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Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean Project Overview

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Seaweed beds can serve as a significant carbon dioxide (CO_2) sink while also satisfying global needs for food, fodder, fuel, and pharmaceutical products. The goal of our Korean Project has been to develop new baseline and monitoring methodologies for mitigation and adaptation within the context of climate change. Using innovative research approaches, we have established the Coastal CO_2 Removal Belt (CCRB), which comprises both natural and man-made plant communities in the coastal region of southern Korea. Implemented on various spatial–temporal scales, this scheme promotes the removal of CO_2 via marine forests. For example, when populated with the perennial brown alga *Ecklonia*, a pilot CCRB farm can draw down ~10 t of CO_2 per ha per year. This success is manifested by an increment in biomass accumulations and a decrease in the amount of dissolved inorganic carbon in the water column.

Keywords: blue carbon, carbon sink, Coastal CO_2 Removal Belt (CCRB), kelp forest, seaweed.

Introduction

Covering 71% of the earth's surface, seawater plays a dominant role in regulating climate, offering great potential for fixing and removing atmospheric carbon dioxide (De Vooys, 1979; Raven and Falkowski, 1999; Falkowski *et al.*, 2000; Pelejero *et al.*, 2010). Although they account for <2% of the sea surface, macrovegetated marine habitats contribute ~210–244 Tg C $year^{-1}$ or ~50% of all carbon sequestered in the global coastal oceans (Duarte *et al.*, 2005).

The potential for coastal marine vegetation, mangroves, salt marshes, and seagrass meadows to store carbon can be husbanded and enhanced through various management approaches, including marine area protection, marine spatial planning, area-based fisheries management techniques, regulated coastal development, and ecosystem restoration (Laffoley and Grimsditch, 2009). This important vegetation, also known as blue carbon, is cycled through food chains and metabolic processes in seas and oceans, where it becomes bound or sequestered in natural systems (Nellemann *et al.*, 2009). Knowing the scale of conversion of inorganic carbon into biomass, its subsequent sinking to the seabed and its sequestration over thousands of years are basic to our understanding of the ocean as a potential sink for increasing levels of atmospheric CO_2. The other modes of fate of seaweed biomass depend on natural processes. This seaweed can be consumed by herbivores, whose faeces sink to the bottom and may remain there for a while. Moreover, distal portions of the fronds disintegrate during the summer season and those fragments enter the detritus food chain. Exudation as a dissolved organic material can be a critical loss. Therefore, some of the seaweed carbon will return to the water column and be either recaptured during photosynthesis or eventually returned to the atmosphere.

However, depending on location, currents, etc., a significant fraction of the algal carbon can be sequestered on the sea floor for a long period, perhaps centuries. This has been suggested for microalgae, where "about half of (. . . phytoplankton . . .) bloom biomass sank to depths of 1,000 metres or more, well below the upper mixed layer . . . Carbon sunk in this way can stay stored for centuries, until deep, slow ocean currents eventually bring it back to the surface" (Smetacek *et al.*, 2012). Sun *et al.* (2008) have reported that, in a massive algal bloom of three million tonnes fresh weight along the coast of China, an estimated two-thirds settled into deep waters. Thus, there is reason to deduce that a massive removal of algal carbon to deep water and to the sea floor can result from a large-scale CCRB that could be positioned on the surface over relatively deep water. Because the Clean Development Mechanism (CDM) project does not allow harvesting for any economic income, the lifespan of seaweeds in the CDM farm might be ∼5 years before it dies (such as for *Ecklonia*). In addition to carbon sequestration, seaweed could be harvested to produce biofuels, thereby ensuring that CO_2 is not simply recycled back into the air, but instead replaces fossil fuel with renewable fuel.

Seaweed cultivation is among the many measures that have been introduced for mitigating global warming through enhanced natural sinks. Matthews (1996) has reviewed several climate engineering proposals and has provided a comprehensive resource and ideas for countering this environmental problem. Seaweed has loomed large in those early ocean algae proposals. There, kelp farms are designed to encompass tens of thousands of square kilometres of the open ocean. Seaweed beds act as effective sinks by drastically reducing the level of dissolved inorganic carbon (DIC). To determine the extent of transfer between air and sea, a rigorous assessment of the CO_2 fluxes that are driven by kelp/seaweed beds requires a comprehensive survey of the partial pressure of CO_2 (pCO_2) in the surrounding waters, coupled with an appraisal of water mass advection (Delille *et al.*, 2009) and other carbon sources and sinks in coastal regions.

