

Using marine macroalgae for carbon sequestration: a critical appraisal

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Received: 27 July 2010 / Revised and accepted: 24 September 2010 / Published online: 19 October 2010
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Abstract There has been a good deal of interest in the potential of marine vegetation as a sink for anthropogenic C emissions (“Blue Carbon”). Marine primary producers contribute at least 50% of the world’s carbon fixation and may account for as much as 71% of all carbon storage. In this paper, we analyse the current rate of harvesting of both commercially grown and wild-grown macroalgae, as well as their capacity for photosynthetically driven CO₂ assimilation and growth. We suggest that CO₂ acquisition by marine macroalgae can represent a considerable sink for anthropogenic CO₂ emissions and that harvesting and appropriate use of macroalgal primary production could play a significant role in C sequestration and amelioration of greenhouse gas emissions.

Keywords Blue carbon · Macroalgae · Photosynthesis · CO₂ sequestration

Introduction

The global environment is going through a period of rapid change, the pace of which is unprecedented in our geological history, and life on the planet is being threatened by elevated temperatures and ocean acidification associated with the release of greenhouse gases. While CO₂ levels and global temperatures have both been higher, sometimes much higher, in the geological past than they are at present, it is the current rate of change that will pose problems for biota. It is thus critical for the future of our planet that significant changes are made to our emissions of greenhouse gases, of which CO₂ is the greatest contributor at present.

Various solutions to the problem of excess emissions have been proposed, and many countries are making good progress in stabilising or even reducing their CO₂ outputs. However, rapid economic growth in developing countries has seen their yearly CO₂ emissions continue to rise, and the latest IPCC report suggests that unless major steps are taken, CO₂ concentrations in the atmosphere will continue to increase exponentially well into the future (Meehl et al. 2007). It is therefore of paramount importance that all possible steps are taken to reduce our atmospheric CO₂ load to sustainable levels if severe damage to ecological function, including food chains and ecosystem services, is to be avoided.

Recently, there has been a good deal of interest in the potential of marine vegetation as a sink for anthropogenic C emissions (“Blue Carbon”—Nellemann et al. 2009). Nellemann et al. (2009) point out that marine primary producers contribute at least 50% of the world’s carbon fixation and may account for as much as 71% of all carbon storage in oceanic sediments. Clearly then, the algae and higher marine plants such as mangroves and

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seagrasses that comprise the vast majority of oceanic primary producers have the potential to make a real contribution to CO₂ removal and carbon storage. In this paper, we have analysed the current rate of harvesting of both commercially grown and wild-grown macroalgae, as well as their capacity for photosynthetically driven CO₂ assimilation and growth. We suggest that CO₂ acquisition by marine macroalgae can represent a considerable sink for anthropogenic CO₂ emissions and that harvesting and appropriate use of macroalgal primary production could play a significant role in C sequestration and amelioration of greenhouse gas emissions.

The nature of the problem: current rates of CO₂ emission

We live in an era where atmospheric CO₂ levels are rising at a rate unprecedented in geological history. Some 7.2 ± 0.3 Pg C ($1 \text{ Pg} = 10^{15} \text{ g}$ or 1 Gigatonne) are released annually from fossil fuel combustion and cement production, while land-use changes and deforestation release a further 1.6 ± 1 PgC year⁻¹ (Denman et al. 2007). The oceans have played a role as a major sink for anthropogenic CO₂ emissions, accounting for 48% of emissions since the Industrial Revolution (Sabine et al. 2004). Behrenfeld et al. (2002) estimate the annual oceanic sink for CO₂ as 2 ± 0.8 Pg C with an additional missing sink element of 1.8 Pg C involving both terrestrial and oceanic elements of the biosphere. Despite the drawdown from these biotic and abiotic activities of the oceans, the atmospheric CO₂ pool is currently increasing by $\sim 4.1 \pm 0.1$ Pg C year⁻¹ (Denman et al. 2007). This rapid increase in atmospheric CO₂ has occurred over the last ~200 years, from a value of 280 ppm (28 Pa) in 1800 to ~385 ppm (38.5 Pa) at present. Most of this increase has occurred over the last 100 years (Denman et al. 2007). Forecasts are quite variable, depending on the values used for growth in CO₂ emissions in the models used, but the most likely scenario is for a two- to threefold increase in atmospheric CO₂ concentration over the next 100 years (Meehl et al. 2007).

