

Use of macroalgae for marine biomass production and CO₂ remediation: a review

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Abstract

Biomass production from macroalgae has been viewed as important mainly because of the need for pollution abatement. Environmental considerations will increasingly determine product and process acceptability and drive the next generation of economic opportunity. Some countries, including Japan, are actively promoting "green" technologies that will be in demand worldwide in the coming decades. Should an international agreement on CO₂-reduction be ratified, its effective use for energy production would be of high priority. This report shows that macroalgae have great potential for biomass production and CO₂ bioremediation. Macroalgae have high productivity, as great or greater than the most productive land plants, and do not compete with terrestrial crops for farm land. The review focuses on recent data on productivity, photosynthesis, nutrient dynamics, optimization and economics. Biomass from macroalgae promises to provide environmentally and economically feasible alternatives to fossil fuels. Nevertheless, the techniques and technologies for growing macroalgae on a large-scale and for converting feedstocks to energy carriers must be more fully developed.

Introduction

Most of the world's energy supply is derived from non-renewable fossil fuels. Moreover, combustion of these fuels has resulted in a sharp increase in the global CO₂ concentration over the last 100 years, an increase which has been associated with a rise in global temperature. Over 150 countries have now signed the Climate Convention arising from the UN Conference on Environment and Development, Rio de Janeiro. That document exhorts developed nations to limit emissions of CO₂ and other greenhouse gases with the goal of returning individually or collectively to 1990 emission levels by the year 2000 (Williamson, 1992).

It is clear that environmentally and economically feasible alternatives to fossil fuels must be identified and developed. The use of marine biological resources for conversion of solar energy has great potential in mitigating global warming (Ritschard, 1992; Orr & Sarmiento, 1992). Energy carriers, for

example methane, hydrogen and methanol, can readily be produced from marine biomass through biologically mediated degradation or thermochemical gasification (Chynoweth *et al.*, 1987; Calvin & Taylor, 1989) and photosynthetically generated biomass can also be used directly in a combustion cycle. If biomass were grown for energy to an amount equal to that consumed during any given period, there would be no net build-up of CO₂ in the atmosphere. The potential for reducing CO₂ emissions in this way depends on the fuel displaced and on the efficiency with which alternatives can be produced. A gigajoule (GJ) of biomass substituted for coal would reduce emissions by the carbon content of 1 GJ of coal, about 0.025 t C. Hall *et al.* (1991) argue that adapting the integrated gasifier/combined-cycle (IGCC) technology now being developed for power generation with coal to biomass would involve lower unit capital cost and could be commercialized more quickly than the corresponding coal versions, because the latter require techniques for sulphur removal. The

net cost of off-setting CO₂ emissions by substituting biomass for fossil fuels could often be near zero or even negative. Global CO₂ emissions could be reduced to half the 1985 level by the year 2050, if biomass energy production were sufficient to displace 5.4 Gt yr⁻¹ C from fossil-fuel combustion. The authors argue that plausibly this could be achieved by substituting biomass for coal.

Ultimately, success in using 'bioenergy' will depend on the economic feasibility of obtaining significant amounts of biomass and the technical feasibility of its large-scale utilization as fuel. Both factors must be addressed before technical demonstrations are called for and before biomass-derived fuels can be considered seriously as an acceptable alternative to fossil fuels. Within this conceptual framework, what is the potential for marine macroalgal biomass? Can macroalgae be utilized as a source of energy? What are the advantages of using macroalgae for biomass production as compared to the use of other photosynthetic organisms?

Biomass production by macroalgae

Productivity

Productivity of large brown algae (e.g. *Macrocystis*, *Laminaria*, *Ecklonia*, *Sargassum*) ranges from 1000 to 3400 g m⁻² yr⁻¹ C (Table 1) or about 3300–11,300 g m⁻² yr⁻¹ dry wt. * Red algae show a similar range of production. Cultivated macroalgae can give even higher values. Production of cultivated *Laminaria japonica* reached more than 15,000 g m⁻² dry wt (150 t ha⁻¹) for a 7-month growing season (see Brinkhuis *et al.*, 1987).

To put these values in perspective, let us compare macroalgal productivity to sugarcane, the most productive of land plants under cultivation. Sugarcane production in the USA ranges from 61 to 95 t ha⁻¹ yr⁻¹ fresh wt. Production can reach 180 t ha⁻¹ yr⁻¹ when seed cane is planted each year (Nathan, 1978). The production of uncultivated brown algae is equivalent to 33–113 t ha⁻¹ yr⁻¹ dry wt. Using a conservative ratio of 5 : 1 (fresh wt : dry wt) for macroalgae, uncultivated production by brown and red algae is equivalent to 165–565 t ha⁻¹ yr⁻¹ fresh wt. Thus

* Calculated by converting C in Table 1 to dry wt based upon percentage C content of dry wt as reported by Atkinson and Smith (1983).

uncultivated macroalgae demonstrate a productivity up to 2.8 times that for sugarcane when maximum values for both crops are compared (i.e. 180 : 565, sugarcane:algae). The projected production of cultivated *Laminaria japonica* on an annualized basis is equivalent to 1300 t ha⁻¹ fresh wt or 6.5 times the maximum projected yield for sugarcane on an areal basis.

Utilization of macroalgae

In addition to pharmaceutical, chemical and food uses, macroalgae have been used for waste-water treatment and the recycling of nutrients. Ryther *et al.* (1979) estimated that macroalgae were capable of removing up to 15.4 kg ha⁻¹ d⁻¹ N. Because of the capacity for the uptake of inorganic N and P, macroalgae are used for waste-water treatment in Europe (Schramm, 1991) and as biofilters for marine fishpond effluents, "macroalgal nutrient traps", in Israel (Cohen & Neori, 1991) and Japan (Hirata & Xu, 1990).

In laboratory and field experiments the effects of municipal secondary sewage effluents on macroalgae have been reported to be growth enhancing (see Schramm, 1991). In southern France, the influence of various factors on growth of *Ulva lactuca* and *Enteromorpha intestinalis* in sewage-enriched seawater has also been investigated (Sauze, 1983). *E. intestinalis* adapted to brackish water was successfully grown outdoors in basins or in semi-artificial environments. In Denmark, the annual production of macroalgae in Odense Fjord was 9 t ha⁻¹ dry wt, or approximately 10,000 t dry wt for the total harvest area. The average nutrient content of the dried algae was 3.6% N and 0.5% P. The removal of nutrients was 56% of the 800 t N and 39% of the 140 t P discharge into the fiord in 1985. The biomass harvested was equivalent to 63,000 GJ per year. In Italy the 50,000 ha lagoon of Venice receives urban and industrial waste waters together with agricultural run-off from approximately 200,000 ha of farmland and 60 m³ s⁻¹ of heated seawater from power and stream plants. The effect on macroalgal production is evident: the annual harvest of *Gracilaria* has increased from about 120 t dry wt in 1946 to 1700 t dry wt in 1985. Schramm (1991) estimates that the untapped potential for the lagoon stands at 110,000 t yr⁻¹ dry wt.