Although kelp forests are important for metabolizing and cycling carbon, they have received little consideration within the context of sequestration (N'Yeurta *et al.*, 2012). Unlike other blue carbon sectors (mangroves, seagrasses, and salt marshes) that accumulate and retain large amounts of carbon in sediments, kelp forests and seaweed beds do not have such sedimentary substrata. Instead, their carbon-rich biomass detaches and is broken down in food chains by organisms that range in scale from grazing animals to pelagic and seabed bacteria. Because sediment is absent from kelp forests and seaweed beds, such that they lack functionality as large carbon sinks, it is unlikely that the benefit of these marine resources can be addressed through carbon markets and management strategies that are strictly based on long-term (centennial) sequestration. However, there is substantial potential to develop seaweed CDM methodologies by capturing carbon through algal photosynthesis and using the resulting biomass as a substitute for fossil hydrocarbons. Moreover, although shallow nearshore waters are the natural habitat of most cultured macroalgae, their range can be easily extended to the open sea (Buck *et al.*, 2004). This has been suggested as a win-win mitigation strategy for encouraging sustainable and environmentally sound ocean-based production of plants such as algae and seaweed (Laffoley and Grimsditch, 2009).

As primary producers in the marine ecosystem, seaweeds fix abundant CO_2 through photosynthesis (Smith, 1981; Orr and Sarmiento, 1992; Ritschard, 1992; Gao and McKinley, 1994). Macroalgal communities are very successful; those dominated by *Laminaria hyperborea* can have annual production rates of up to 3 kg C m^{-2} (Abdullah and Fredriksen, 2004). Gao and McKinley (1994) and Muraoka (2004) have also reported algal carbon capture rates of >3 kg C m^{-2} $year^{-1}$. Nearly 0.7 million tonnes of carbon are removed from the sea each year within commercially harvested seaweeds (Turan and Neori, 2010). Although seaweed communities occupy only a very small area of the coastal region, they are essential because of their biotic components, valuable ecosystem services, and high primary productivity (Mann, 1982). The unique three-dimensional habitats of kelp forests also make them biodiversity hotspots in cold waters (Christie *et al.*, 2003; Graham, 2004; Coleman *et al.*, 2007).

Unlike seagrasses and mangroves, seaweeds are photosynthetic algal organisms and, as such, are non-flowering. These primary producers grow in much the same way as their terrestrial counterparts, assimilating carbon through photosynthesis and generating new biomass by taking up nitrogen, phosphorus, and many other essential minerals and trace substances. The quantity of algal biomass that accumulates is normally stated as the amount of carbon fixed by photosynthesis per unit area of space or volume, per unit of time. Most estimates are expressed as net primary production, taking into account the costs of respiration.

Whereas some seaweeds have been cultivated for many centuries, others have traditionally been collected from natural stocks or "wild" populations. Unfortunately, certain of these cultivated species are now in decline due, in part, to overharvesting. Recent advances in mariculture techniques have led to increased production of seaweeds as a true "marine crop" (Chritchley and Ohno, 1998; Yarish and Pereira, 2008). Large-scale seaweed cultivation is attractive because of its decades-proven, low-cost technologies and the multiple uses that can be made of its products. Turan and Neori (2010) have reviewed the current state of commercial seaweed production and CO_2-assimilation capacities. Although seaweed farming already represents ∼25% of the world's aquaculture production, its potential has not been fully exploited.

