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Potential Blue Carbon from Coastal Ecosystems in the Republic of Korea

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Abstract – The sequestration of carbon dioxide (CO_2) from the atmosphere and ocean into coastal ecosystems such as seaweed beds, seagrasses, saltmarshes, and tidal flats is an important and emerging area of interest due to their valuable role in carbon storage and potential for moderating climate conditions. Here, we investigated how these ecosystems in Korea can serve as carbon sinks and estimated the amount of CO_2 that might be removed through aquaculture beds, artificial reefs, and sea forests. We also examined the benefits of restoring degraded coastal ecosystems. In total, we estimated that the 0.38×10^6 ha covered by Korean coastal ecosystems could potentially lock up approximately 1.01×10^6 t of CO_2.

Key words – blue carbon, coastal ecosystem, carbon accumulation, CO_2 sequestration

1. Introduction

In 2009, blue carbon initiatives for mitigating the effects of climate change were proposed (Nellemann et al. 2009). The goal was to protect and restore lost CO_2 sink capacity and prevent the additional loss of deposits by cultivating seaweed beds and reefs in coastal areas. The surrounding soil and vegetated biomass produced by mangroves, tidal salt marshes, and seagrass beds can act as large reservoirs for atmospheric and oceanic CO_2. In fact, this carbon is termed 'blue carbon' because it is associated with marine ecosystems (Murray et al. 2011; Grimsditch and Chung 2012; Siikamaki et al. 2012; Howard et al. 2014). Seaweed beds, representing an important ecological and economical ecosystem for Korea, may potentially provide similar carbon storage benefits.

Natural coastal ecosystems of seagrasses, tidal marshes, and mangroves sequester and store large quantities of carbon in both the plants and the sediment beneath (International Working Group on Coastal Blue Carbon 2011). Rates of carbon sequestration and storage at those sites are comparable to, and often higher than, values calculated for carbon-rich terrestrial ecosystems such as tropical rainforests or freshwater peatlands. However, unlike most land-based systems, which attain soil-carbon equilibrium within decades, the deposition of CO_2 into coastal sediments can continue over millennia (Grimsditch and Chung 2012).

Despite their value, wild seaweed beds, tidal flats, and areas of seagrass and saltmarsh are declining in size primarily because of pressures from large-scale reclamation, such as restoration of tidal flats, development of port hinterlands, and construction of industrial complexes (Kim 2013). Koo et al. (2011) have also reported that, since the 1980s, the coastal wetlands of Korea have been rapidly degraded and destroyed mainly due to reclamation and the establishment of landfills to accommodate coastal development.

Compared with marine organisms, e.g., phytoplankton, macrophytes such as seaweeds and seagrasses can be more effective carbon sinks because of their large biomass and relatively long turnover time (Gao and McKinley 1994; Delille et al. 2009). Macroalgae have also gained interest for CO_2 bioremediation programs (Chung et al. 2011, 2013). Seaweeds can transform dissolved inorganic carbon (DIC) directly or indirectly from seawater via photosynthesis, thereby decreasing the pCO_2 in seawater. Therefore, by removing a significant amount of carbon from the ocean when they are harvested (Tang et al. 2011), these life forms serve as valuable tools for both biomass production and CO_2 sequestration (Duarte et al. 2005). Table 1 shows the mean and range value of soil

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Table 1. Levels of soil carbon stocks (to 1 m depth) in mangrove, tidal marsh, and seagrass ecosystems, and CO_2 equivalents (IPCC 2013)

Ecosystem	Carbon stock ($Mg \cdot ha^{-1}$)	Range ($Mg \cdot ha^{-1}$)	CO_2 ($Meq \cdot ha^{-1}$)
Mangrove	386	55-1,376	1,415
Tidal salt marsh	255	16-623	935
Seagrass	108	10-829	396

organic carbon stocks up to 1 m deep in the sediments of mangrove, tidal marsh, and seagrass ecosystems together with their CO_2 equivalents per hectare.