In closed animal mariculture systems, accumulation of nutrients, ammonia, nitrite, urea and even nitrate, to toxic levels is a serious problem. Cohen and Neori (1991) reported that 1 kg wet wt of *Ulva*

Table 1. Productivity of large brown and red algae. Productivity values for the brown algae are based upon measurements of natural populations or experiments with uncultivated plants. Values reported for red algae are based upon biomass measurements in cultivated stands. The values reported as dry wt "a" or fresh wt "b" were converted to C based upon organic carbon percentages of dry wt reported by Atkinson and Smith (1983). Fresh wt values were converted to dry wt using a fresh to dry ratio of 5:1. Reported daily values ($\text{g m}^{-2} \text{d}^{-1} \text{C}$) approach maximal rates for productivity. Annual values ($\text{g m}^{-2} \text{yr}^{-1} \text{C}$) show yearly yields based upon monthly, bimonthly or seasonal measurements.

Species	Location	Productivity		References
		($\text{g m}^{-2} \text{d}^{-1} \text{C}$)	($\text{g m}^{-2} \text{yr}^{-1} \text{C}$)	
Phaeophyta				
<i>Ascophyllum nodosum</i>	(Massachusetts, USA)		1179	Roman <i>et al.</i> (1990)
<i>A. nodosum</i>	(Nova Scotia, Canada)		959(a)	Cousens (1984)
<i>Ecklonia cava</i>	(Izu Peninsula, Japan)	5(a)	1044(a)	Yokohama <i>et al.</i> (1987)
<i>E. radiata</i>	(Sydney, Australia)		1116(a)	Larkum (1986)
<i>E. radiata</i>	(Goat Island, New Zealand)		2160(a)	Novaczek (1984)
<i>Laminaria japonica</i>	(Qingdao, China)		2200	Wu <i>et al.</i> (1984)
<i>L. longicuris</i>	(Connecticut, USA)		3400(b)	Egan & Yarish (1990)
<i>L. longicuris</i>	(Nova Scotia, Canada)		2000	Mann (1972)
<i>Macrocystis integrifolia</i>	(British Columbia, Canada)		1300	Wheeler & Druehl (1986)
<i>Sargassum horneri</i>	(Matsushima, Japan)		1496(b)	Taniguchi & Yamada (1988)
<i>S. muticum</i>	(southwest Netherlands)	74		Critchley <i>et al.</i> (1990)
Rhodophyta				
<i>Euclima sp.</i>	(unknown/Philippines?)		1440(a)	Doty (1987)
<i>Gracilaria chilensis</i>	(Santiago, Chile)	30(a)	1800(a)	Ugarte & Santelices (1992)
<i>G. tikvahiae</i>	(Florida, USA)	13(a)	3683(a)	Hanisak & Ryther (1984)
<i>G. tikvahiae</i>	(Florida, USA)	10(a)		Debusk & Ryther (1984)
<i>Palmaria palmata</i>	(Nova Scotia, Canada)	8(a)		Morgan <i>et al.</i> (1980)
<i>Porphyra sp.</i>	(Tokyo, Japan)	18(a)		Imada <i>et al.</i> (1987)

lactuca in 1 m² tanks 60 cm deep, removed over 90% of the ammonia from the fishpond effluents at flows up to 10 $\mu\text{moles l}^{-1} \text{h}^{-1}$: 10 m² of *Ulva* biofilter can remove 90% of the ammonia produced by 1 kg of daily feed ration or approximately 75 kg of fish.

The use of seaweeds for treatments of secondary municipal sewage effluents, recycling of nutrients and marine biomass production was also examined in the USA at Woods Hole, Massachusetts and Fort Pierce, Florida, in the 1970s (Ryther *et al.*, 1972, 1979). Yields were high for both locations. In Massachusetts values in summer ranged from a maximum 43 $\text{g m}^{-2} \text{d}^{-1}$ dry wt for *Gracilaria tikvahiae* to 41 $\text{g m}^{-2} \text{d}^{-1}$ dry wt for *Agardhiella subulata*.

Optimization of biomass production

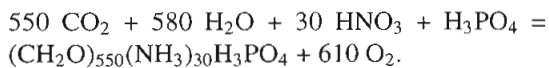
Environmental factors limiting macroalgal productivity

Irradiance, temperature, nutrients, grazing and stand density are the most important parameters affecting biomass production in the sea. Parameters which affect photosynthesis affect primary productivity. Macroalgae show diel and seasonal variations in photosynthetic rate as well as variation in pigmentation related to light conditions, such as shading or with increased depth (Dring, 1986). Macroalgae inhabiting the upper part of intertidal zone are exposed to high irradiance and must adapt as "sun plants", whereas in the sublittoral zone availability of light of various wavelengths influences pigmentation and photosynthetic behavior.

Photosynthetic rates also depend on additional external parameters such as nutrients and water motion, and biological parameters such as age and species. The photosynthetic rate in macroalgae can be enhanced up to 4 times that in still water by increased current speed (Wheeler, 1980a; Gao, 1991a; Gao *et al.*, 1992). The effect of light depends on nutritive condition. For instance, intracellular inorganic N concentrations affect photosynthesis (Gao & Nakahara, 1990). According to Henley *et al.* (1991), when thalli of *Ulva rotundata* were transferred from low (100 $\mu\text{mol photon m}^{-2} \text{s}^{-1}$) to high (1700 $\mu\text{mol photon m}^{-2} \text{s}^{-1}$) light conditions, daily surface area growth rates in N-sufficient plants increased six fold and light-saturated net photosynthetic capacity increased by 50%.

Canopy loss was observed in *Macrocystis* kelp beds of southern and Baja California during summer when the supply of inorganic N and P was low (North, 1987). Changes in nutrients in conjunction with changes in temperature and solar radiation lead to seasonality in primary productivity. Photosynthesis of *Sargassum horneri* showed seasonality correlated to temporal changes in nitrate concentration and water temperature (Gao, 1990a). Light-saturated photosynthetic rate increased by 45% in nutrient-limited *S. thunbergii* plants when cultured in N- and P-enriched seawater for 7 days and growth was 3 times faster in the nutrient-rich seawater (Gao & Nakahara, 1990). Lapointe (1986) demonstrated increased photosynthesis accompanying additions of P to floating colonies of *S. natans* and *S. fluitans*.