Despite incomplete surveys, the global standing kelp crop, allowing for seasonal and spatial variances, is as much as 20 Tg C, based on a biomass density of 500 g C m^{-2} (Reed and Brzezinski, 2009). Net primary production of global kelp forests (deep tropical kelp) has been conservatively estimated to be as much as 39 Tg C $year^{-1}$ (Graham *et al.*, 2007; Reed and Brzezinski, 2009). Overall, seaweeds contribute 16–18.7% of the total marine-vegetation sink. Currently, ∼100 seaweed taxa are under cultivation by standardized, routine, and economical techniques. The genera *Saccharina* (=*Laminaria*), *Undaria*, *Porphyra*, *Eucheuma*, *Kappaphycus*, and *Gracilaria* account for >80% of global production (FAO, 2012). Worldwide rates for aquatic plants in 2010 were $\sim 19.2 \times 10^6$ t; for brown seaweeds, 6.8×10^6 t; red seaweeds, 9.0×10^6 t; green seaweeds, 0.2×10^6 t; and miscellaneous aquatic, 3.2×10^6 t. Based on these figures, Muraoka (2004) has estimated that ∼1000 t of carbon is temporarily sequestered, making the sea as important a carbon sink as terrestrial ecosystems.

Highly productive seaweed species can contribute significantly to the annual biological drawdown of CO_2 and the global carbon cycle (Turan and Neori, 2010). However, to comprehend the magnitude of this drawdown, researchers must determine the quantity and the rate at which this fixed carbon is recycled. Here, we propose practical implementation of seaweed cultivation as a tool for increasing biomass over a designated period. We apply well-established culturing techniques to estimate the amount of carbon sequestered in seaweeds. By doing so, such methods provide measurable, reportable, and verifiable means for utilizing such species as CO_2 sinks.

Korean project: a case study of the practical implementation of seaweed as a mitigation and adaptation measure against global warming

Project overview

Particularly in the tropics, seaweed cultivation holds great promise as a significant CO_2 sink while also meeting, to some extent, the global demand for food, fodder, fuel, and pharmaceutical materials (Sinha *et al.*, 2001). This topic was discussed at the fourth Asian Pacific Phycological Forum (APPF) in Bangkok and was initiated within the "Asian Network for Using Algae as a CO_2 Sink" that was approved by Asian Pacific Phycological Association (APPA).

Recently, the idea has been revived in Korea (http://agw-seaweed.org) through the project "Greenhouse gas (GHG) emissions reduction using seaweeds". This 5-year study was begun in 2006 and was funded first by the Ministry of Maritime Affairs and Fishery and later by the Ministry of Land, Transport and Maritime Affairs of Korea. Our project utilized innovative research on seaweeds to develop new baseline and monitoring methodologies for the CDM and Project Design Document (PDD) of the Kyoto Protocol. Concurrently, members of the project and the APPA played a key role in obtaining international recognition of seaweeds as a GHG sink (Chung, 2007; Chung *et al.*, 2011). The project had two main components: seaweed research and seaweed CDM development. With the data obtained from efficiency evaluations of seaweed CO_2 removal, as well as conservation and technological management of the Coastal CO_2 Removal Belt (CCRB, Figure 1), the seaweed CDM PDD is now being developed.

Currently in its first trial, the seaweed CDM project presents a major challenge because of the need for appropriate control when managing for ecosystem-based aquaculture and the integrated coastal zone. A critical step in achieving the CDM project goals is to formulate and submit a PDD that sets out methodological concepts and paradigms with respect to lifespan and scale. The requisite new PDD for both the CCRB and the seaweed CDM can be adapted from the Afforestation and Reforestation (A/R) PDD (http://cdm.unfccc.int/Reference/Guidclarif/pdd/PDD_guid03.pdf).

Coastal CO_2 Removal Belt

The goal of the CCRB is to establish both natural and man-made plant communities in the coastal region of southern Korea that will accomplish CO_2 removal in the manner of a forest and which can be implemented along various spatial–temporal scales. This project has several operational definitions: (i) it can be a man-made marine plant community that is managed by CDM project participants; (ii) it must have a definite scale of area or volume, as designated in the PDD and approved by the CDM Executive Board; and (iii) it should be operated during the proposed crediting period. As a new concept, the CCRB requires open discussion.

By accommodating the above-mentioned constraints, actual approval of a Seaweed CDM Project by the United Nations Framework Convention on Climate Change (UNFCCC) will lead to the enhancement of sustainable management for the marine environment and marine resources, which will greatly benefit Korea and other countries.

