for soil organic matter content and above-ground biomass for the two sites. For the Impacted Salt Marsh, soil organic matter content and above-ground standing biomass of *Phragmites* community both showed a lognormal distribution, with parameter values of 1.96, 0.35 and 764.46, 0.82, respectively. For the pristine salt marsh, soil organic matter content followed a uniform distribution while above-ground standing biomass of *Phragmites* followed a Weibull distribution. Parameter values were 714.9, 1.62, and 0.

Table 1 shows the estimated carbon storage in estuarine salt marshes. Each value is a mean estimated by Monte Carlo simulation with 90% confidence intervals. The total carbon storage in the Impacted Salt Marsh was 27.7 Gg, with 27.2 Gg in soil and 0.5 Gg in the

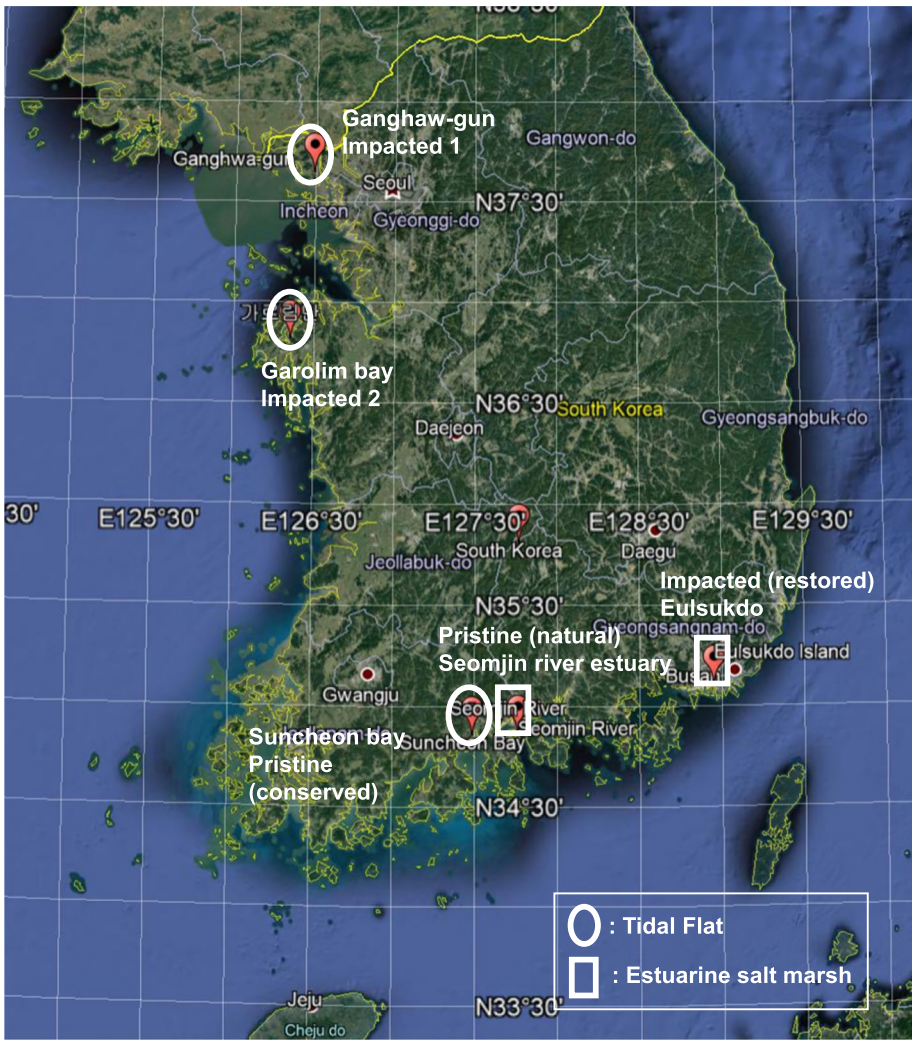

Fig. 1 Map of South Korea showing locations of the five study sites

Phragmites community. This was estimated from data in 2005, conducted for a year (Ministry of Oceans and Fisheries 2005). The mean carbon storage per unit area was estimated as 14.5 kg C m^{-2}. Total carbon storage for the Pristine Salt Marsh was 40.3 Gg, of which soil contained 39.7 Gg, and the *Phragmites* community contained 0.6 Gg. The mean carbon storage per unit area was estimated as 19.8 kg C m^{-2}. Pristine Salt Marsh significantly captured more soil organic carbon per unit area than the Impact Salt Marsh (t test; $t = -2.2267$, df = 48, P values = 0.031, r software).

Carbon storage in tidal flats

Figure 2e, f, and g show the results of Monte Carlo simulations for soil organic matter content for each tidal flat. The Pristine Mud Flat had a mean value (± SD) of 4.46 ± 2.28 and followed a normal distribution. Impacted Mud Flat 2 followed a gamma distribution with a scale factor of 1.42 and shape factor of 2.89. Impacted Mud Flat 1 followed a lognormal distribution with parameter values of 2.47 and 0.53.