Photosynthesis in aquatic environments is accompanied by the assimilation of NO_3^- , NH_4^+ and HPO_4^{2-} (Stumm & Morgan, 1981). For macroalgae, Atkinson and Smith (1983) generalized a mass-balance equation based on the median C : N : P ratio:



While Atkinson and Smith (1983) regarded this deviation from the Redfield ratio of 106:16:1, generally employed for microalgae, to be a result of nutrient limitation, the deviation could well be a result of the greater fraction of biomass in cell walls and extracellular matrix materials in multicellular forms.

The uptake of N and P by macroalgae can be affected by factors such as light, temperature, water motion and even CO_2 and O_2 concentrations. Nitrate and phosphate concentrations in temperate coastal seawaters usually show seasonal variation (Chapman & Craigie,

1977; Hanisak, 1979) with summer minima and winter maxima. Tissue nitrate and total N in *Macrocystis pyrifera* paralleled ambient nitrate levels (Wheeler & Srivastava, 1984) and the growth rate of *M. integrifolia* was reported as a linear function of tissue N (Wheeler & North, 1980).

Table 2 shows maximum inorganic N uptake rates reported for various macroalgae. Ranges within species reflect nutritive conditions or seasonality. N uptake rate for green algae ranges from 3–400 $\mu\text{mol g(dry wt)}^{-1} \text{h}^{-1}$; that of the brown algae from 7–31 $\mu\text{mol g(dry wt)}^{-1} \text{h}^{-1}$; and that of the red algae from 3–29 $\mu\text{mol g(dry wt)}^{-1} \text{h}^{-1}$. Maximum rates for uptake of nutrients vary considerably depending on external environmental conditions, as well as upon internal factors such as species-specific physiological properties, internal nutrient status (i.e. nutritive condition), and state of development and age (DeBoer *et al.*, 1978; Birch *et al.*, 1981; Wallentinus, 1984; Lehnberg & Schramm, 1984). The uptake rate is usually higher in N-starved than in N-sufficient thalli (Wheeler & Srivastava, 1984; Fujita, 1985; Cohen & Neori, 1991). In the red alga *Gracilaria tikvahiae* grown in seawater enriched with 0–1500 $\mu\text{M N}$, tissue N content varied between 1.3–5.3% (Bird *et al.*, 1981). The N uptake has also been found to be enhanced by enrichment with CO_2 in two *Gracilaria* species (Gao *et al.*, 1993).

Optimization and nutrient conditioning

Rapid water motion facilitates the uptake of nutrients by macroalgae even in seawater of low nutrient concentration. Photosynthesis, accompanied by the uptake of nutrients, has been found to be enhanced by water current speed in *Macrocystis pyrifera* (Wheeler, 1980a), *Sargassum thunbergii* (Gao, 1991a) and *Porphyra yezoensis* (Gao *et al.*, 1992). Water motion results in higher productivity, as reported for *P. tenera* (Matsumoto, 1959) and *S. muticum* (Gellenbeck & Chapman, 1986). Primary productivity of algal turfs in coral reefs was increased significantly by increasing current speed (Carpenter *et al.*, 1991). Growing macroalgae in flowing seawater apparently enables them to assimilate nutrients more efficiently. Note, however, that very high current speeds can affect morphological development (Raven, 1992a).

The application of exogenous fertilizer (e.g. ammonium nitrate, orthophosphate) has been used in commercial operations for algae in the Orient, but this practice adds significantly to the cost. For the biomass production to be cost-effective, inexpensive sources of

Table 2. Maximal inorganic nitrogen uptake rates for macroalgae as $\mu\text{mol N h}^{-1}$ on the basis of dry wt (dw), fresh wt (fw), or thallus area (cm^{-2}).

Species	NO_3^- ($\mu\text{mol h}^{-1}$)	NH_4^+ ($\mu\text{mol h}^{-1}$)	Temp. ($^\circ\text{C}$)	Light ($\mu\text{mol photon m}^{-2} \text{s}^{-1}$)	Reference
Chlorophyta					
<i>Codium fragile</i> ssp.	3.3–3.9 g dw ⁻¹	24.0–27.0 g dw ⁻¹	12–24	7–28	Hanisak & Harlin (1978)
<i>Enteromorpha linza</i>	129 g dw ⁻¹		15	76	Harlin (1978)
<i>Ulva curvata</i>	43, 65 g dw ⁻¹		16, 20	72	Rosenberg & Ramus (1984)
<i>U. lactuca</i>		50–390 g dw ⁻¹		>100*	Cohen & Neori (1991)
Phaeophyta					
<i>Fucus spiralis</i>	0.2 cm ⁻²		15	20**	Haines & Wheeler (1978)
<i>Laminaria longicuris</i>	1.6 g fw ⁻¹		15	76	Harlin & Craigie (1978)
<i>L. longicuris</i>	7.0–10.0 g dw ⁻¹		15	76	Harlin & Craigie (1978)
<i>Macrocystis integrifolia</i>	4.8–5.6 g fw ⁻¹		15	100	Wheeler & Srivastava (1984)
<i>M. pyrifera</i>	30.5 g dw ⁻¹		16	20**	Haines & Wheeler (1978)
<i>M. pyrifera</i>	0.1 cm ⁻²		16	20**	Haines & Wheeler (1978)
<i>M. pyrifera</i>	3.1 g fw ⁻¹	2.4 g fw ⁻¹	16	20**	Haines & Wheeler (1978)
Rhodophyta					
<i>Gracilaria chilensis</i>	0.9–2.0 g fw ⁻¹		20	300	Gao <i>et al.</i> (1993)
<i>G. foliifera</i>	9.7 g dw ⁻¹		20	20**	Haines & Wheeler (1978)
<i>G. tikvahiae</i>	3.0–8.0 g dw ⁻¹		16, 20	72	Rosenberg & Ramus (1984)
<i>G. tikvahiae</i>		19.0 g fw ⁻¹		>100*	Friedlander & Dawes (1985)
<i>Hypnea musciformis</i>	28.5 g dw ⁻¹		26	20**	Haines & Wheeler (1978)

* "Outdoor" light reported by authors. Assume "outdoor" light is $>100 \mu\text{mol photon m}^{-2} \text{s}^{-1}$.