Material and methods

Construction of the pilot CCRB farm

We applied the midwater rope-culture technique for this pilot CCRB farm. This aquaculture technology for perennial *Ecklonia* has been well-established by the National Fisheries and Research Development (NFRDI) of Korea (http://www.nfrdi.go.kr). As our reference site, we monitored the adjoining Triton artificial reef, which was populated with natural seaweed vegetation. Triton was constructed from steel slag, an environmentally safe by-product of the manufacturing process that is obtained after being separated from the molten ore. It is used widely for cement, fertilizer, and road construction materials. This is one of the Ocean Ecosystem Conservation Activities of the Pohang Iron and Steel, Co., Ltd, Korea (POSCO).

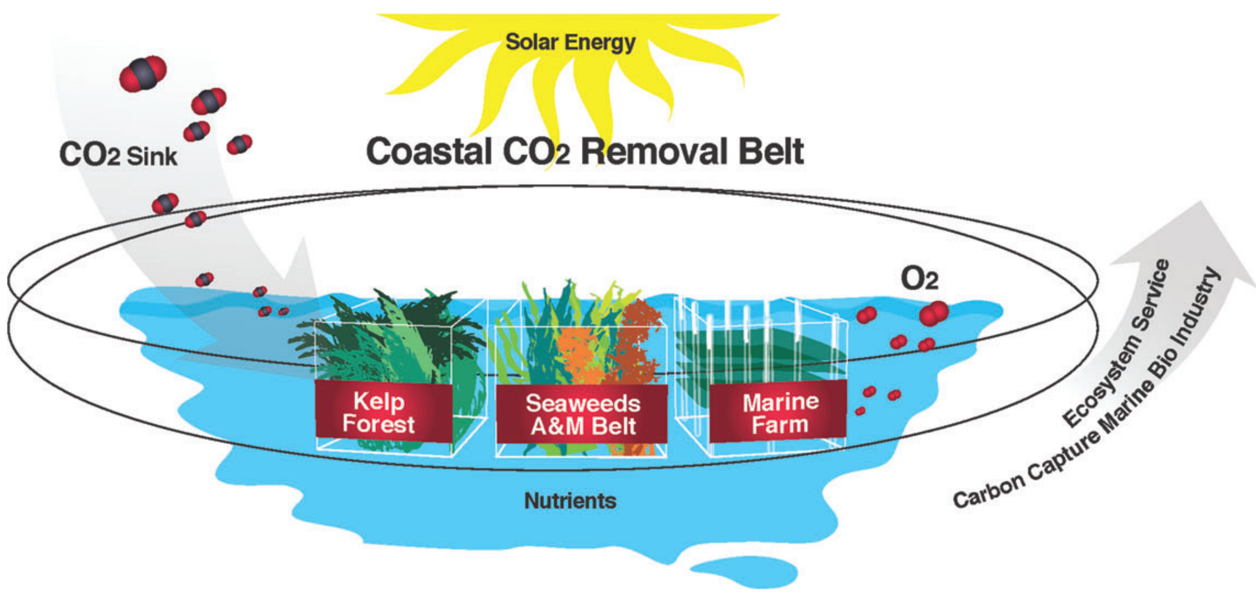

Figure 1. Conceptual schematic diagram of Seaweed *A* & *M* belt within CCRB. *A*, adaptation; *M*, mitigation.

The cultivation facility comprised "longline"-type horizontal ropes held in place at 3–5 deep by a series of buoys, each of which was linked at its ends to concrete blocks. Seedling strings were attached to the horizontal ropes culturing (Figure 2). This 0.5-ha seaweed CCRB was positioned in the waters of Pyeongsan-1-li, Namhae-gun, Gyeongnam-do, on the southern coast of Korea (34°45′49″N 127°50′10″E).