However, these coastal ecosystems are also among the most threatened, with global losses being as much as 67% for mangroves, 35% for tidal salt marshes, and 29% for seagrasses (Howard et al. 2014). Predictions are that 30 to 40% of all tidal marshes and seagrasses and nearly 100% of existing mangrove ecosystems could be lost in the next 100 years (Duke et al. 2007; IPCC 2007; Pendleton et al. 2012).

Intertidal habitats, including mudflats, seagrass meadows, tidal salt marshes, and mangroves, are among the most productive ecosystems in the world because they sequester CO_2 and provide safe spawning areas and nurseries for fish and crustaceans upon which coastal fisheries depend (Yusoff et al. 2006). Although only a small fraction of the coastal marine area is occupied by such vegetation, those types of ecosystems account for 46.9% of the total carbon found in ocean sediments (Duarte et al. 2005; Nellemann et al. 2009). Because of their potential to sequester CO_2, we compared carbon storage estimates between natural environments and cultivated coastal ecosystems such as seaweed aquaculture beds (SABs), manmade seaweed reefs, and sea forests.

Saltmarshes

Because of the large difference between flow and ebb tides, salt marshes are prominent along the western and southern coasts of Korea, where they now occupy 2.7% of the total area (Han 2008), or approximately 1,648 ha (Park et al. 2008). In most regions, however, these marshes have been exploited by humans for salterns, farming, and reclamation (Lee et al. 2012). This high intensity of use has meant that numerous marshes have been damaged or have already disappeared (Ministry of Environment 2006). Major species found in Korean salt marshes include *Suaeda maritima*, *S. japonica*, *Carex kobomugi*, *Elymus mollis*, and *Aster tripolium*.

Tidal flats

Tidal flats are a major habitat type in the Yellow Sea (West Sea), especially in Korean coastal areas. Approximately 6,990 local flats have been identified in that nation. Because of differences in coastal slopes and tidal ranges, these wetlands are not distributed evenly, with approximately 83% being found on the west coast and 17% along the south coast (Moore 2002). In 1998, those flats covered approximately 280,000 ha, with most lacking any vegetation. However, a survey in 2013 showed that this size had decreased to 248,720 ha (Tidal Flat Korea 2014). Despite the absence of plants in most flats, some smaller regions tend to support *Suaeda* saltmarsh.

Wild seaweed beds

The 624 seaweed species found in Korea include 48 blue green algae, 81 green algae, 135 brown algae, and 360 red algae (Lee and Kang 1986). Data collected in 2006 by the Korean government Ministry of Ocean and Fisheries (KACCC 2013) indicated that these habitats are most abundant in bedrock regions along the coasts of the East, South, and Yellow Seas, where they are estimated to cover 53,838 ha. Most wild seaweeds are found in shallow rock-exposed areas, sandstones, conglomerate outcrops, sand, and mud. In all of those Seas, communities are dominated by boreal species within *Saccharina*, *Costaria*, and *Coccophora* as well as temperate species within *Undaria*, *Sargassum*, *Ecklonia*, and *Pachymeniopsis* (Kang 2010).

Seaweed aquaculture beds

Seaweed aquaculture beds are cultivated ecosystems designed to provide the same services as wild beds. Both natural and farmed stocks of seaweeds have long been extensively exploited in Korea. Currently, the major seaweeds being produced are *Pyropia* spp. (gim), *Undaria pinnatifida* (miyeok), *Sargassum fusiforme* (formerly *Hizikia fusiforme*), and kelp (or dasima), primarily *Saccharina japonica* (*Laminaria*) (Jung 1988). These SABs are concentrated in western and southern coastal areas such as Wando, Mokpo, Yeosu, and Busan. In Korea, approximately 72,461 ha of SABs are being cultivated (KOSTAT 2012).

Artificial seaweed reefs

Korea's interest in developing artificial seaweed beds began at the end of the 1990s, when several construction techniques were tested. Some of those methods proved effective in the restoration of damaged beds while others were either not persistent or else did not fulfill environmentally friendly purposes (Kim et al. 2013). No accurate data are available concerning the area currently utilized by artificial seaweed reefs in Korea.

Sea forests

Wild seaweed forests have been severely damaged along Korean coasts because of algal whitening events. The impact of this expanded from 6,954 ha in 2004 to 14,317 ha in 2010 (KACCC 2013). In 2009, the Ministry of Oceans and Fisheries launched the Sea Forest Development program to prevent their further destruction. As of 2013, sea forests covered a total of 3,263 ha.