Table 2 shows the estimated carbon storage in tidal flat soils. Each value is a mean calculated using the Monte Carlo simulation with 90% confidence intervals. Total soil carbon storage in the Pristine Mud Flat was 800.3 Gg, with storage per unit area estimated as 28.6 kg C m^{-2}. Total soil carbon storage in Impacted Mud Flat 2 was 1141.6 Gg, with estimated storage per unit area of 13.9 kg C m^{-2}. Impacted Mud Flat 1 had a total soil carbon storage of 4431.5 Gg, with storage per unit area estimated as 18.2 kg C m^{-2}. Total carbon storage in soil was therefore highest in Impacted Mud Flat 1, followed by Impacted Mud Flat 2 and the Pristine Mud Flat (Table 2). This ranking reflects the respective areas of the three study sites. However, soil carbon storage per unit area was highest in the Pristine Mud Flat (Table 2).

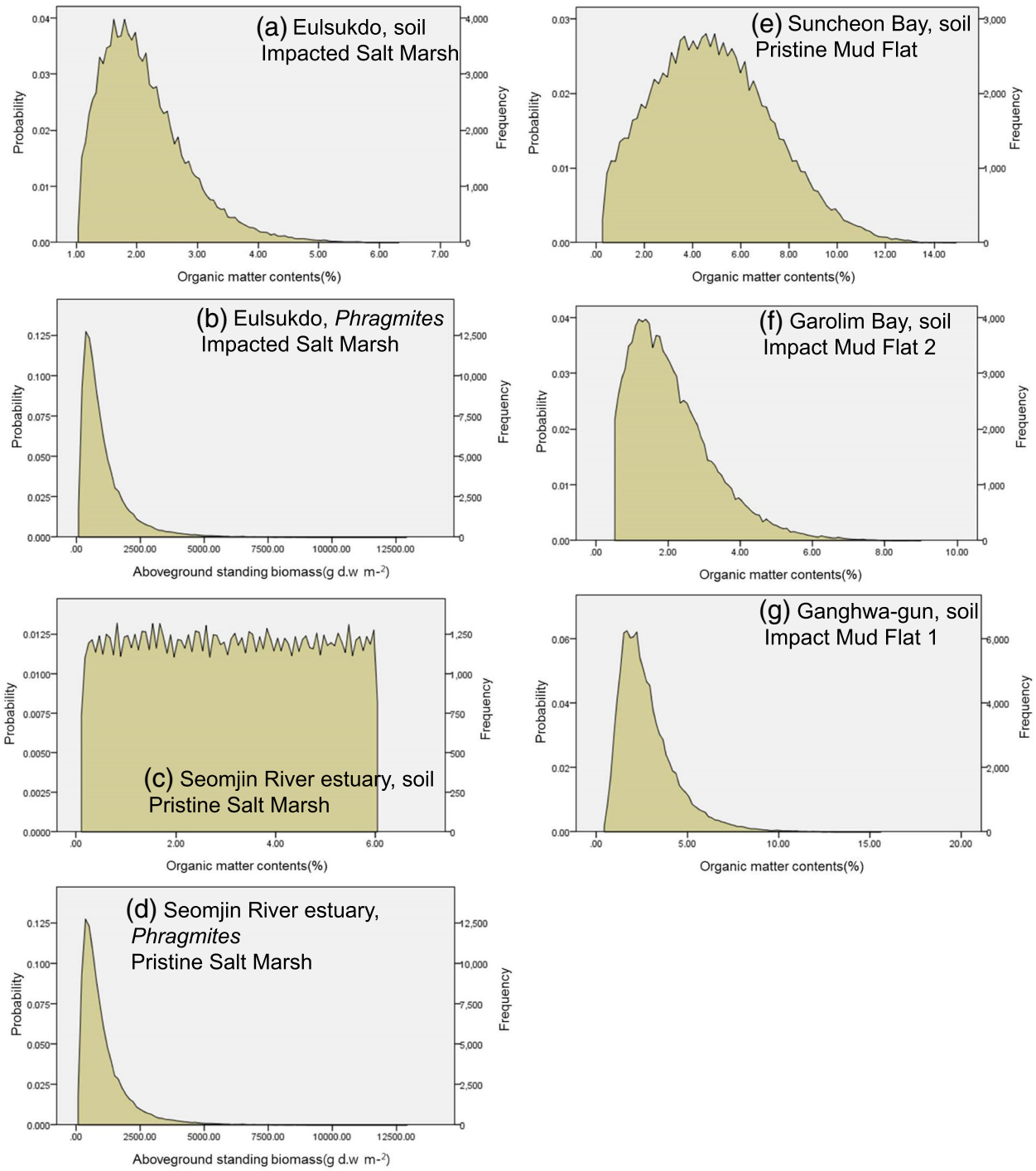

Fig. 2 Organic matter content of soil and above-ground standing biomass of *Phragmites* (where present) at the study sites, estimated by Monte Carlo simulation. **a** Eulsukdo, soil. **b** Eulsukdo, *Phragmites*. **c** Seomjin River estuary, soil. **d** Seomjin River estuary, *Phragmites*. **e** Suncheon Bay, soil. **f** Garolim Bay, soil. **g** Ganghwa-gun, soil. There were no plants in the tidal flat, so there are no figures for the aboveground standing biomass

Comparison with other ecosystems

Estimated carbon storage in soil per unit area of coastal wetland was compared with values for terrestrial ecosystems. In South Korea, these include agricultural land, forests, and freshwater wetlands, while at a global scale, inland wetlands, forests, and peatland were selected for comparison. We chose these areas based on data availability and relevance for our study. Values for soil carbon storage per unit area were obtained from the published literature.