Young sporophytes of the perennial brown seaweeds *Ecklonia cava* and *Ecklonia stolonifera* ("Gamtae" and "Gompee" in Korean, respectively) were transplanted into the farm in July 2009. Afterward, they were measured monthly until April 2011 (total of 22 months). Their vegetative growth along a 1-m long rope was recorded three times. Divers collected samples to determine various growth characteristics, e.g. wet weights, frond lengths, and widths of seaweed specimens. If a rope contained more than 30 plants, the largest 30 were used for measurements. Tissue elemental contents were assessed by a CHNS/O elemental analyzer (Perkin Elmer 2400 Ser. II), and dry weights were taken after the samples were oven-dried for 48 h at 70°C.

Monitoring of total inorganic carbon and net community production

Total alkalinity (TA) was measured by the classic Gran electrotitration method, using 100-ml GF/F filtered samples. The accuracy of measurements was $\pm 3\ \mu\mathrm{mol\ kg^{-1}}$. Total inorganic carbon (TIC) was determined by extracting CO_2 from a seawater sample and quantitatively transferring it to a coulometric titration unit via the VINDTA (Versatile INstrument for the Determination of Total inorganic carbon and titration Alkalinity) system. In addition, CO_2 speciation and pH were calculated with the CO2SYS Package (Pelletier *et al.*, 2007), using the CO_2 acidity constants of Mehrbach *et al.* (1973), as refitted by Dickson and Millero (1987), plus the CO_2 solubility coefficient of Weiss (1974). Both TA and TIC were normalized to an average salinity for the seaweed bed during each survey.

To evaluate net production, we roughly assessed TIC uptake by the seaweed bed community ($TIC_{seaweed}$) from the difference in concentrations between the exterior and the interior of the seaweed bed according to the following formula: $\Delta TIC_{seaweed} = TIC_{outside\ (ambient)} - TIC_{inside\ (seaweed)}$. At each surveying time point, sampling for $TIC_{ambient}$ and $TIC_{seaweed}$ was done simultaneously for 24–72 h.

We assumed that primary productivity by the phytoplankton community was similar inside and outside. Because the dense canopy of the seaweed bed covered a substantial portion of the air–sea interface, preventing gas exchange, we did not consider the air–sea exchange of CO_2 in our calculations due to the difficulty of estimating the transfer velocity above the bed. Analyses of DIC and pCO_2 surveys of surrounding waters were performed 20 m distant from the farm and reference sites. Time-course measurements of DIC (spanning 48 h) were conducted bimonthly, and concentrations were computed by the CO2SYS software program.

Results

We estimated the net amounts of anthropogenic GHG that were removed by our carbon sink over a specified crediting period, using either directly measured dry weights or calculations based on wet weights (dry value being ~13% of the wet weight for *Ecklonia*). Data were collected and archived for use in monitoring verifiable changes in pooled carbon stocks within the boundaries. Values representing monthly growth from July 2009 to April 2011 are shown in Figure 3.

Plants of *E. cava* and *E. stolonifera* grew steadily between July 2009 and May 2010 before those rates began to decline gradually