Seagrasses

Most seagrass beds near the Korean Peninsula have rapidly disappeared in the past two or three decades due to human activities such as reclamation, dike-building, urbanization, and industrialization. These beds cover 3,580 ha along the southern, eastern, and western intertidal areas. *Zostera marina*, *Z. caulescens*, *Z. caespitosa*, *Z. asiatica*, *Z. japonica*, *Phyllospadix japonicus*, *P. iwatensis*, and *Halophila nipponica* are the most widely distributed species in those regions.

2. Materials and Methods

Estimates of blue carbon storage are generally based on the amount of biomass produced by coastal vegetation. The Intergovernmental Panel on Climate Change (IPCC) has developed a three-tier method for obtaining detailed carbon inventories that reflect the degree of certainty or accuracy of a carbon stock inventory or assessment (Howard et al. 2014). For the purpose of our study, we referred to Tier 1, based on a simplified assumption of blue carbon in coastal ecosystems, because we lacked site-specific data on carbon stocks. The percentage of carbon thought to be stored in seaweed has ranged widely in previous research. Muraoka (2004) estimated contents of approximately 25 to 31% and 32 to 34% C in *Saccharina* and *Ecklonia*, respectively. Rates for *Pyropia* and *Saccharina* have been reported as 27.30% and 23.60%, respectively (Fei 2004), and 27.39% C for *P. yezoensis* (Tang et al. 2011). Carbon levels have been calculated at between 29 and 36% for *Laminaria digitata* and from 20 to 31% for *Macrocystis pyrifera* (Beavis and Charlier 1987). The accumulation of C has been assumed to be 30% of total dw for artificial seaweed reefs, SABs, and sea forests (Mann 1972; Gao and McKinley 1995; Zemke-White and Ohno 1999).

To obtain the total area used for SAB production in 2012, we examined data from the Food and Agricultural Organization (FAO 2014) and Korean Statistics (KOSTAT 2012). The amount of accumulation and sequestration within wild seaweed beds was then estimated according to the area containing bedrock, i.e., 53,838 ha (KACCC 2013), which was assumed to be dominated by species within *Ecklonia*, *Eisenia*, *Saccharina*, and *Sargassum*. For example, the total potential C accumulation by seaweed was determined by the following procedure. First, the total amount of seaweed produced was converted to a dry weight value, which was considered to be equal to 10% of the wet weight (Mann 1972), then multiplied by 30% to obtain total C accumulation. Next, that quantity was multiplied by 3.67 (a conversion factor based on the molecular weight of CO_2) to compute the potential amount of sequestered CO_2. Finally, totals for potential C accumulation and CO_2 sequestration were calculated by multiplying the amount of either C accumulated or CO_2 sequestered (adjusted value), respectively, by the entire area covered by seaweed beds along the Korean coasts. To determine the total area occupied by tidal flats in Korea, we utilized statistical data (Tidal Flat Korea 2014) for intertidal marshes (i.e. salt marshes, salt meadows, salterns, and raised salt marshes, both brackish and fresh-water) (Park et al. 2008). The size of seagrass beds in Korea and information about their resident species were obtained through personal communications with Lee Sang Yong (National Fisheries Research and Development Institute, Korea). Previous estimates of the potential CO_2 sequestration have varied among tidal wetlands. Chmura et al. (2003) have reported that saltmarshes and mangroves can accumulate 550 to 917 g CO_2 e m^{-2} y^{-1}. Seagrasses account for approximately 15% of all carbon stored in the ocean, at a rate of 83 g C m^{-2} y^{-1} (Kennedy and Bjork 2009). Our procedures for computing accumulations and sequestration rates by tidal flats, saltmarshes, and seagrass followed those described by Duarte et al. (2005). The potential amount of C that could be accumulated by a coastal ecosystem was calculated by multiplying the C-accumulation rate in each type of ecosystem (tidal flat = 45 g C m^{-2}, saltmarsh = 151 g C m^{-2}, and seagrass = 83 g C m^{-2}) by the total area covered by that type. Potential CO_2 sequestration was calculated by multiplying the amount of accumulated C in an ecosystem by the conversion factor of 3.67.