Table 1 Basic characteristics of the study sites (organic matter content, above-ground biomass, wetland area, vegetation area, dominant species) and mean soil organic carbon content in estuarine salt marshes, mean (5th to 95th percentile). *N* refers to number of sampling points from other studies. This is done by Monte Carlo simulation from values in literature. Source of references are listed in Additional file 1: Table S1

Study site	*N*	Soil organic matter content (%)	Above-ground biomass (g m^{-2})	Costal wetland area (km^2)	Vegetation area (km^2)	Dominant species
Impacted Salt Marsh	40	1.05–4.15 (2.09)	61–3764 (1039.19)	1.907	0.96	*Phragmites australis*
Pristine Salt Marsh	36	0.1–6.05 (2.89)	20–1640 (642.45)	2.04	2.04	*Phragmites australis*
Pristine Mud Flat	85	0.3–11.35 (4.46)	–	22.6	–	–
Impacted Mud Flat 1	54	0.39–13.21 (2.85)	–	243.6	–	–
Impacted Mud Flat 2	39	0.48–6.73 (2.03)	–	81.9	–	–
Study site		C storage per unit area (kg m^{-2})	C storage in soil up to 1 m (Gg)	C storage in *Phragmites* community (Gg)	Note	
Impacted Salt Marsh		14.6 (8.5–23.2)	27.2 (16.2–42.9)	0.5 (0.1–1.3)	Restored area	
Pristine Salt Marsh		19.8 (3.0–34.8)	39.7 (6.0–69.7)	0.6 (0.1–1.3)	Natural area	

Within South Korea, the coastal study sites contained more stored carbon per unit area than terrestrial ecosystems (Fig. 3a). Agricultural land had the highest soil carbon content per unit area among the terrestrial ecosystems considered, but this was only half of the value obtained from Impacted Mud Flat 2, which had the lowest figure among the target coastal sites. The biggest contrast was that between freshwater wetlands and the Pristine Mud Flat, with the latter storing > 20 times more carbon per unit area.

At a global scale, the degree of contrast with terrestrial ecosystems varied with the study site (Fig. 3b). Impacted Mud Flat 2 and Impacted Salt Marsh had less soil carbon per unit area than any terrestrial ecosystem considered. Impacted Mud Flat 1 had a higher value than forest ecosystems, but lower values than freshwater wetland and peatland. Soil carbon storage per unit area in the Pristine Salt Marsh was higher than that in forest ecosystems, similar to that in freshwater wetlands, and lower than that in peatland. Soil carbon storage in the Pristine Mud Flat was higher than that in all other ecosystems with the exception of peatland.

CO_2 equivalent and economic value

Total carbon storage for each study site was multiplied by 3.67 to calculate the equivalent of CO_2. Estimated values for each site were then added to estimate the total potential CO_2 storage. Consequently, the potential CO_2 storage of the combined study sites was estimated as 23.7 Tg CO_2 (Table 3).

From the mean soil organic content of the three studied tidal flats (Pristine Mud Flat, Impacted Mud Flat 1, and Impacted Mud Flat 2) and total tidal flat area (2387.2 km^2) in South Korea (assuming that these three sites represent the entire tidal flat habitat in South Korea), the potential CO_2 storage is 190.8 Tg CO_2, which is equivalent to 27.7% of the total greenhouse gas emission in South Korea.

Discussion

Carbon storage in estuarine salt marsh

As shown in Table 1, the Pristine Salt Marsh captured more carbon than the Impacted Salt Marsh. The size difference in wetland area in the two regions is only 0.1 km^2, but the Pristine Salt Marsh contains more carbon per unit area than the impacted site. This implies that the Pristine Salt Marsh, a natural wetland, accumulates more organic matter in its soil. This pattern is similar to other studies (Fenstermacher et al. 2016). Pools of organic matter may be bigger in natural pristine wetlands than recently restored wetlands because of the long length of time enhanced organic matter accumulation has been occurring and the level of soil inundation, as well as the hydrogeomorphic class (Hogan et al. 2004;

Table 2 Mean carbon storage in tidal flat soils to 1-m depth, mean (5th to 95th percentile). This is done by Monte Carlo simulation from values in literature

Study site	C storage per unit area (kg m^{-2})	C storage in soil (Gg)	Note
Pristine Mud Flat	28.6 (7.8–47.9)	800.3 (217.1–1341.8)	Conserved area
Impacted Mud Flat 1	18.2 (7.3–34.9)	4431.5 (1768.3–8508.7)	Natural area
Impacted Mud Flat 2	13.9 (4.8–27.2)	1141.6 (394.7–2224.1)	Natural area