Marine productivity and capacity for C drawdown

Marine photosynthesis accounts for 50% of the total primary productivity of the planet ($54\text{--}59$ PgC year⁻¹ from a total of $111\text{--}117$ PgC year⁻¹, Beardall and Raven 2004 and references therein). Of this, marine macrophytes (seaweeds and seagrasses) in the coastal regions account for ~ 1 PgC year⁻¹. However, marine macroalgae such as the kelps *Macrocystis* and *Laminaria* are capable of very high rates of photosynthesis and productivity of $\geq 3,000$ gC m⁻² year⁻¹

(30×10^6 g ha⁻¹ year⁻¹; Jackson 1987; Gao and McKinley 1994; Muraoka 2004). As such, they could potentially make a significant contribution to the annual biological drawdown of CO₂ and the global C cycle (Ritschard 1992; Gao and McKinley 1994; Muraoka 2004). Figure 1 shows rates of photosynthesis, on a gram fresh weight basis, for a range of chlorophyte, phaeophyte and rhodophyte algae. A range of other species, not presently cultivated for food and other materials, have high productivities and could also be utilised. Species of genera *Sargassum*, *Ascophyllum* and *Fucus* feature among the highest photosynthetic rates in the phaeophytes, while *Porphyra* and *Palmaria* head the rhodophytes with faster photosynthetic rates than the brown algae. In the chlorophytes, simple genera such as *Ulva* and *Enteromorpha* also achieve high rates of CO₂ assimilation per gram fresh weight.

In terms of productivities per unit area substrate, Fig. 2 summarises a range of studies of areal productivity of important phaeophyte and rhodophyte species. A number of species are capable of productivities per unit area substrate in excess of $1,000$ gC m⁻² year⁻¹. These include *Ascophyllum nodosum*, *Macrocystis integrifolia*, *Sargassum horneri*, *Postelsia capillacea* and *Ecklonia radiata*. *Euchema* and *Gracilaria*, among the red algae, are also capable of sustained productivity at this level.

It is informative to compare these rates of productivity with values for terrestrial ecosystems and for crops that have been put forward as possible sources of second generation biofuels. Fig. 3 shows the productivity of selected algae from Fig. 2, expressed as dry wt. ha⁻¹ year⁻¹, compared with estimates for the biomass yield of switchgrass (*Panicum virgatus*) and *Miscanthus* (*Miscanthus* × *giganteus*), which are frequently cited as potential crops for second generation biofuel, and corn (currently used in a number of countries as a source of bioethanol, Heaton et al. 2008). Clearly the potential annual yields of many of the highly productive algal species are considerably higher than those of the terrestrial plants considered useful candidates for biofuel production, although it should be noted that estimates of areal biomass yield from macroalgae could be influenced by “edge” effects, with the flexibility of macroalgal fronds ascribing a larger surface area than suggested by holdfasts alone. Such effects would be less marked in the more rigid terrestrial species mentioned here.

Current usage of marine macroalgae

The uses of marine macroalgae (seaweeds) are well known. Out of approximately 20,000 known species of seaweed distributed in different parts of the world, only about 221 species are used commercially (Critcheley and Ohno 1998).

Fig. 1 Rates of primary production for selected members of different algal divisions: **a** Phaeophyta; **b** Chlorophyta and **c** Rhodophyta. Only data for species with photosynthetic rates $>20 \text{ mg CO}_2 \text{ g FW}^{-1} \text{ day}^{-1}$ are shown. Production rates are expressed as $\text{mg CO}_2 \text{ gFW}^{-1} \text{ day}^{-1}$. In cases when the original data were not expressed per g FW, ratios from articles in the literature were used to compile a dataset for conversion between FD and DW, and surface area and FW. If data for the appropriate genus were not available, we used the average for the whole group (Chlorophyta, Phaeophyta and Rhodophyta) as a conversion factor. In cases where multiple data for the same species were available, an average of these values was used. References used for calculating conversion factors were: Raven et al. (1989); Beardall and Roberts (1999); Mercado et al. (1998); Johnston et al. (1992) and Raven and Osmond (1992). Sources of data are: 1 Atkinson and Smith (1983), 2 Beardall and Roberts (1999), 3 Brinkhuis (1977), 4 Brown and Tregunna (1967), 5 Dring (1982), 6 Einar and Beer (1993), 7 Fernandez et al. (1990), 8 Fleurence et al. (1994), 9 Gao and Nakahara (1990), 10 Gao and Umezaki (1989a, b, c), 11 Gao et al. (1991), 12 Gao et al. (1993b), 13 Hanisak et al. (1988), 14 Herbert and Waaland (1988), 15 Israel and Hophy (2002), 16 Israel et al. (1999), 17 Johnston et al. (1992), 18 Kremer (1981), 19 Lapointe (1986), 20 Lapointe and Tenore (1981), 21 Levavasseur et al. (1991), 22 Maegawa (1980), 23 Maegawa and Aruga (1983), 24 Middelboe and Hansen (2007), 25 Raven and Osmond (1992), 26 Schaffelke (1999), 27 Titlyanov et al. (2007), 28 Yokohama (1973)