3. Results

Wild seaweed beds

Assuming that the 53,838 ha of wild seaweed along the Korean coast is dominated by species within *Eisenia/Ecklonia*, *Saccharina*, and *Sargassum*, then their respective concentrations of organic carbon would be 1.67 kg m^{-2}, 0.13 kg m^{-2}, and 0.60 kg m^{-2} (Ito et al. 2009). Total amounts predicted for accumulation and sequestration by each species are shown in Table 2, based on data from 2013.

Artificial seaweed reefs

Five artificial reefs have been developed at different locations on Jeju Island, Korea, covering a total area about 330 ha. Rates of accumulation and sequestration by *Undaria*, *Pyropia*, and *Saccharina* are presented in Table 3.

Seaweed aquaculture beds

Table 4 illustrates the carbon status in SABs during 2012 for *Undaria*, *Pyropia*, *S. japonica*, *Sargassum fusiforme*, and *Sargassum* spp.

Seagrasses

Estimated yields in 2012 are shown in Table 5 for Korean seagrass beds that contained *Zostera marina*, *Z. caulescens*, *Z. caespitosa*, *Z. asiatica*, *Z. japonica*, *Phyllospadix japonicus*,

Table 2. Potential carbon accumulation and potential sequestration of CO_2 in 2013 for Korean beds of wild seaweed

Seaweed	Carbon accumulation (t)	Potential CO_2 sequestration (t)
Eisenia/Ecklonia	116,882.30 (2.17 t·ha^{-1})	428,958.03 (7.97 t CO_2·ha^{-1})
Saccharina	69,989.40 (1.30 t C·ha^{-1})	256,861.10 (4.77 t CO_2·ha^{-1})
Sargassum	323,028.00 (6.00 t C·ha^{-1})	1,185,512.76 (22.02 t CO_2·ha^{-1})

Table 3. Estimates of carbon accumulation and potential CO_2 sequestration by *Undaria*, *Pyropia*, and *Saccharina* on the artificial seaweed reefs of Jeju Island, Korea (1999)

Seaweed	Area (ha)	Carbon accumulation (t)	Potential CO_2 sequestration (t)
Undaria	330	990.00 (3.00 t C·ha^{-1})	3,633.30 (11.01 t CO_2·ha^{-1})
Pyropia	330	5,940.00 (18.00 t C·ha^{-1})	21,799.80 (66.06 t CO_2·ha^{-1})
Saccharina japonica	330	2,376.00 (7.20 t C·ha^{-1})	8,719.92 (26.42 t CO_2·ha^{-1})

Table 4. Estimates of carbon accumulation and potential CO_2 sequestration in 2012 for commercially important seaweeds in Korean SABs

Seaweed	Area (ha)	Carbon accumulation (t)	Potential CO_2 sequestration (t)
Undaria	5,846	10,197.72 (1.74 t·ha^{-1})	37,425.63 (6.40 t·ha^{-1})
Pyropia	56,922	10,494.81 (0.18 t·ha^{-1})	38,515.95 (0.68 t·ha^{-1})
Saccharina japonica	7,300	9,258.03 (1.27 t·ha^{-1})	33,976.97 (4.65 t·ha^{-1})
Sargassum fusiforme	1,939	390.72 (0.20 t·ha^{-1})	1,433.94 (0.74 t·ha^{-1})
Sargassum spp.	454	40.62 (0.09 t·ha^{-1})	149.08 (0.33 t·ha^{-1})
Total	72,461	30,381.90 (3.48 t·ha^{-1})	111,501.57 (12.80 t·ha^{-1})

Table 5. Estimates of carbon accumulation and potential CO_2: potential sequestration in 2012 for seagrass beds in Korea

Seagrass	Area (ha)	C accumulation (t)	Potential CO_2 sequestration (t)
Zostera marina	3,482.78	2,890.71	10,608.89
Z. caulescens	78.82	65.42	240.11
Zostera caespitosa	2.47	2.05	7.52
Z. asiatica	5.57	4.62	16.96
Z. japonica	5.71	4.74	17.40
Phyllospadix japonicus	0.35	0.29	1.06
P. iwatensis	3.87	3.21	11.78
Halophila nipponica	0.57	0.47	1.73
Total	3,580.14	2,971.51	10,905.45