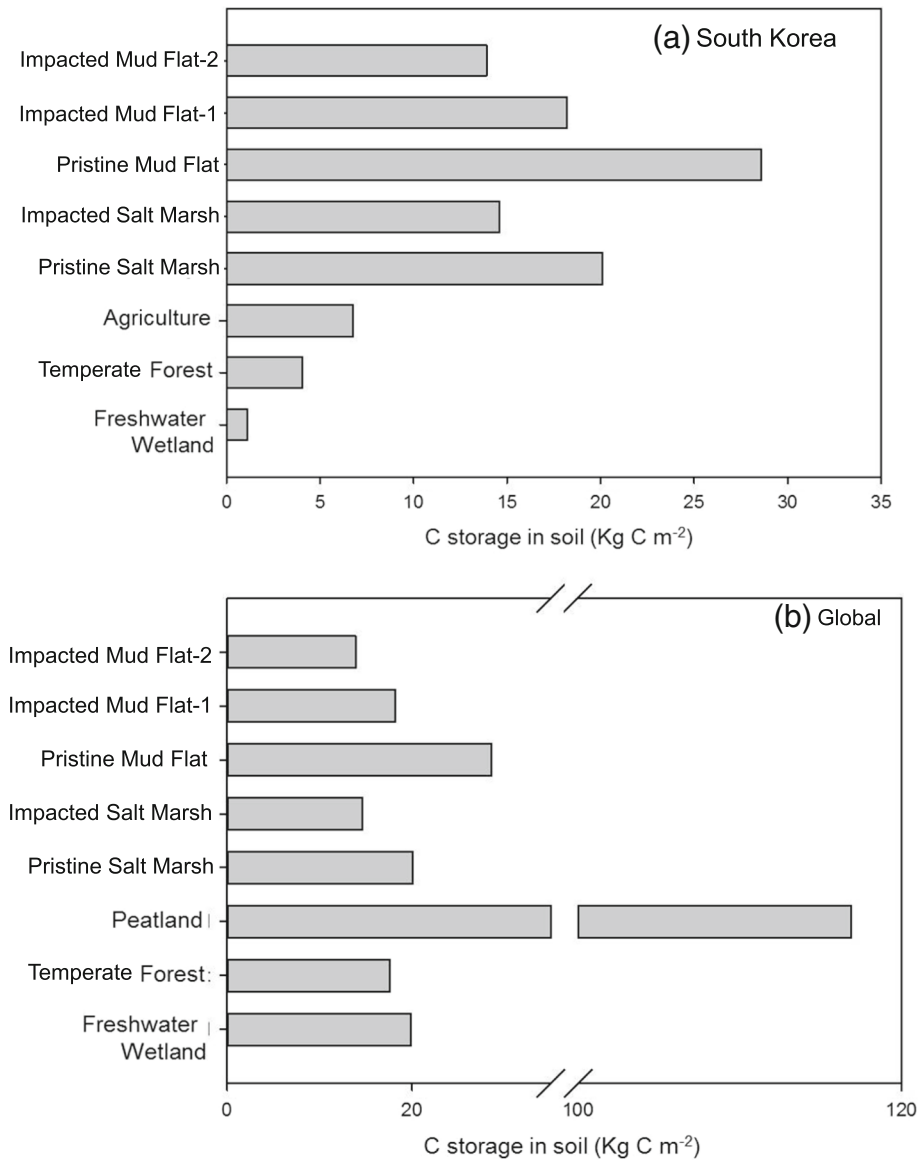

Fig. 3 Comparison of soil carbon storage per unit area in selected coastal and terrestrial ecosystems. **a** Korea. **b** Global. Source of references about soil carbon storage per unit area in other ecosystems are listed in Additional file 1: Table S2

Table 3 Mean potential CO_2 emissions and equivalent economic costs for the five study sites

Study site	C storage (Gg)	Potential CO_2 emissions (Tg CO_2)	Economic cost (million US$)	Note
Impacted Salt Marsh	27.7	0.1	0.9	Restored area
Pristine Salt Marsh	40.3	0.1	0.9	Natural area
Pristine Mud Flat	800.3	2.9	25.1	Conserved area
Impacted Mud Flat 1	4431.5	16.3	140.8	Natural area
Impacted Mud Flat 2	1141.6	4.2	36.3	Natural area
Total	6441.4	23.7	204.0	

Shaffer and Ernst 1999). In general, the long periods of submergence experienced by coastal wetlands generate anaerobic soil conditions that slow the decomposition of organic matter and promote its long-term accumulation (Brevik and Homburg 2004; Chmura et al. 2003; Lo Iacono et al. 2008). The organic layer therefore deepens over time. For example, the seagrass meadow in Portlligat Bay (Spain) and mangrove soil in Belize have both accumulated organic layers > 10 m thick for over 6000 years (Howard et al. 2014). Therefore, the natural coastal wetland of the Pristine Salt Marsh has a higher soil organic content than the Impacted Salt Marsh (a restored wetland), resulting in more carbon storage at the former site.