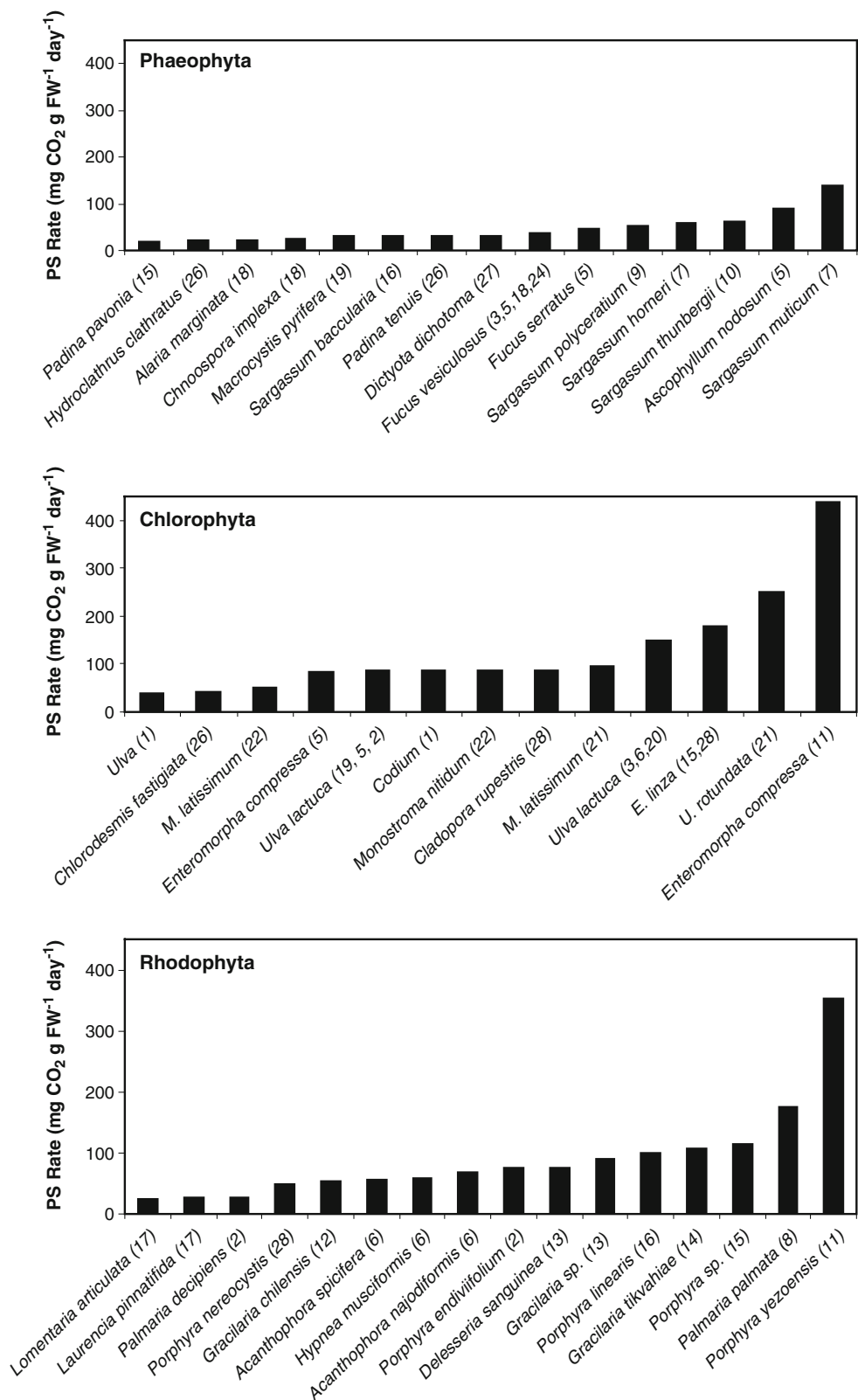
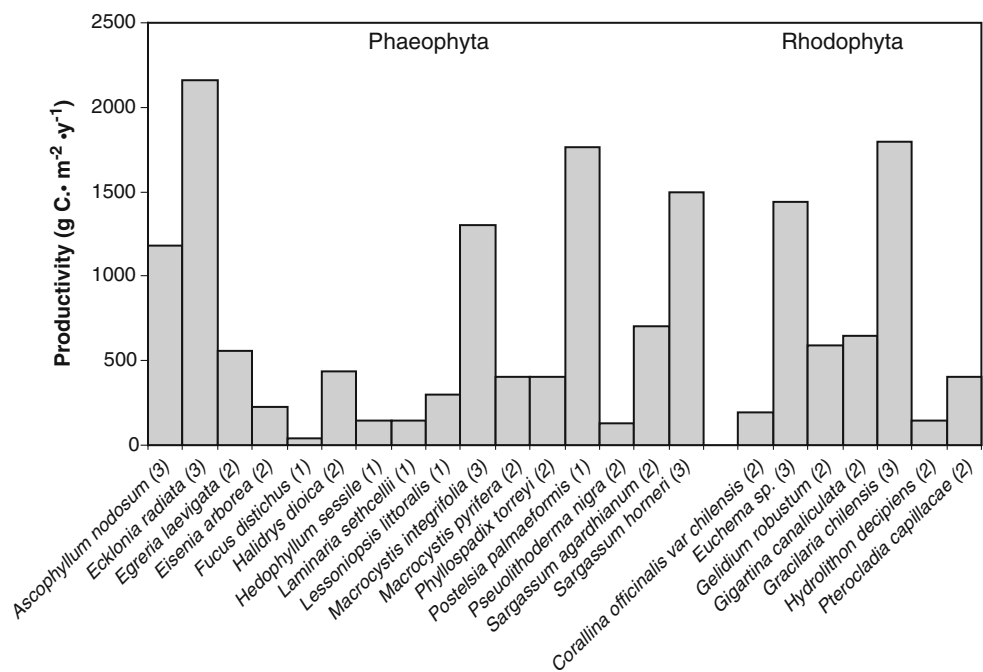