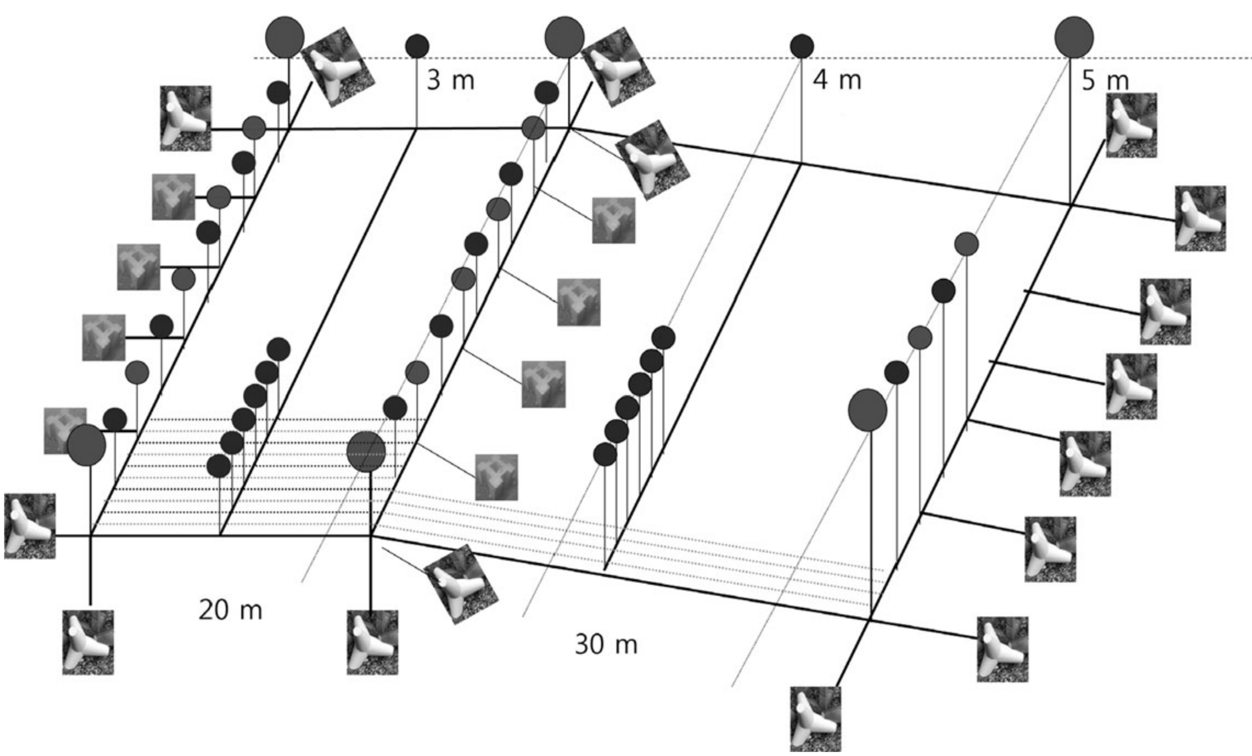

Figure 2. Schematic structural diagram of midwater rope-culture system for pilot seaweed CCRB farm installed along southern coast of Korea.

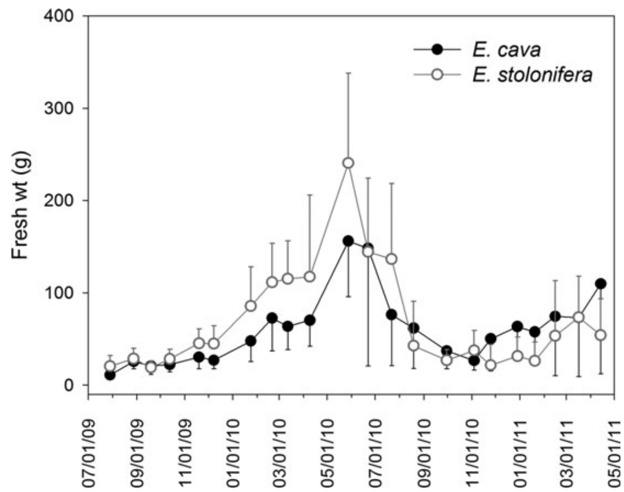

Figure 3. Growth of *E. cava* in pilot seaweed farm along southern coast of Korea.

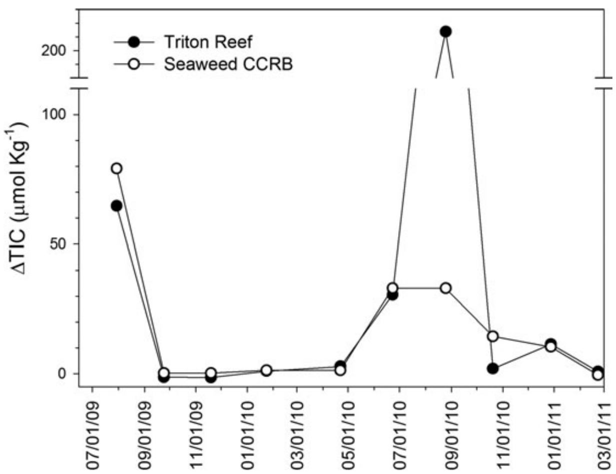

Figure 4. Differences in DIC contents between CCRB farm and reference site (natural seaweed vegetation on Triton artificial reef) from July 2009 to February 2011.