As shown in Table 4, our estimated values were smaller than those reported in previous studies (Duarte et al. 2013; Howard et al. 2014; Murray et al. 2011). In particular, the quantity of soil carbon per unit area in the Gulf of Mexico (Murray et al. 2011) is 2.5 times greater than that in the region studied here. The global mean carbon storage in soil per unit area was higher than the value from this study (Bridgham et al. 2006; Duarte et al. 2013; Howard et al. 2014). One possible explanation is that there are limitations of using literature values to calculate carbon stored in soil in this study. On the other hand, the difference reflects the soil texture of the study sites. Most of our sites are composed of mineral-rich soils, which typically store lower amounts of organic matter than the salt marshes in the USA (Murray et al. 2011). A mineral-rich soil layer develops where large amounts of sediment are deposited from terrestrial ecosystems. In the case of estuary site (Howard et al. 2014), a sandbank has developed downstream in the Seomjin River (Ministry of Environment 2005) and in the Impacted Salt Marsh, which is an alluvial island located in an estuary that is representative of river deltas in South Korea. In the lower reaches of rivers, sandbanks or deltas formed by sediment deposition contain large amounts of sand that result in formation of inorganic soil layers. As shown in Table 1, sediments of both the Pristine and Impacted Salt Marsh sites were mainly inorganic soil, characterized by relatively smaller carbon storage per unit area than in soils in previous studies.

Carbon storage in tidal flats

Total soil carbon storage in tidal flats was estimated as 800.3 Gg (Pristine Mud Flat), 4431.5 Gg (Impacted Mud Flat 1), and 1141.6 Gg (Impacted Mud Flat 2) (Table 2). Table 5 compares our results for soil carbon storage per unit area with data from previous studies of tidal flats. Soil carbon storage per unit area in the Pristine Mud Flat was 28.6 kg C m^{-2}, a value greater than the global mean, greater than the mean for California, and comparable to that for Florida (Murray et al. 2011). Estimated values for Impacted Mud Flats 1 and 2 were lower than those from previous studies (Bridgham et al. 2006; Duarte et al. 2013; Howard et al. 2014). In particular, the value for Impacted Mud Flat 2 was 10 kg lower than that for California, which has the smallest value in the study (Murray et al. 2011).

The IUCN (International Union for Conversion of Nature) blue carbon manual reported that the composition and density of vegetation in coastal wetlands affect the total carbon stock. Among our study sites, the Pristine Mud Flat differed from the other study sites because halophyte communities including *Phragmites* were dominant in the upper zone of the tidal flat. *Phragmites* is a perennial plant, and the surrounding soil of a *Phragmites*

Table 4 Reported and estimated carbon storage per unit area in salt marsh soils (top 1 m). This is done by Monte Carlo simulation from values in literature

Study site/region	Mean (kg m^{-2})	Range (kg m^{-2})	Reference
Impacted Salt Marsh	14.6	8.6–24.0	This study
Pristine Salt Marsh	20.1	3.0–35.6	This study
Global	25.5	1.6–62.3	(Howard et al. 2014)
	–	1–295.5	(Duarte et al. 2013)
	–	4.74–189.8	(Murray et al. 2011)
	–	19.5	(Bridgham et al. 2006)
Northeast Canada	34.5	18.0–73.0	(Murray et al. 2011)
Gulf of Mexico	51.8	10.0–189.8	(Murray et al. 2011)
New England	36.7	20.0–60.0	(Murray et al. 2011)
Chesapeake Bay, Maryland	32.5	24.6–44.0	(Murray et al. 2011)
Florida	27.8	15.4–46.2	(Murray et al. 2011)
California	23.5	9.0–43.3	(Murray et al. 2011)
North Carolina	31.6	4.7–55.5	(Murray et al. 2011)

Table 5 Carbon storage per unit area of tidal flat soils (this study, estimated) and salt marsh soils (from published literature). All data refer to the top 1 m soil. This is done by Monte Carlo simulation from values in literature

Study site/region	Mean (kg m^{-2})	Range (kg m^{-2})	Reference
Pristine Mud Flat	28.6	7.8–47.9	This study
Impacted Mud Flat 2	13.9	4.8–27.2	This study
Impacted Mud Flat 1	18.2	7.3–34.9	This study
Global	25.5	1.6–62.3	(Howard et al. 2014)
	–	1–295.5	(Duarte et al. 2013)
	–	4.74–189.8	(Murray et al. 2011)
	–	19.5	(Bridgham et al. 2006)
Northeast Canada	34.5	18.0–73.0	(Murray et al. 2011)
Gulf of Mexico	51.8	10.0–189.8	(Murray et al. 2011)
New England	36.7	20.0–60.0	(Murray et al. 2011)
Chesapeake Bay, Maryland	32.5	24.6–44.0	(Murray et al. 2011)
Florida	27.8	15.4–46.2	(Murray et al. 2011)
California	23.5	9.0–43.3	(Murray et al. 2011)

community contains large amounts of organic matter derived from dead plants (Kang et al. 2008). High primary production and slow litter decomposition within *Phragmites australis* communities did not translate into greater carbon accumulation in the soil (Rothman and Bouchard 2007). When the exotic C4 grass *Spartina alterniflora* invades tidal coastal wetlands, it facilitates soil organic carbon storage (Zhang et al. 2010). With respect to soil organic matter content, the mean value for the halophyte-dominated zone in the bay was 8.6%. This is higher than the total mean organic matter content of soil in the Pristine Mud Flat (4.5%). Thus, halophyte communities may be responsible for the higher soil carbon storage per unit area than in the other study sites. In addition, soil carbon storage per unit area in the Pristine Mud Flat may be higher than in the upper zone of the tidal flat.