** Converted from $1.6 \mu\text{W cm}^{-2} \text{nm}^{-1}$ assuming equal energy over the photosynthetically active radiation (PAR) range.

nutrients will have to be used. Residues of the biomass from fuel conversion processes have been applied to algal cultures and this has proven adequate as a nutrient source (Hanisak, 1981). Sewage and agricultural run-off may also be utilized. As discussed earlier, macroalgae have been used for waste-water treatment and recycling, as well as for biomass production.

Another approach for growth enhancement is the utilization of nutrient-rich deep ocean seawater.† Experiments conducted by North and his colleagues showed that deep seawater supported good growth of

Macrocystis, and that a 50/50 mixture of deep and surface waters led to an even higher growth rate than that obtained using deep seawater alone (North, 1987). *Porphyra tenera* has been successfully grown using deep seawater in Hawaii ($60 \text{ g m}^{-2} \text{d}^{-1}$ dry wt) (Mencher & Katase, 1988). Thus deep waters can supply macroalgae with the nutrients needed. In some areas this occurs naturally ("upwellings"), but in others pumping would be necessary. The cost of pumping could perhaps be defrayed by combining algal farms with either conventional power plants or OTEC (ocean thermal energy conversion) plants, both types requiring large quantities of cooling water.

OTEC-related research has been conducted in Hawaii for increasing aquacultural productivity uti-

† Deep seawater (586 m) in Hawaii contains nitrate at $39.0 \mu\text{mol l}^{-1}$ and phosphate at $3.0 \mu\text{mol l}^{-1}$ (Smith & Walsh, 1988).

lizing deep ocean water. A 210 KW-gross open-cycle demonstration OTEC plant has been operational on the island of Hawaii since February 1993. A 100-MW OTEC power installation would discharge (cold and warm water at 1:1) $69 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ water, delivering approximately 20 t N to the euphotic zone each 24-h period. This quantity of deep ocean water could generate approximately 73,000 t dry wt of kelp (equivalent to approximately 40,000 barrels of oil), or 7300 t fresh wt of fish per year (McKinley & Fast, 1991).

Optimization of biomass density

Biomass yield can vary with stand density. When the density is high, light availability, nutrients and inorganic carbon sources become limited. Optimal density for maximum yield of a natural *Macrocystis pyrifera* population in central California has been estimated at 5–6 kg m^{-2} wet wt (Gerard, 1987). Production of *Gracilaria tikvahiae* under small-scale, intensive culture conditions was highest at 2–4 kg m^{-2} wet wt. (Ryther *et al.*, 1979). *Chondrus crispus* maintained in land-based tanks with air agitation showed increasing production at densities up to 12 kg m^{-2} wet wt with the added benefit of reduced epiphytism at high densities (Bidwell *et al.*, 1985).

For optimal harvesting efficiency biomass should be removed at a rate that does not cause reduced production, but enhances production by maintaining population densities near optimal levels. In Japan high production for cultivated *Porphyra* has been obtained with a harvesting interval of 2 weeks. For *Macrocystis pyrifera* biomass turnover rate has been estimated at 6–8 times per year with optimal harvesting frequency greater than 3 times per year (Gerard, 1987).

Macroalgae for the effective utilization of CO_2

On geological time scales, removal of CO_2 from the atmosphere requires marine sequestration, because terrestrial sequestration of carbon leads to the release of CO_2 from the oceans to balance decreases in atmospheric concentrations (Broecker, 1982; Broecker & Denton, 1989). By examining the ratio of various isotopes of carbon over the past 20 years, Quay *et al.* (1992) concluded that CO_2 from the combustion of fossil fuels has been taken up by the ocean and is playing a role in oceanic carbon processes. This section examines the utilization of CO_2 by marine macroalgae for possible sequestration and remediation.

Uptake of inorganic carbon by macroalgae

The ocean pool of carbon contains dissolved inorganic carbon (DIC), as CO_2 , HCO_3^- and CO_3^{2-} , more than 50 times that present in the atmosphere as gaseous CO_2 . In ordinary seawater (pH 8.2–8.3), more than 90% of DIC is HCO_3^- , less than 1% is as dissolved gaseous CO_2 . DIC concentrations for seawater (equilibrated with air) range from 2.0–2.2 mM. Because of its greater abundance, the use of HCO_3^- by marine algae would appear to be to their advantage, although it must be acknowledged that it is CO_2 that is incorporated during carboxylation by ribulose-1,5- biphosphate (RuBP) carboxylase (see Raven, 1992b).

Within algal cells, HCO_3^- is converted to CO_2 via catalysis of intracellular carbonic anhydrase (CA), the existence of which has been demonstrated in many macroalgae (Graham & Smillie, 1976; Giordano & Maberly, 1989). Macroalgae capable of using HCO_3^- are shown in Table 3. The green *Halimeda tuna* and *H. discoidea* (Borowitzka & Larkum, 1976), the brown *Alaria esculenta*, *Ascophyllum nodosum*, *Fucus vesiculosus* (Surif & Raven, 1989), *F. crispus* (Smith & Bidwell, 1987), *F. serratus*, *F. spiralis*, *Laminaria digitata*, *L. hyperborea*, *L. saccharina*, *Pelvetia canaliculata* (Surif & Raven, 1989), and the red *Serraticardia maxima* (Okazaki, 1972) and *Gracilaria conferta* (Israel & Beer, 1992) possess extracellular CA. These macroalgae utilize HCO_3^- through CA-catalyzed interconversion before transporting CO_2 across cell membranes. The green *Ulva lactuca* (Drechsler & Beer, 1991), the brown *Fucus distichus*, *Pelvetiopsis limitata*, and the red *Gigartina exasperata*, *Hymena flabelligera*, *Palmaria palmata* and *Porphyra occidentalis* (Cook *et al.*, 1986) do not possess extracellular CA. These species may possess an active transport pump for HCO_3^- . The green *Enteromorpha linza* (Brown & Tregunna, 1967), the brown *Carpophyllum* spp. (Dromgoole, 1978), and the red *Gigartina latissima* (Brown & Tregunna, 1967) are reported to be incapable of using HCO_3^- . The green *Cladophora rupestris*, the brown *Ascophyllum nodosum*, *Fucus serratus* (Bidwell & McLachlan, 1985), *F. distichus*, *Pelvetiopsis limitata* (Cook *et al.*, 1986), *Sargassum muticum* (Thomas & Tregunna, 1968), *Turbinaria turbinata* (Holbrook *et al.*, 1988), and the red *Chondrus crispus* (Smith & Bidwell, 1987), *Gigartina exasperata*, *Hymena flabelligera*, *Palmaria palmata* and *Porphyra occidentalis* (Cook *et al.*, 1986) are reported to be incapable of using CO_2 . Because CO_2 can easily pass through the

Table 3. Use of various forms of inorganic carbon and the presence or absence of extracellular carbonic anhydrase (CA). CA: +, detected; -, not detected. Ability to use CO₂ and/or HCO₃⁻: Y, Yes; N, No; P, Possible.