Table 1. Growth characteristics and estimates of carbon contents from *Ecklonia* specimens sampled in May 2010 from the pilot seaweed farm.

	Ecklonia cava	*Ecklonia stolonifera*
Frond wet weight (g)	156.00	240.60
Frond dry weight (g) (13% of wet weight)	20.28	31.28
Number of fronds per metre rope	81	109
Dry weight per unit rope length (g DW m^{-1})	1642.68	3409.52
Carbon content in frond tissue (%)	26.50	26.10
Carbon content per unit rope length (g C m^{-1})	435.20	889.90
Baseline emissions per unit area[a] ($tCO_2eq\ ha^{-1}$)	7.82	15.99

[a]The framework of the midwater rope-culture system could accommodate 49 lines of 100-m long rope, placed at 2-m intervals to create a 1-ha substrate space overall.

in June. The average frond density for rope culture was determined by tallying the number of attached fronds per metre. After transplanting in July 2009, *E. cava* bore 92 vs. 103 fronds m^{-1} for *E. stolonifera*. Those respective densities decreased to 54 and 58 in December 2009 before rising to 81 and 109 in May 2010. This increase in density may have been due to the growth of young fronds that matured under suitable conditions as well as the outgrowth of fronds from new holdfast propagation (data not shown).

The framework of this midwater rope-culture system could accommodate 49 lines of 100-m long rope, placed at 2-m intervals to create a 1-ha substrate space overall. The carbon sink per 100 m of rope was 43.5 kg C for *E. cava* and 88.9 kg C for *E. stolonifera*. Those values were calculated from the highest frond weights over the study period, as recorded in May 2010 (Table 1). We estimated that, based on increments in biomass during the 22 months, ~10 t $CO_2\ ha^{-1}\ year^{-1}$ could be drawn down in the seaweed CDM by these perennial brown algae.

Values for $\Delta TIC_{seaweed}$ at the reference Triton seaweed reef ranged from −1.39 in September 2009 to 213.416 in August 2010 (Figure 4). Net production in the kelp community over 20 months was $1.17–1.24\ g\ C\ m^{-2}\ d^{-1}$. This daily estimate was achieved by integrating $\Delta TIC_{seaweed}$ over the depth of the water column (3 m). It was calculated as $\Delta TIC_{seaweed} = TIC_{ambient} - TIC_{seaweed}$. The monitoring of $\Delta TIC_{seaweed}$ ranged from 32.5 to 34.4 μmol kg^{-1}; those were equivalent to 390–413 mg C m^{-3} and ~15.7–16.6 t $CO_2\ ha^{-1}\ year^{-1}$ when integrating $\Delta TIC_{seaweed}$. Net community production (over the 3-m column) was 390–413 mg C m^{-3} × 3 m= 1.17–1.24 g C $m^{-2}\ d^{-1}$= 15.7–16.6 t $CO_2\ ha^{-1}\ year^{-1}$.

Discussion

To aid in our development of new methodological protocols for evaluating seaweed carbon sinks, we estimated the level of carbon that could possibly be sequestered in a pilot seaweed CDM farm along the southern coast of Korea. A simple growth method was applied to determine the amount of biomass produced. That value was then converted to carbon content. This approach can also be used with other commercially important species or those that dominate in a natural environment, without compromising biodiversity. Indeed, man-made structures might have ecosystem advantages, such as providing enhanced nutrient uptake or improved habitats for other marine organisms.

As CO_2 sinks, seaweeds have the potential to sequester carbon in their biomass throughout their lifespan. Perennial kelps, such as *Ecklonia*, *Laminaria*, and *Saccharina*, can survive more than 5 years. In temperate regions, brown seaweeds show seasonal growth patterns.