Recently, developed or developing countries such as South Korea and China have modified their coastal ecosystems substantially, but there is little information regarding carbon storage in different management schemes. For example, most coastal wetlands in South Korea exist in the form of tidal flats, which is recognized as one of the world's five largest tidal flats (Hong et al. 2013). Choi (2004) reported a value of US \$14,700 ha^{-1} for the ecosystem services of tidal flats in South Korea. Nevertheless, the current total area of tidal flats has been reduced by 22% since 1987 (Ministry of Oceans and Fisheries 2013), and many tidal flats are exposed to development pressure. Therefore, management scheme is also a factor influencing carbon storage capacity since development pressure can reduce the carbon storage capacity of coastal wetlands (Armentano and Menges 1986; Bauer et al. 2013; Howard et al. 2014). The value of the Pristine Mud Flat was recognized by its 2003 designation as a wetland protection area, and it was first registered as a coastal wetland under the Ramsar Convention in 2006. In addition, it was designated as a National Heritage in 2008 due to its scenic and ecological value (Jang and Cheong 2010). The Pristine Mud Flat is conserved effectively through continuous monitoring and maintenance even though it is surrounded by the Suncheon industrial complexes and sewage treatment plant. This protection appears to preserve stable functioning of the tidal flat ecosystem, allowing carbon storage capacity to be maintained even in the face of high development pressure. Comparison with the other two sites, Impacted Mud Flats 1 and 2, illustrates the effect of conservation measures (Table 6). Some parts of Impacted Mud Flat 1 fall within the military's protective region and the site has lower development pressure. Impacted Mud Flat 2 is also a well-conserved natural tidal flat, but it experiences relatively higher anthropogenic impact and development pressure than Impacted Mud Flat 1 and it is not managed well compared with the Pristine Mud Flat. Thus, reducing the development pressure through conservation affects the carbon storage capacity of the coastal wetlands.

Tidal flats in South Korea do not have fully covered vegetation unlike salt marsh at their inland reaches unlike those of the European North Sea and North American coasts (Koh 2001). Salt marsh supports a rich vegetation community, with significant impacts on the total carbon stock. Furthermore, salt marsh soils are rich in organic matter derived from dead plant material, and thus contain more carbon than tidal flat soils (Benner et al. 1991). This is apparent from comparison of the Pristine Mud Flat with the other two sites. The

Table 6 Soil texture at the salt marsh study sites, from published literature

Study site	Texture parameter (%)				Reference
	Gravel	Sand	Silt	Clay	
Impacted Salt Marsh	–	72.7	23.3	4.1	(Kim 2011)
	–	77.6	6.1	16.3	(Chung et al. 2008)
Pristine Salt Marsh	–	60.8	36.7	2.5	(Ministry of Environment 2005)
	4.32	87.98	4.9	2.81	(Ministry of Oceans and Fisheries 2010)

well-developed halophyte community in the upper zone of the Pristine Mud Flat is reflected in the higher soil organic content.

Tidal flats are formed by deposition of terrestrial sediments and suspended particles from seawater. The west coast of South Korea receives large amounts of sediment from the Yangtze and Yellow Rivers in China, and together with the contribution from large domestic rivers, this favors the development of inorganic soil (Howard et al. 2014; Koh 2001). Mean soil organic content measured in this study was very low, with values of 4.5% in the Pristine Mud Flat, 2.8% in Impacted Mud Flat 1, and 2.0% in Impacted Mud Flat 2. However, soil carbon storage per unit area was highest in the Pristine Mud Flat (Table 2), which likely reflects the contribution of *Phragmites* and other halophyte communities. In addition, the sand-silt or sand-clay contents of soils at each site were high. Soils of the study areas would therefore be expected to have higher inorganic content, resulting in lower carbon storage per unit area than reported for other regions.

Comparison with terrestrial ecosystems

The estimated mean carbon storage per unit area of coastal wetlands was four times higher than the mean value for terrestrial ecosystems in South Korea (Fig. 3a). This implies that coastal wetland soils have the highest carbon storage per unit area in South Korea.

Soil carbon storage in the Pristine Mud Flat was also higher than that in all other ecosystems considered, with the exception of peatland (Fig. 3b). The coastal wetland study sites other than the Pristine Mud Flat are expected to have lower soil carbon storage per unit area than terrestrial ecosystems.

CO_2 storage and economic value

The mean potential CO_2 emission of the study sites was estimated as 23.7 Tg CO_2 (Table 3) if the site would be destructed and organic matter be completely decomposed. Total greenhouse gas emission in South Korea in 2012 was reported to be 688.3 Mt CO_2eq (Greenhouse Gas Inventory and Research Center of Korea 2014), a value equivalent to 3.44% of the total global greenhouse gas emissions, and similar to the greenhouse gas emission of agricultural fields in 2012. The potential CO_2 emission from destruction of 190.8 Tg CO_2 represents 27.7% of the total greenhouse gas emission of 688.3 Tg CO_2 for South Korea (Den Elzen et al. 2013). Thus, each estimated value is lower than for other salt marshes in the world (Table 4), but the contribution to greenhouse gas emissions for South Korea is not negligible.