Fig. 2 Production rates of selected Phaeophyte and Rhodophyte algae expressed on the basis of area of substrate. Sources of data are 1 Leigh et al. (1987); 2 Littler and Murray (1974); 3 Gao and McKinley (1994)



Many of the species are exploited from their natural habitats as the technology for their cultivation is not yet developed. During the last 50 years, approximately 100 seaweed species have been tested in field farms, but only a dozen are being commercially cultivated (Sahoo and Yarish 2005). Today, around 7.5–8 million tonnes wet weight seaweeds are harvested annually both from wild and cultivated sources. China is the largest producer of seaweeds with 5 million tonnes (wet weight) followed by Korea (800,000 tonnes) and Japan (600,000 tonnes). As detailed by

the FAO (2003), although more than a dozen species of macroalgae are cultivated, the bulk of the annual production is attributable to only five genera: *Laminaria* (4,580,000 tonnes wet weight), *Porphyra* (1,011,000 metric tonnes wet weight), *Undaria* (311,105 tonnes wet weight), *Eucheuma* and *Kappaphycus* (628,576 tonnes wet weight) and *Gracilaria* (12,510 tonnes wet weight). While China's contribution mainly comes from the cultivation of *Laminaria japonica*, 50% of Korea's production is contributed by *Undaria pinnatifida* and 75% of Japan's harvest is based on

Fig. 3 Annual areal production rates of selected algae compared to those of terrestrial plants associated with biofuel production. Data are derived from 1 Leigh et al. (1987); 2 Littler and Murray (1974); 3 Gao and McKinley (1994). Data for terrestrial plants are from Heaton et al. (2008)