Table 6. Estimates of carbon accumulation and potential CO_2 sequestration in 2013 for tidal flats along the western and southern coasts of Korea

Site	Area (ha)	Carbon accumulation (t)	Potential CO_2 Sequestration (t)
Western coast	208,450	93,802.50	344,255.18
Southern coast	40,270	18,121.50	66,505.91
Total	248,720	111,924.00	410,761.09

Table 7. Estimates of carbon accumulation and potential CO_2 sequestration by saltmarshes in four Korean provinces in 2008

Province	Area (ha)	Carbon accumulation (t)	Potential CO_2 sequestration (t)
Gyeonggi	36.13	54.55	200.21
Chungcheongnam	24.80	37.44	137.42
Jeollabuk	1,583.57	2,391.19	8,775.67
Jeollanam	3.50	5.29	19.40
Total	1,648.00	2,488.47	9,132.70

P. iwatensis, and *Halophila nipponica*.

Tidal flats

Table 6 shows that annual accumulations and sequestration rates differed between the western and southern coasts of Korea in 2013.

Saltmarshes

Carbon yields and CO_2 sequestration rates in saltmarshes from four provinces in Korea during 2008 are presented in Table 7.

Sea forests

Table 8 illustrates the levels of C accumulation and CO_2 sequestration by sea forests in Korea in 2013, based on a total area of 3,263 ha.

Table 8. Estimates of carbon accumulation and potential CO_2 sequestration by Korean sea forests in 2013

Genus	Carbon accumulation (t)	Potential CO_2 sequestration (t)
Undaria	9,789 (3.00 t·ha^{-1})	35,926 (11.01 t·ha^{-1})
Pyropia	58,734 (18.00 t·ha^{-1})	215,554 (66.06 t·ha^{-1})
Saccharina	23,494 (7.20 t·ha^{-1})	86,222 (26.42 t·ha^{-1})

4. Discussion

Intertidal habitats are increasingly being recognized for their capacity to store carbon (Decho 2000). However, such habitats in Korea are being lost at increasing rates. For example, the total area covered by flats decreased from 320,350 ha in 1987 to 248,720 ha in 2013 (Tidal Flat Korea 2014). An important consideration is that, as such ecosystems become degraded or disappear, most of the blue carbon within their sediments is released into the atmosphere and ocean where it can form CO_2 through oxidation. The global rate of decline by saltmarshes has increased from a median of 0.9% yr^{-1} before 1940 to 7% yr^{-1} since 1990 (Waycott et al. 2009). Murray et al. (2011) have estimated that the size of coastal ecosystems has been reduced by approximately 340,000 to 980,000 ha annually. If these trends were to continue, a further 30 to 40% of all tidal marshes and seagrasses could be lost in the next 100 years (Pendleton et al. 2012).

Table 9. Total carbon accumulation and potential CO_2 sequestration by the vegetation in Korean coastal ecosystems.

Ecosystem	Area (ha)	Carbon accumulation (t)	CO_2 sequestration (t)
SAB	72,461.00	30,381.90 (3.48 t·ha^{-1})	111,501.57 (12.80 t·ha^{-1})
Seagrass	3,580.14	2,971.51 (0.83 t C·ha^{-1})	10,905.45 (3.05 t CO_2·ha^{-1})
Saltmarsh	1,648.00	2,488.47 (1.51 t C·ha^{-1})	9,132.70 (5.54 t CO_2·ha^{-1})
Tidal flat	248,720	111,924.00 (0.05 t C·ha^{-1})	410,761.09 (0.17 t CO_2·h^{-1})
Seaweed artificial reef (*Undaria*)	330.00	990.00 (3.00 t C·ha^{-1})	3,633.30 (11.01 t CO_2·ha^{-1})
Sea forest (*Undaria*)	3,263.00	9,789.00 (3.00 t C·ha^{-1})	35,926.00 (11.01 t CO_2·ha^{-1})
Wild seaweed bed (*Ecklonia*)	53,838.00	116,882.30 (2.17 t C·ha^{-1})	428,958.03 (7.97 t CO_2·ha^{-1})
Total	383,840.14	275,427.18	1,010,818.27