The greenhouse gas emission trading system was opened on January 12, 2015, in South Korea. Using the greenhouse gas emission price of the opening day, US \$8.6 t CO_2^{-1}, as the reference price, the estimated economic value of potential CO_2 emission was approximately US \$204 M. Economic value estimated using total tidal flat area in Korea (assuming this to be represented by the three study sites) was US \$1.6 billion. Value per unit area was taken to be US \$6600 ha^{-1}.

The economic value of tidal flats, assuming that the three examples in our study represent the entire habitat in South Korea, is US \$1.6 billion. Their value per unit area is US \$6600 ha^{-1}. Choi (2004) reported a value of US \$14,700 ha^{-1} for South Korean tidal flats with respect to aquatic products and water purification. The potential CO_2 emissions estimated in this study contribute an additional US \$21,300 ha^{-1} of value.

Conclusions

Estimating the scale of blue carbon storage on tidal flats and estuarine salt marshes allowed us to assess the effects of conservation and restoration on carbon capture in South Korea. By comparing these results with data from terrestrial ecosystems, the economic value of coastal wetlands could be estimated, with the following conclusions:

1. The Pristine Mud Flat, which is a conserved region, had the highest soil carbon storage per unit area. Carbon storage per unit area of the Impacted Salt Marsh (a restored site) was slightly lower than that of the Pristine Salt Marsh (a natural site). However, the Pristine Mud Flat, which is a well-conserved site, stored more carbon per unit area than Impacted Mud Flats 1 and 2. The results suggest that, for carbon capture, conservation is more effective than restoration and well-conserved natural habitats can provide higher carbon storage capacity.

2. In terms of storage per unit area, the coastal study sites stored more carbon than terrestrial ecosystems. This implies that the coastal ecosystem stores more carbon in soil per unit area than any other environment.
3. The potential CO_2 emission was 23.2 Tg CO_2, with an equivalent economic value of US $204 M. For the entire tidal flat environment in Korea, the value is US $1.6 billion. Combining the economic value estimated for aquatic products and water purification with the value of potential CO_2 emissions, the total was calculated as US $21,300 ha^{-1}.

These results provide the basis for future research into the blue carbon potential of coastal wetlands. Future research needs to include various types of coastal wetlands such as mangrove in Asia. Mangroves are very common in some south Asian country; however, some main blue carbon plants as mangroves were not included and analyzed in this paper, so it is hard to say if it can be applied to other Asian countries, as marine coastal ecosystem of South Korea is really different to other tropical Asian countries. Nonetheless, this study is particularly valuable given the lack of blue carbon data for developing countries in Asia.

With appropriate and timely action for conservation, increased recognition of the importance of coastal blue carbon systems will lead to improved management and regulation of coastal areas. It will also provide a basis for incentives, including financial mechanisms, to conserve or restore these systems and to manage emissions, supporting mitigation of the impacts of and adaptation to climate change.

Materials and methods

For this study, two estuarine salt marshes and three tidal flats were selected including one restored estuarine salt marsh and one well-conserved tidal flat to observe the effect of coastal wetland restoration on carbon capture (Fig. 1).

Estuarine salt marsh

Eulsukdo (Impacted Salt Marsh, hereafter) and Seomjin River estuary (Pristine Salt Marsh, hereafter) were selected as examples of restored and natural estuarine salt marsh, respectively. The ecosystem of the Impacted Salt Marsh, which is an alluvial island located in the mouth of the Nakdong River, was severely damaged by construction of an estuary bank in 1987 (Lineman et al. 2014). From 2003 to 2005, a restoration project involved the construction of artificial wetlands as a habitat for migratory birds (Nakdong Estuary Eco Center 2011). A *Phragmites australis* community is locally dominant in this wetland. The Pristine Salt Marsh extends across five provinces including Chonnam Gwangyang and Suncheon and is the only large conserved natural estuary in South Korea (Yoo 2007). Alluvial plain development is weak due to the steep downstream slope, and *Phragmites australis* is the dominant community in South Korea (Ministry of Environment 2005).

Tidal flat

Suncheon Bay (Pristine Mud Flat, hereafter) was selected as a well-conserved tidal flat area. The site is located in the southern mid-west and is a registered coastal wetland under the Ramsar Convention (Lee et al. 2013). Its value has also been recognized by designation as a National Heritage in 2008. A large-scale brackish wetland with a *Phragmites australis* community occupies the inland bay side, with a large-scale tidal flat with *Suaeda japonica* community on the shore side. The site is the major eco-tourist destination in South Korea and is actively conserved as a natural ecological park.