The basic cultivation technique consists of inducing zoospore release from fertile adult sporophyte blades, settling these onto seed strings, providing for gametophyte development on the string with adequate tank conditions during summer, and eventually transferring those sporophyte-bearing seed strings to the sea in autumn(Westermeier *et al.*, 2006; Yarish and Pereira, 2008). Generally, sporophytes grow in winter and spring (Kain, 1991), reaching their maximum size in late spring and early summer. As the water temperature increases, the blades disintegrate, leaving only holdfasts and stems with meristodermal regions at the thallus base that persist throughout the first summer (Hayashida, 1984). In the second year, thicker and larger stems and blades grow intercalary from that meristodermal region, again reaching a maximum size in late spring, after which the old blades break down (Figures 3 and 5).

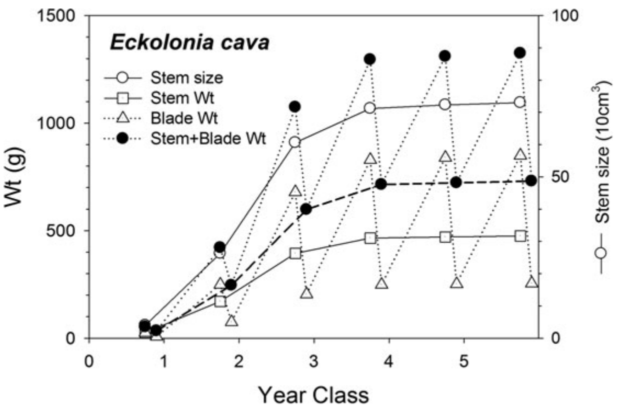

Figure 5. Growth of perennial brown seaweed *E. cava* over the study period. Calculations: stem size= stem length × stem diameter^2; blade weight= 0.5233 × stem weight$^{1.1993}$ (modified from the method of Hayashida, 1984).

Ecklonia cava was selected for assessment because this perennial macroalga is important from ecological and fisheries perspectives. Hayashida (1984) has reported that, after 3 years of growth, this species can attain a biomass of 1300 g in late spring, decreasing to 720 g in summer when blade loss is ~70%. This demonstrates that seaweed beds have the capacity to boost human efforts in carbon sequestration.

To avoid the risk of grazing by sea creatures, managers of seaweed farms prefer to use hanging midwater rope-culture techniques (Mann, 1977; Halpern *et al.*, 2006). When applied to conditions in the open sea, this technique is also advantageous because it can be combined with other facilities such as offshore wind farms and platforms (Buck *et al.*, 2004). We noted that cumulative values for DIC decreased by ~10 tonnes of CO_2eq within the seaweed farm when compared with the reference site. That level was nearly the same as the amount of seaweed biomass that accumulated in the farm. This supports our hypothesis that seaweeds can convert stored carbon to biomass. Therefore, a very reliable figure when demonstrating CCRB potential as a carbon sink would be ~10 t CO_2eq ha^{-1} $year^{-1}$.

Conclusions

The results of our scientific research can be used to achieve the goals of CDM and CCRB, which require a consolidation of CO_2 removal technologies. By working with other international parties, we can create a favourable environment for evaluating and approving the methodologies employed in seaweed CDM project activities. To be successful, we must also develop economic analyses and business plans for sales and emissions-trading that satisfy the terms dictated during enactment of the Kyoto Protocol. However, it appears unlikely that, under the REDD or REDD+ criteria, algae will be able to subsidize some environmental or market benefits as blue carbon when one considers the measurability or permanence of carbon sequestration.

Human-driven production of algae has a long history. Although it already represents ~25% of the world's aquaculture, its potential is far from being fully exploited. Recent advances in mariculture techniques have led to greater supplies of seaweeds as a true "marine crop" (Chritchley and Ohno, 1998; Yarish and Pereira, 2008). Because of this, we believe we have good reasons to propose that algae can be beneficial when marketing blue carbon through CDM. The results gained from further studies will provide economic incentives for maintaining the health of coastal marine environments while also producing materials that can replace fossil hydrocarbons in a wide range of applications, from fuels to chemical substrata. An immediate priority will be research that clearly establishes the carbon benefits of algal culture and sets a foundation for developing the necessary marketing and regulatory frameworks by which those benefits can be realized. In the longer term, the potential to extend algal cultivation to deeper waters via raft and string techniques may substantially contribute to the management of human impacts on atmospheric and oceanic carbon cycle interactions.

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