Species	CO ₂	HCO ₃ ⁻	CA	Reference
Chlorophyta				
<i>Cladophora rupestris</i>	N	Y		Bidwell & McLachlan (1985)
<i>Cladoporopsis variegat</i>	P	Y		Holbrook <i>et al.</i> (1988)
<i>Codium fragile</i>	P	Y		Raven & Osmond (1990)
<i>Enteromorpha linza</i>	Y	N		Brown & Tregunna (1967)
<i>Halimeda discoidea</i>	Y	P	+	Borowitzka & Larkum (1976)
<i>H. tuna</i>	Y	P	+	Borowitzka & Larkum (1976)
<i>Ulva fasciata</i>	P	Y		Beer <i>et al.</i> (1990)
<i>U. lactuca</i>	P	Y		Sand-Jensen & Gordon (1984)
<i>U. lactuca</i>	P	Y	-	Drechsler & Beer (1991)
Phaeophyta				
<i>Alaria esculenta</i>	P	Y	+	Surif & Raven (1989)
<i>Ascophyllum nodosum</i>	N	Y		Bidwell & McLachlan (1985)
<i>A. nodosum</i>	P	Y	+	Surif & Raven (1989)
<i>A. nodosum</i>	P	Y		Johnston & Raven (1986)
<i>Carpophyllum</i> spp.	Y	N		Dromgoole (1978)
<i>Dictyota dichotoma</i>	P	Y		Raven & Osmond (1990)
<i>Dilophus guineensis</i>	P	Y		Holbrook <i>et al.</i> (1988)
<i>Fucus crispus</i>	P	Y	+	Smith & Bidwell (1987)
<i>F. distichus</i> ssp <i>edantatus</i>	N	Y	-	Cook <i>et al.</i> (1986)
<i>F. serratus</i>	P	Y	+	Surif & Raven (1989)
<i>F. serratus</i>	N	Y		Bidwell & McLachlan (1985)
<i>F. spiralis</i>	P	Y	+	Surife & Raven (1989)
<i>F. spiralis</i>	P	Y		Madsen & Maberly (1990)
<i>F. vesiculosus</i>	P	Y		Sand-Jensen & Gordon (1984)
<i>F. vesiculosus</i>	P	Y	+	Surif & Raven (1989)
<i>F. vesiculosus</i>	P	Y		Raven & Osmond (1990)
<i>Laminaria digitata</i>	P	Y		Bidwell & MacLachlan (1985)
<i>L. digitata</i>	P	Y	+	Surif & Raven (1989)
<i>L. hyperborea</i>	P	Y	+	Surif & Raven (1989)
<i>L. saccharina</i>	P	Y	+	surif & Raven (1989)
<i>Pelvetia canaliculata</i>	P	Y	+	Surif & Raven (1989)
<i>Pelvetiopsis limitata</i>	N	Y	-	Cook <i>et al.</i> (1986)
<i>Sargassum muticum</i>	N	Y		Thomas & Tregunna (1968)
<i>S. filipendula</i>	P	Y		Raven & Osmond (1990)
<i>Turbinaria turbinata</i>	N	Y		Holbrook <i>et al.</i> (1988)
Rhodophyta				
<i>Ceramium rubrum</i>	P	Y		Sand-Jensen & Gordon (1984)
<i>Chondrus crispus</i>	N	Y		Smith & Bidwell (1987)
<i>Gigartina latissima</i>	Y	N		Brown & Tregunna (1967)
<i>G. exasperata</i>	N	Y	-	Cook <i>et al.</i> (1986)
<i>Gracilaria chilensis</i>	P	Y		Gao <i>et al.</i> (1993)
<i>G. conferta</i>	P	Y	+	Israel & Beer (1992)
<i>G. foliifera</i>	N	Y		Bidwell & McLachlan (1985)
<i>G. secundata</i>	P	Y		Lignell & Pedersen (1989)
<i>Gracilaria</i> sp.	Y	P		Gao <i>et al.</i> (1993)
<i>G. tikvahiae</i>	N	Y		Bidwell & McLachlan (1985)
<i>Hymena fabelligera</i>	N	Y	-	Cook <i>et al.</i> (1986)
<i>Palmaria palmata</i>	N	Y	-	Cook <i>et al.</i> (1986)
<i>Polyneura latissima</i>	Y	N		Brown & Tregunna (1967)
<i>Porphyra occidentalis</i>	N	Y	-	Cook <i>et al.</i> (1986)
<i>P. yezoensis</i>	P	Y		Gao <i>et al.</i> (1991)
<i>Serraticardia maxima</i>	P	Y	+	Okazaki (1972)

cell membrane when there is a positive gradient in concentration, such information must be approached with caution. For example, Bidwell and McLachlan (1985) reported that *Fucus serratus* could not use CO₂, but Surif and Raven (1989) reported that the same species could do so.

Utilization of HCO₃⁻ by macroalgae usually results in increases of pH even under elevated CO₂ concentrations (Gao *et al.*, 1991, 1993). Increased pH of seawater with constant alkalinity raises the dissolution of CO₂. Stumm and Morgan (1981) suggested that a doubling of CO₂ in the atmosphere would result under equilibrium conditions in a lowering of pH by 0.279 units in the mixed surface of the sea. However, if the primary production in the sea increased with increasing concentrations of CO₂, the lowering of pH due to increased dissolution of CO₂ would be offset by the rise of pH from the photosynthetic utilization of HCO₃⁻. This would, of course, only occur if rates of photosynthesis were CO₂-limited. Riesbesell *et al.* (1992) suggest that this is in fact the case.

A better understanding of the use of inorganic C by macroalgae under elevated CO₂ concentrations is important for predicting the effects of CO₂ on biomass production. In the case of the utilization of deep seawater, CO₂ fixation by macroalgae would be enhanced by the enrichment of nutrients, gaseous CO₂ and DIC. Inorganic N, gaseous CO₂ and DIC in deep seawater (586 m) have been demonstrated at 200, 3.3 and 1.2 times that of surface water (8 m) in Hawaii (Smith & Walsh, 1988).