Tidal flats in Gangwha-gun (Impacted Mud Flat 1, hereafter) and Garolim Bay (Impacted Mud Flat 2, hereafter) were selected as examples of natural tidal flats with human intervention. There are many islands nearby, including Gwanghwa Island in Impacted Mud Flat 1, and also a large tidal flat formed by inflow from the Imjin and Han Rivers (Kim et al. 2007). Halophyte communities are poorly developed since much of the tidal flat has been reclaimed by Korean government to expand agricultural fields. Impacted Mud Flat 2 is a semi-closed back bay surrounded by the Taean-gun and Seosan shores and has a relatively well-conserved natural tidal flat (Yoo and Lee 2008). This is the largest bay in South Korea and is subject to high development pressure as its high tides make it an optimal location for tidal power generation.

Data collection

The major carbon pools in a tidal salt marsh are above-ground biomass and below-ground biomass and soil. Soil and below-ground biomass are here considered as a single carbon pool since it is difficult to partition the two components (Chmura et al. 2003; Howard et al. 2014). Data on soil organic matter content, coastal wetland area, and above-ground biomass of dominant vegetation were obtained from a literature survey (Table 1). Emergent vegetation is not a major primary producer in tidal flats in South Korea (Ministry of Oceans and Fisheries 2005), and it was assumed that its contribution to carbon capture was negligible.

Estimation of carbon storage and economic impact

Monte Carlo simulation was used to estimate carbon storage values. This method is commonly used to

estimate values with high variability and very large uncertainty ranges (Binder et al. 1993). Simulation was performed using SPSS 21.0. One million runs were performed for each study site, giving a mean value with 90% confidence interval.

Calculation of carbon stored in soils

Total carbon storage capacity is generally calculated by multiplying dry bulk density, soil organic carbon content, the depth of the organic layer, and the wetland area (Howard et al. 2014). Carbon storage was calculated as shown in Eq. 1. The depth of the organic layer was assumed to be 1 m, which is a typical estimate for coastal areas in temperate regions (Howard et al. 2014).

$$\begin{gathered} C_{\text{soil}}(\text{Mg}) = \rho_b(\text{Mg}\,m^{-3}) \times [\text{OC}(\%)/100] \times A_{\text{cw}}(m^2) \times 1m \\ \rho_b(\text{Mg}\,m^{-3}) = (2.684 - 140.943 \times 0.008) \times \exp\left[-0.008 \times \text{OC}(g\,\text{kg}^{-1})\right] \\ \text{OC}(\%) = 0.47 \times \text{OM}(\%) + 0.0008 \end{gathered} \quad \text{(Eq.1)}$$

where C_{soil} is the carbon storage capacity of soil up to 1 m, ρ_b is the dry bulk density of soil, OM is the soil organic matter content, OC is the soil organic carbon content, and A_{cw} is the area of coastal wetland. Equations for calculating ρ_b and OC were obtained from the literature review (Howard et al. 2014; Ruehlmann and Körschens 2009).

Table 4 compares our estimates for carbon storage per unit area of salt marsh soils (top 1 m) with data from previous studies. Table 6 summarizes the soil texture of the salt marsh study sites, showing that sand content is high in both regions. According to literature data for these study sites, soil organic matter content was ~ 2.9% for the Pristine Salt Marsh and 2.1% for the Impacted Salt Marsh (Table 1).

Calculation of carbon stored in plant biomass

Total carbon storage in vegetation is calculated by multiplying the vegetation biomass, the carbon conversion factor, and the area (Howard et al. 2014). The carbon conversion factor represents the fraction of carbon in vegetation and varies with vegetation type (Howard et al. 2014). This study considered only the dominant vegetation of the estuary salt marsh communities, *Phragmites australis*, for which the carbon conversion factor is 0.45 (Howard et al. 2014). This value is specifically for *Phragmites australis*. Values were estimated as shown in Eq. 2.

$$C_{\text{plant}}(g) = \text{SB}\left(g\,m^{-2}\right) \times 0.45 \times A_{\text{plant}}\left(m^2\right) \quad \text{(Eq.2)}$$

where C_{plant} is the carbon storage in the *Phragmites* community, SB is the above-ground standing biomass of *Phragmites*, and A_{plant} is the area occupied by the *Phragmites* community.

Estimation of economic value

The total economic value of the study area was estimated using a mean total carbon stock. Potential CO_2 emission was used to calculate the economic value for each site assuming a conversion factor of US \$8.6 t CO_2^{-1} (Howard et al. 2014). The reference price for CO_2 was obtained from the greenhouse gas emissions trading system opened in 2015.

Additional file

Additional file 1: Table S1. Raw data sampling point of soil organic carbon storage per unit areas and source for literature to create Table 1. Table S2 Source of reference for carbon stock in different ecosystem for Fig. 3. (DOCX 27 kb)

Acknowledgements

This work has supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT)(2018R1C1B6005351). We are grateful to NRF (2016R1D1A1A02937049, 2017096A001719BB01) for financial support.

Funding

This work has supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT)(2018R1C1B6005351). We are grateful to NRF (2016R1D1A1A02937049, 2017096A001719BB01) for financial support.

Availability of data and materials

Please contact author for data request.

Authors' contributions

CB wrote the manuscript and revised the manuscript. SL carried out the data analysis and writing of the general draft of the manuscript. HK revised the manuscript. All authors read and approved the final manuscript.

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

Received: 4 December 2018 Accepted: 25 February 2019
Published online: 22 March 2019

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