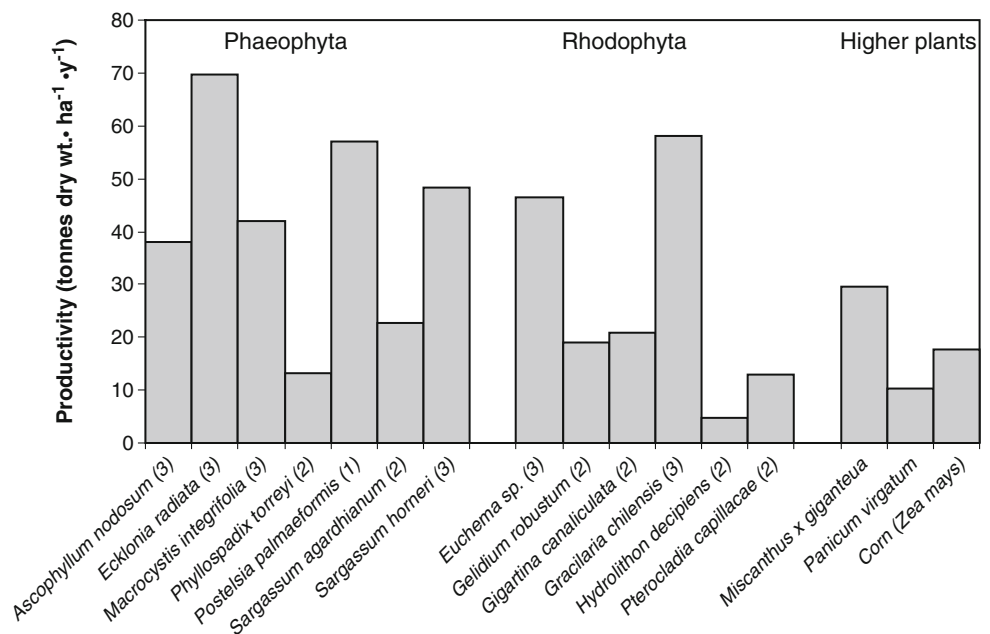


Table 1 Major seaweed production through large scale cultivation and wild harvests (data from FAO 2003)

Country	Production (metric tonnes)	Species	Uses
China	5×10^6 (wet wt.) 550,000 (dry wt.)	<i>Laminaria japonica</i> (more than 70% contribution)	Alginates, food and other industries
Korea	800,000 (wet wt.) 98,400 (dry wt.)	<i>Undaria pinnatifida</i> (nearly 50% contribution)	Food
Japan	600,000 (wet wt.) 71,820 (dry wt.)	<i>Porphyra yezoensis</i> <i>P. tenera</i> (75% of total production)	Food
Philippines	70,102 (dry wt.)	<i>Kappaphycus alvarezii</i> <i>Eucheuma denticulatum</i>	Carrageenan
Indonesia	61,447 (dry wt.)	<i>Kappaphycus alvarezii</i> <i>Eucheuma denticulatum</i>	Carrageenan
	13,447 (dry wt.)	<i>Gracillaria</i> sp.	Agar
Tanzania	5,000 (dry wt.)	<i>Kappaphycus</i> <i>Eucheuma</i>	Carrageenan
India	500 (dry wt.)	<i>Kappaphycus</i> + <i>Gracillaria</i>	Carrageenan agar

the cultivation of *Porphyra* sp. (Table 1). In addition, countries such as The Philippines, Indonesia, Tanzania and India are involved mainly in the cultivation of *Kappaphycus alvarezii* and *Eucheuma denticulatum* (carrageenophytes) as well as *Gracillaria* species (agarophytes). The growth rate of the various species varies depends on the site of cultivation, the season and the cultivation methodology. For example the daily growth rate of *K. alvarezii* varies between 3% and 12% and that of *Gracillaria* spp. between 3.3% and 8.4% depending on various factors.

The above figures give an annual harvest for these species alone of 0.87×10^6 tonnes dry matter. Macroalgae have, on average, 30% carbon so this figure represents 0.26×10^6 tonnes C incorporated into harvested algae annually. Other species such as *A. nodosum* are also harvested, at rates of $\sim 5 \times 10^4$ tonnes year⁻¹ for alginates and animal fodder (Morand et al. 1991; Moen et al. 1997), so the above figures are a conservative estimate of the potential drawdown of C by macroalgae generally. It should be noted though that these are average figures and achieved yields will be affected by a range of environmental and genetic (strain-specific) factors.