The loss of macroalgae habitats has been widespread on rocky coastlines along the eastern Korean Peninsula. Damage associated with whitening events has been reported following a rise in water temperatures in adjacent seas due to recent climate change (KACCC 2013). These events also have negative impacts on fisheries production because seaweed colonies have important functions as spawning grounds and habitat for marine organisms. Their disruption causes severe reductions in fish and shellfish populations. Efforts are increasing to restore and create macroalgal beds that might mitigate those losses. One popular method is to deploy artificial reefs made from concrete pyramids to which kelp is attached (Kang et al. 2008). Of particular interest in Korea are species within *Sargassum*, *Saccharina*, and *Ecklonia*. Such constructions are considered necessary if we are to recover these natural resources. In addition, artificial reefs have been designed to mitigate the loss of kelp forests. If installed properly, they could be used to expand those habitats and thereby increase the storage of kelp carbon (Reed and Brzezinski 2009).

Seaweed beds and kelp forests are also likely candidates for blue carbon sequestration and storage. However, unlike other blue carbon ecosystems, these communities lack soil substrates. Thus, they do not retain large amounts of carbon in their sediments even though they can act as carbon sinks by reducing DIC (Grimsditch and Chung 2012). Those ecosystems play important roles in maintaining biodiversity, providing coastal protection, improving water quality, and sequestering some carbon. We believe that, although SABs are artificial ecosystems, their services are similar to those gained from natural beds simply because both types sustain life on earth. Chung et al. (2013) have also demonstrated that, as CO_2 sinks, seaweeds can sequester/convert carbon within their biomass throughout their entire life span.

Carbon from SABs can be used as a component of animal feed or food products for humans. When doing so, the CO_2 is regenerated during respiration and no uptake of carbon occurs. As an alternative fate, it can be utilized by bacterial communities and converted to DIC, buried in the sediment, or transported to the deep ocean where it can be retained for hundreds of years (Harrold et al. 1998; Dierssen et al. 2009). Ito et al. (2009) have stated that the main process in carbon fixation is the sedimentation of withered grass bodies and underground stems without degradation. Examples of this include beds of *Zostera marina*, *Eisenia*, *Ecklonia*, or *Sargassum*, where drifting plant material is eventually transferred to offshore mesopelagic zones.

Biomass production from SABs in Korea has increased steadily in the past several decades and was estimated in 2012 to be more than 1,000,000 t (wet wt). This rise in production rates has become more pronounced since the 1980s because of various technical improvements, transplantation of new species of *Pyropia*, and expansion into new culture grounds (Sohn 2014). Consequently, that type of ecosystem has promoted carbon accumulations and CO_2 sequestration. Another approach has been to develop sea forests. In fact, by 2012, projects by the Ministry of Oceans and Fisheries in Korea had been implemented at 36 coastal sites (1,926 ha). An additional nine (1,337 ha) were added in 2013. The goal is to have another 30,000 ha in operation by 2030 (KACCC 2013).

Estimates for total amounts of potential carbon accumulation and CO_2 sequestration by Korean coastal ecosystems are shown in Table 9. Even though soil carbon is by far the largest carbon pool for the focal coastal habitats (i.e., seagrasses 500 t CO_2 e ha^{-1} and salmarshes 917 t CO_2 e ha^{-1}) (Murray et al. 2011), our study results demonstrate the promising roles these ecosystems have. Moreover, if cultivation via SABs remains stable, then the introduction of seaweed farming to additional areas will provide new standing stock for accumulating carbon and sequestering CO_2 in Korea.

5. Remarks

Determining the exact amount of blue carbon stored in Korean coastal ecosystems is still an active area of research. However, it is clear that these sites strongly contribute to environmental health as carbon sinks. Efforts to expand the areas used for establishing SABs, artificial reefs, and sea forests, especially in Korea, mean that more carbon can be accumulated and CO_2 levels can be reduced.

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