"CO₂" concentration and photosynthetic rate of macroalgae

Is the DIC concentration in seawater high enough to bring about maximum photosynthetic rates for macroalgae (i.e. does the DIC concentration saturate macroalgal photosynthesis)? The answer to this question is important in evaluating the effects of increasing CO₂ on marine ecology and air-sea exchanges. Table 4 presents CO₂ or DIC concentrations resulting in maximum photosynthetic rates (photosynthesis-saturating concentrations) for macroalgae demonstrated by a variety of techniques.

By exposing *Cladophora rupestris*, *Ulva lactuca* and *Fucus vesiculosus* to air Bidwell and McLachlan (1985) found that concentrations of CO₂ five times the ambient for ordinary air were needed to saturate the photosynthetic apparatus of these algae. Brown and Tregunna (1967) measured the photosynthesis of

Enteromorpha linza, *U. expensa*, *F. crispus*, *Sargassum muticum*, *Gigartina latissima*, and *Iridaea cordata* in pH 5 medium with aeration and also discovered that algal photosynthesis could not be saturated by the ambient concentration of CO₂ in the atmosphere. Madsen and Maberly (1990) reported that the photosynthesis of *F. spiralis* was neither saturated by CO₂ when exposed to air nor by DIC in seawater when submerged. Photosynthesis and calcification by the articulated coralline alga, *Corallina pilulifera* increases with increasing DIC and a limit for this species could not be reached even at 10 mM DIC at pH 8.2 (Gao *et al.*, 1993). Wheeler (1980a) reported that the photosynthesis of *Macrocystis pyrifera* was saturated in still seawater at 2 mM DIC, but did not saturate until 8 mM DIC in moving seawater (7 cm s⁻¹). Thus it appears that macroalgal photosynthesis is for the most part limited by availability of inorganic sources of C in natural seawater.

The photosynthetic rate can be used as an indicator of capacity for CO₂ capture. Table 5 shows the light-saturated photosynthetic rates for macroalgae using different measurement methodologies and techniques. For the green algae, the light-saturated net photosynthetic rates range from 400–1800 μmol CO₂ g (dry wt)⁻¹ h⁻¹, with *Enteromorpha compressa* the highest. For the brown algae, the light-saturated net photosynthetic rates range from 100 to 1670 μmol CO₂ g (dry wt)⁻¹ h⁻¹, with *Sargassum muticum* the highest. The net photosynthetic rate of the red algae ranges from 250 to 2232 μmol CO₂ g (dry wt)⁻¹ h⁻¹, with *Porphyra* the highest. Increasing DIC concentrations in seawater at pH 8.2 from 2 to 10 mM raised the photosynthetic rate of *Porphyra yezoensis* from 1560 to 2230 μmol CO₂ g (dry wt)⁻¹ h⁻¹ and that of *Gracilaria* sp. from 62 to 108 μmol CO₂ g (dry wt)⁻¹ h⁻¹.

The photosynthetic rates of large brown algae are usually based upon only a small portion of the plant. However, photosynthesis usually shows higher activities in younger portions (e.g. Küppers & Kremer, 1978; Gao, 1991b), so it is important to try to take into account "whole individuals" before attempting to assess productivity on the basis of photosynthetic rates.

Biological response of some macroalgae to high CO₂ concentrations

It has only been in the last few years that the response of macroalgae to high CO₂ concentrations has been examined. Johnston and Raven (1990) reported that *Fucus serratus* survived in 5% CO₂ for 3 weeks and its pho-

Table 4. "CO₂" concentrations saturating the photosynthesis of macroalgae.

Species	CO ₂ (ppm)	DIC (mM)	Measurement technique	Temp. (°C)	Light ($\mu\text{mol photon m}^{-2}\text{s}^{-1}$)	Reference
Chlorophyta						
<i>Cladophora rupestris</i>	>1500		Emersed, IRGA	18–20	400	Bidwells & McLachlan (1985)
<i>Codium fragile</i>		>2.5	O ₂			Raven & Osmond (1990)
<i>Enteromorpha linza</i>	>500		IRGA, pH5	20	150–200	Brown & Tregunna (1967)
<i>Halimeda tuna</i>		3.0	O ₂	26	56	Borowitzka & Larkum (1976)
<i>Ulva expansa</i>	>500		IRGA, pH 5	20	150–200	Brown & Tregunna (1967)
<i>U. lactuca</i>	>2000		Emersed, IRGA	18–20	400	Bidwell & McLachlan (1985)
<i>U. lactuca</i>		>3.0	O ₂	15	1000	Sand-Jensen & Gordon (1984)
Phaeophyta						
<i>Carpophyllum</i> spp.		>2.2	O ₂	20	500	Dromgoole (1978)
<i>Fucus crispus</i>	>1900		IRGA, pH 5	20	150–220	Brown & Tregunna (1967)
<i>F. crispus</i>	>2000		Emersed, IRGA	18	400	Smith & Bidwell (1985)
<i>F. spiralis</i>	>750		Emersed, IRGA	15	2000	Madsen & Marberly (1990)
<i>F. spiralis</i>		>3.1	Submerged, DIC	15	2000	Madsen & Maberly (1990)
<i>F. vesiculosus</i>		>3.0	O ₂	15	1000	Sand-Jensen & Gordon (1984)
<i>F. vesiculosus</i>	>1800		Emersed, IRGA	18–20	400	Bidwell & McLachlan (1985)
<i>Macrocystis pyrifera</i>		>8.0	O ₂	15	125	Wheeler (1980)
<i>S. filipendula</i>		>2.5	O ₂			Raven & Osmond (1990)
<i>Sargassum muticum</i>	>500		IRGA, pH 5	20	150–220	Brown & Tregunna (1967)
Rhodophyta						
<i>Amphiroa anceps</i>		3.0	O ₂	28	600	Borowitzka (1981)
<i>A. foliacea</i>		3.0	O ₂	18–22	600	Borowitzka (1981)
<i>Ceramium rubrum</i>		2.2–3.0	O ₂	15	1000	Sand-Jensen & Gordon (1984)
<i>Gelidium cartilagineum</i>		>3.0	O ₂	16	160	Tseng & Sweeney (1946)
<i>Gigartina latissima</i>	>500		IRGA, pH 5	20	150–220	Brown & Tregunna (1967)
<i>Gracilaria chilensis</i>		>10.0	TOC analyzer	20	300	Gao <i>et al.</i> (1993)
<i>Gracilaria</i> sp.		>10.0	TOC analyzer	20	300	Gao <i>et al.</i> (1993)
<i>Iridaea cordata</i>	>500		IRGA, pH 5	20	150–220	Brown & Tregunna (1967)
<i>Porphyra yezoensis</i>		>2.2	Mass spectrometer	15	600	Gao <i>et al.</i> (1991)