Consideration of the scale of harvesting in the top ten algae-producing countries (Table 2) indicates the extent to which their current harvest might contribute to any offset against their CO₂ emissions. These figures exclude calcification, so they do not include for instance the large harvest of maerl in France (Zemke-White and Ohno 1999) which contains a very high level of mineral carbonates. With current levels of harvest photosynthetic incorporation of CO₂ into algal biomass represents, for most countries, only

a small proportion of C emissions. However, it should be noticed that most countries have a low level of harvest given the extent of their coastlines. If other countries were able to increase their production in line with the values achieved by Korea, then some at least would be in a position where algal utilisation could make significant inroads into their annual C emissions (Table 2). Furthermore, improved production by high producing countries such as China and Korea could enhance drawdown further. Clearly geographic and other constraints will influence the extent to which this can be realised, but it does indicate that there is a significant potential for improved macroalgal based CO₂ remediation.

Uses of macroalgae for C sequestration/remediation

Biofuels

Considerable interest and effort has been centred on the possibility of using biofuels (ethanol, biodiesel) as a substitute for fossil fuels. Although the carbon in biofuels is re-released as CO₂, it is the anthropogenic release of C from fossil reserves that is largely responsible for the increase in atmospheric CO₂ and the ensuing greenhouse effect that we are experiencing. The use of substitutes for fossil fuels thus offers an opportunity to minimise the increase in atmospheric CO₂ that has been so evident over the last two centuries or so.

However, although there has been a flurry of activity associated with production of biofuels such as biodiesel

Table 2 Comparison between CO₂ emissions of the top ten algal harvesting countries, their current seaweed harvest and potential for C sequestration with improved utilisation of coastline for seaweed cultivation (harvest data from Zemke-White and Ohno 1999; emissions data from UN Millennium Development Goals Indicators (<http://mdgs.un.org/unsd/mdg/>))

Country	Algal harvest (tonnes dry matter y ⁻¹)	C in harvest (tonnes year ⁻¹)	Annual CO ₂ emissions (thousand tonnes)—2004	C in annual emissions (thousand tonnes)	C in harvest/C in emissions (%)	Coastline (km)	Harvest (tonnes dry matter year ⁻¹) km ⁻¹	Harvest if increased to the per km level of Korea	Harvest increase (fold)	Harvest C as% emissions	Harvest C as % yearly increase in emissions
China	698,529	209,559	5,010,169	1,366,410	0.0153	14,500	48.2	826,500	1.18	0.02	0.17
Korea	138,499	41,550	465,643	126,994	0.0327	2,413	57.4	138,499	1.00	0.03	0.34
Japan	123,074	36,922	1,257,962	343,081	0.0108	29,751	4.1	1,695,807	13.78	0.15	5.00
Chile	109,308	32,792	62,418	17,023	0.1926	6,435	17.0	366,795	3.36	0.65	7.54
Norway	40,632	12,190	87,602	23,891	0.0510	25,148	1.6	1,433,436	35.28	1.80	29.5
Philippines	46,218	13,865	80,511	21,958	0.0631	36,289	1.3	2,068,473	44.75	2.83	42.5
Indonesia	26,894	8,068	378,250	103,159	0.0078	54,716	0.5	3,118,812	115.97	0.91	64.1
France	16,762	5,029	373,692	101,916	0.0049	3,427	4.9	195,339	11.65	0.06	4.0
USA	15,330	4,599	6,049,435	1,649,846	0.0003	19,924	0.8	1,135,668	74.08	0.02	23.3
Mexico	10,205	3,062	43,8021	119,460	0.0026	9,330	1.1	531,810	52.11	0.13	10.9

from oil bearing plants like oil palm and canola, and bioethanol from sugar cane and corn, it is becoming rapidly apparent that terrestrial production of biofuel has a very significant ecological and social cost and may not compare well with forest restoration as a C mitigation approach (Righelato and Spracklen 2007). Stripping of primary rainforest or savannah and turning arable land over to crops for biofuel can have major impacts on ecosystem health (Tilman et al. 2006; Jordan et al. 2007; Sawyer 2008), biodiversity (Koh 2007) and on the ability of the planet to provide food for humanity (Dalgaard et al. 2006; Fargione et al. 2008). Land clearance changes may also lead to net C release (Searchinger et al. 2008). It must be recognised though that algal harvesting, unless done in a sustainable manner, can also potentially impact on ecosystem functions in coastal areas.