photosynthetic physiology was affected in much the same way as that reported for microalgae (i.e., increased CO₂ compensation point, decreased CO₂ affinity, lowered pH compensation point). Gao *et al.* (1991, 1993) demonstrated that elevated CO₂ concentrations, up to 5 times atmospheric levels, enhanced the growth of *Porphyra yezoensis*, *Gracilaria* sp. and *G. chilensis* under optimal light and nutrient conditions, together with biomass densities similar to that encountered in nature. Increased atmospheric CO₂ concentrations are

also likely to increase primary production by marine phytoplankton (Riebesell *et al.*, 1992; Raven, 1992b).

Addition of CO₂ to cultures of a calcifying articulated red alga, *Corallina pilulifera*, inhibited calcification (Gao *et al.*, 1993), while calcification in another articulated red alga, *Bossiella orbigniana*, was enhanced in artificially buffered seawater with elevated CO₂ concentrations (Smith & Roth, 1979). The inhibition in *Corallina pilulifera* with high CO₂ was attributed to the lowering of pH in the culture. Photosynthetic carbon removal by these forms is apparently

Table 5. Light-saturated net photosynthetic rate (Pn) as $\mu\text{mol CO}_2 \text{ h}^{-1}$ on the basis of dry wt (dw), fresh wt (fw), or thallus area (dm^{-2}). Note: "*" indicates the values reported as C fixation rate, other values were converted from O_2 evolution rates taking the photosynthetic quotient as 1. A value of 2 mM DIC indicates that the investigators used ordinary seawater. Values in "()" are gaseous CO_2 . These experiments were conducted in air. Other experiments were conducted in ordinary seawater or C-enriched seawater.

Species	Pn ($\mu\text{mol CO}_2 \text{ h}^{-1}$)	Temp. ($^{\circ}\text{C}$)	DIC or (CO_2) mM	Reference
Chlorophyta				
<i>Cladopora rupestris</i>	83 g fw ^{-1*}	18–20	(0.018)	Bidwell & McLachlan (1985)
<i>Enteromorpha compressa</i>	1786 g dw ⁻¹	20	2	Yokohama (1973)
<i>E. linza</i>	223 g fw ^{-1*}	20	(0.013)	Brown & Tregunna (1967)
<i>Monostroma nitidum</i>	670 g dw ⁻¹	20	2	Yokohama (1973)
<i>M. latissimum</i>	378 g dw ⁻¹	14	2	Maegawa (1980)
<i>M. latissimum</i>	625–875 g dw ⁻¹	18–20	2	Maegawa & Aruga (1983)
<i>Ulva rotundata</i>	140–288 dm^{-2}	20	2	Levavasseur <i>et al.</i> (1991)
<i>U. rotundata</i>	194–212 dm^{-2}	25	2	Levavasseur <i>et al.</i> (1991)
<i>U. rotundata</i>	274–310 dm^{-2}	25	20	Levavasseur <i>et al.</i> (1991)
Phaeophyta				
<i>Ascophyllum nodosum</i>	86 g fw ^{-1*}	18–20	(0.018)	Bidwell & McLachlan (1985)
<i>Fucus serratus</i>	43 g fw ^{-1*}	18–20	(0.018)	Bidwell & McLachlan (1985)
<i>Laminaria longissima</i>	223 dm^{-2}	15	2	Sakanishi <i>et al.</i> (1990)
<i>Macrocystis pyrifera</i>	104 dm^{-2}	15	2	Wheeler (1980)
<i>Sargassum fluitans</i>	83–175 g dw ⁻¹	28–30	2	Lapointe (1986)
<i>S. horneri</i>	415 g dw ⁻¹	27–29	2	Gao (1990b)
<i>S. muticum</i>	95 g dw ⁻¹	15	2	Fernandez <i>et al.</i> (1990)
<i>S. muticum</i>	267–1667 g dw ^{-1*}	21–30	2	Critchley <i>et al.</i> (1990)
<i>S. natans</i>	83–125 g dw ⁻¹	28–30	2	Lapointe (1986)
<i>S. polyceratum</i>	360 g dw ⁻¹	20	2	Kilar <i>et al.</i> (1989)
<i>S. thunbergii</i>	134–402 g dw ⁻¹	18	2	Gao & Nakahara (1990)
<i>S. thunbergii</i>	500–700 g dw ⁻¹	21–30	2	Gao & Umezaki (1989a, b, c)
Rhodophyta				
<i>Gracilaria chilensis</i>	42–60 g fw ^{-1*}	20	2–10	Gao <i>et al.</i> (1993)
<i>Gracilaria sp.</i>	62–108 g fw ^{-1*}	20	2–10	Gao <i>et al.</i> (1993)
<i>G. tikvahiae</i>	250–917 g dw ⁻¹	24–30	2	Hanisak <i>et al.</i> (1988)
<i>Porphyra nereocystis</i>	108 dm^{-2}	12	2	Herbert & Waaland (1988)
<i>P. suborbiculata</i>	2232 g dw ⁻¹	20	2	Yokohama (1973)
<i>P. yezoensis</i>	964 g dw ⁻¹	15	2	Gao & Aruga (1987)
<i>P. yezoensis</i> (ZGRW)	1560–2230 g dw ⁻¹	15	2–10	Gao <i>et al.</i> (1991)

insufficient to raise the pH in the presence of CO_2 enrichment.

Economics and feasibility

Four countries, namely, China, Japan, Korea and the Philippines produce 2.4×10^6 t of seaweed (wet wt) worth more than US\$ 100×10^6 annually and involve or employ 670,000 people (Tseng & Fei, 1987). In 1983

Table 6. Costs (US\$ GJ⁻¹) for feedstock production of macroalgae by different cultivation methods. "High" and "low" production represents the range of yields from intensive advanced cultivations and commercial cultivations, respectively. Values appear in Bird (1987).