Other benefits of algae for biofuels

While the Asia-Pacific region contributes to nearly 80% of the world's seaweeds production, most of the value addition takes place in developed countries. Of the 221 species harvested currently, 145 species are used for food and 110 species for phycocolloid production (Table 1) (Zemke-White and Ohno 1999). We argue that while the provision of food from macroalgae is of undoubted importance to some nations' nutrition and/or economy, conversion of algal carbon into biofuel could represent a more important global contribution in terms of CO₂ sequestration, analogous to the concept of carbon credits currently being applied in developed, industrialised countries. While the lipid content of macroalgae is considerably less than that of microalgae, and is usually <7% (see e.g. Fleurence et al. 1994), the content of soluble and structural carbohydrate can be much higher (values of >30% soluble carbohydrate are not uncommon for tropical rhodophytes; Renaud and Luong-Van 2006). Lipid can be directly converted to biodiesel, but the other components such as carbohydrate (and protein) can also be chemically converted to useful fuels, including ethanol, and chemical feed-stocks (Petrus and Noordermeer 2006). By converting algal biomass to useful fuels, we decrease our reliance on fossil fuels for both transport and chemical feedstock.

Pulp

Recent development of a red algal pulp could provide an alternative to the use of trees and will thereby minimise further deforestation (Seo et al. 2010). Thus, the use of algal-based fuels and algal pulp would bypass the critical and ecologically damaging conversion of fossil fuel into atmospheric CO₂ and could also play a role in conserving

terrestrial forest which plays an important role in the global C cycle.

Climate change

In planning future development of algal-based CO₂ sequestration programmes, it will be important to take into account the potential impacts of climate change on growth and production of the algae to be used. It is expected that climate change will have an effect on both macroalgal distribution and biodiversity, but also on their physiology and photosynthetic performance. That, in turn, can change their capacity to sequester CO₂. Increased CO₂ concentration, in some cases, can increase their capacity to photosynthesize and grow. For instance, it was shown by Gao et al. (1991) that high CO₂ concentrations increased growth of the macroalga *Porphyra yezoensis* both in length and width, but did not change the morphology. Other species are essentially CO₂ saturated under present day CO₂ levels and are not expected to show increased performance in the future (see Beardall et al. 1998). Differences will be expected between inter-tidal species (where photosynthesis is currently not limited by the availability of inorganic carbon (Ci)), and sub-tidal species that show Ci-limited photosynthesis (Beardall et al. 1998). Differences will also exist between calcifying and non-calcifying species, based on performance of calcifying *Corallina pilulifera*, whose calcification and growth was inhibited by the drop in pH associated with elevated atmospheric CO₂ (Gao et al. 1993a; Gao and Zheng 2010).

Temperature shifts may also affect the ability of macroalgae to perform in particular geographic areas (see e.g. Breeman 1990). Long-term data from the Californian coast, where an increase in 2.2°C was recorded over a period of 60 years, showed a dominance of small turfing species, such as *Endocladia muricata*, *Mastocarpus papillatus*, *Gelidium coulteri*, *Rhodoglossum affine* and *Gigartina canaliculata*, over larger, non-turfing species, including *Pelvetia fastigata* and *Fucus distichus*, which were still common, but not to their previous extent (Barry et al. 1995).

Another long-term study, based on 10 years of observation in waters off the Californian coast, showed that a great majority of species in the nearshore changed abundance, due to an increase in sea surface temperature (Shiel et al. 2004). *Macrocystis* species extended its distribution down to Mexico and showed a wide tolerance of temperature, while *Cryptopleura* could not withstand the change in temperature, but was also adversely affected by changes in light climate that arose because of the increased production of *Macrocystis*. Other species, such as *Mazzaella flaccida* and *E. muricata* completely disappeared from the system, due to the increase in temperature (Shiel et al. 2004).

The disappearance of particular species, due to changes in temperature, might pose another threat via increased grazing pressure (due to “newly open” niches for grazers), which might affect subsequent colonisation of these areas by macroalgae (Shiel et al. 2004).

In species where life cycle is controlled by temperature, changes in temperature might desynchronize reproduction, which can be further translated to the food web. Temperature is critical to the reproductive success of many macroalgae, and a shift in temperature distributions is thus likely to impact strongly on the ability of macroalgae to maintain populations in a given area. Breeman and her co-workers studied temperature dependence of growth and the life history characteristics of a range of species found in the North Atlantic (e.g. Breeman 1990; Pakker and Breeman 1996; Pakker et al. 1996). These studies demonstrated that for some algae even a small change of water temperature could bring about major shifts in distribution. Thus, Breeman (1990) predicted significant changes in community structure associated with the northward shift in the southern boundaries of the major canopy forming species *Laminaria hyperborea*, *L. saccharina* and *L. digitata*. The northward migration of warm to tropical species (which are mainly smaller red, green and brown algae) is not likely to have such a major impact (Beardall et al. 1998).

Any response to UVB levels in macroalgae is going to be species-specific, depending on the presence of UV-absorbing compounds, and their position within a water column. It appears that red macroalgae have higher levels of these compounds, giving them an ecological advantage over the green and brown algae. Thus, latitudinal distribution will play a major role in their resistance to UVB, with higher tolerance in tropical algae, compared to temperate species, due to their evolution in a naturally high UV environment (Diaz-Pulido et al. 2007).

It has been proposed that global warming will lead to greater temperature gradients between land and oceans which will lead to greater storm activity in coastal environments. Both increased storm events and consequent enhanced runoff from land are likely to have impacts on algal growth (Dayton and Tegner 1984; Nielsen 2003; Diaz-Pulido et al. 2007). These effects might be more pronounced in shallow waters, while species such as turf algae and deep-water species with strong holdfasts might show less susceptibility to physical disturbance by wave action and storm events. On the other hand, stronger wave action might help in dispersal, and thus increase their distribution. However, shallow water species might also be strongly affected by the increased runoff, which can bring both increased nutrients, but also high concentration of herbicides and other toxicants. On one side, enhanced nutrient supply might increase the production of species in the shallow water, but algal growth might further be

affected by increased herbicides (Diaz-Pulido et al. 2007). Increased storm activity could also physically disrupt algal farming infrastructure.

Social and economic impacts

Future developments in using marine macroalgae for CO₂ sequestration will need to take into account a range of environmental, social and economic aspects if it is to be used effectively. However, we are living in a time where we are seeing dramatic changes to our planet and there is an urgent need for action if we are not to reach a tipping point in our ecosystems, and enhanced macroalgal utilisation offers a possible strategy for amelioration. However, carbon sequestered by macroalgae will only be effective in ameliorating CO₂ levels if the algal products are used for biofuels or other products that bypass the use of fossil fuels. Use of seaweeds as foodstuffs has no impact on atmospheric CO₂, as the carbon ingested is rapidly respired and re-released into the atmosphere. Algal farming can certainly bring benefits to subsistence level communities (Sievannen et al. 2005). Intensification of macroalgal farming has the potential to cause ecological impacts, though, to our knowledge, there have been few studies directly addressing this possibility. As stated earlier, sustainable running of such ‘algal farms’ will require sensible limits to harvesting to ensure supply of a reasonable number of propagules to “re-seed” cut areas and also to retain sufficient biomass to minimise impacts on the ecosystem functions of macroalgal communities such as providing nursery grounds for animals. In one of the few analyses that have been carried out, Bergman et al. (2001) have shown both increases and decreases in fish diversity associated with algal farming in lagoon systems. One useful approach is to introduce integrated aquaculture, where macroalgal culture is used in parallel with aquaculture of fish or shell fish to ameliorate nutrient release into the environment and improve water quality (Chopin et al. 2001; Neori et al. 2004). Such changes in the use of coastal environments will also undoubtedly have impacts on communities who currently use these resources (Sievannen et al. 2005), and this needs to be taken into consideration in planning future developments.

The present work has not considered the economic costs of algal-based C remediation. Gao and McKinley (1994) suggested that, even over a decade ago, the costs of energy generation from algal biomass were promising. With escalating fossil fuel prices, this is more so today than in the past and only likely to improve the economic plausibility of algal bioremediation of CO₂. However, a full economic analysis, including all level of infrastructure and transport requirements such as that carried out for terrestrial biofuel by Davis et al. (2009), is required before

hard conclusions can be drawn about the economic potential of marine algae for CO₂ remediation.

Acknowledgments This review is the first activity of the WG-Asian Network of the Asian Pacific Phycological Association and has been supported by a grant ‘Greenhouse Gas Emissions Reduction Using Seaweeds’ Project funded by the Korean Ministry of Land, Transport and Maritime Affairs.

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