Methods	High production	Low production
Tidal flat	2.30	3.60
Floating	3.00	6.00
Nearshore farms	3.50	5.50
Rope systems	12.00	44.00

China produced 231,296 t dry wt of *Laminaria* and 9987 t dry wt of *Porphyra* under cultivation. In Japan *Porphyra*, *Undaria* and *Laminaria* have been produced commercially for decades. In 1981 Japanese farmers produced 340,000 t *Porphyra*, 91,000 t *Undaria* and 44,000 t *Laminaria* on a wet wt basis. Annual production in Japan of the cultivated green macroalga *Monostroma* was 1400 t dry wt (Kita, 1990). Macroalgae are clearly "big business".

In the Philippines, seaweed farming offers a promising industry for its developing island communities. A *Euचेuma* farm in Tawi-Tawi of about 0.5 ha per family (Alih, 1990) produces 9 t yr⁻¹ dry wt (18 t ha⁻¹ yr⁻¹) with a potential net annual income of about P 10,250 (US\$ 1360), this income representing more than 3 times the prevailing average family income in the country (Smith, 1987). The production costs for growing *E. spinosum* in 1981 were estimated to be P 2.36 (US\$ 0.31) per kg dry wt for extensively operated farms and P 1.93 (US\$ 0.25) per kg for intensively operated farms.

Gracilaria culture in Taiwan is undertaken in the southern part of the island, the area under cultivation estimated at more than 400 ha in 1977 and involving 200 households. The initial capital cost was US\$ 0.21 per kg dry wt with an annual production of 13 t ha⁻¹ (Smith, 1987). The production cost of cultivating *G. tenuistipitata* in raft culture in China was US\$ 0.10 per kg dry wt (FAO, 1990). The production of this alga can be as high as 750 kg dry wt ha⁻¹ (worth about US\$ 2250) per month.

Costs of energy generation from marine biomass in the USA have been reviewed recently by Bird (1987). The cost for biomass-to-energy systems was divided under two headings: cultivation and harvesting, and biofuel production and purification. The economic target was US\$ 6 GJ⁻¹. This was proposed by the General Electric Company and is competitive with the cost of substitute natural gas from coal gasification (Sullivan *et al.*, 1981). Costs for gas production and purification are relatively low, varying from US\$ 2.50 to 5.50 GJ⁻¹ for advanced and standard systems, respectively.

Feedstock costs vary considerably (Table 6): US\$ 2.30 GJ⁻¹ for a tidal-flat farm (*Gracilaria*, or *Ulva*) with a production of 23 DAFMT (dry ash-free metric t) ha⁻¹ yr⁻¹, and US\$ 3.60 GJ⁻¹, at 11 DAFMT ha⁻¹ yr⁻¹; US\$ 3 to \$ 6 for floating seaweed cultivation (*Sargassum*) with 45 or 22 DAFMT ha⁻¹ yr⁻¹ produced, respectively; between US\$ 3.50 and \$ 5.50 for *Macrocystis* nearshore farms with yields of 50 and 34 DAFMT ha⁻¹ yr⁻¹, respectively; and US\$ 12 and \$ 44 for a rope system farm (*Gracilaria*, or *Laminaria*) with yields of 45 and 11 DAFMT ha⁻¹ yr⁻¹. Similar projections have been made by Ritschard (1992): US\$ 6.67 GJ⁻¹ for open-ocean farms of *Macrocystis* and US\$ 10.00 GJ⁻¹ for coastal facilities.*

Although limited by an inadequate data base the estimates for biofuels production using macroalgae are promising. When combined with estimates for advanced methane production and purification, total estimated costs are at or below the target level (US\$ 6 GJ⁻¹) for high yield feedstock operations in tidal-flat farms, floating seaweed cultivation systems and nearshore installations (i.e., US\$ 4.80, 5.50 and 6.00 GJ⁻¹, respectively). Only tidal-flat farms are projected to be sufficiently productive to be cost-effective using non-advanced (standard) methods for methane generation (i.e., US\$ 7.8 GJ⁻¹). However, all three methods are within plus 50% of the target figure for their respective high yield operations using standard systems for methane production and purification. Low yield farms for these three methods would deliver biofuels at costs ranging from the target figure (i.e., US\$ 6.10 GJ⁻¹) to 192% (i.e. US\$ 11.50 GJ⁻¹) of that figure. For rope systems to be competitive, biomass yields would have to be increased substantially. Only if yields near the 150 t ha⁻¹ dry wt reported earlier for *Laminaria* are achieved on a consistent basis, should this technology

* The figures US\$ 6.67 GJ⁻¹ and US\$ 10.00 GJ⁻¹ were calculated from US\$ 200 t⁻¹ C and US\$ 300 t⁻¹ C assuming 30 GJ t⁻¹ C.

be re-examined. Ritschard's most optimistic projection for *Macrocystis* (above) would result in a total estimated cost of US\$ 9.17 GJ⁻¹ using advanced gas production technologies.

In the USA the area available for growth of marine plants has been estimated at 2.3×10^6 km² (Snow *et al.*, 1979). Assuming a growth yield of 5 kg m⁻² yr⁻¹ dry wt and a heating value of 0.01 GJ kg⁻¹, that area would produce a biomass energy equivalent of 1.15×10^{11} GJ yr⁻¹ (Chynoweth *et al.*, 1987). Assuming an organic carbon content of 30% of dry wt, about 13 Gt of CO₂ or 3.4 Gt C could be removed and recycled annually. The CO₂ emission of the USA is greater than any other country in the world with annual emissions of 1.28 Gt C (23.7% of the world total) (IPCC, 1990). Nevertheless, the annual emitted CO₂ could be removed or recycled by using only 38% of the area available in the USA for macroalgal biomass production. However, the success of large-scale energy-generating marine biomass systems will only be achieved by demonstrating the economic feasibility of ocean farming and by further developing cost-effective processes for conversion of biomass to biofuels.

Conclusions

Biomass production from macroalgae has been viewed as important mainly because of the need for pollution abatement (Morand *et al.*, 1991). Environmental considerations will increasingly determine product and process acceptability and drive the next generation of economic opportunity. Some countries, including Japan, are actively promoting 'green' technologies that will be in demand worldwide in the coming decades. CO₂-induced global warming is in the news and emissions of CO₂ have become an international political issue. Calls have been made to limit industrial emissions of CO₂ (Helm, 1990). Should an international agreement on CO₂-reduction be ratified, a worldwide CO₂-business would be immediately generated, and the recycling of CO₂ for effective use and energy production would be of high priority. Because reductions in emissions of CO₂ will inevitably be costly, biomass-generated fuels stand to become more economically and environmentally attractive as an alternative to conventional fossil fuels.

This report has shown that macroalgae have great potential for biomass production and CO₂ bioremediation. Macroalgae have high productivity and do not compete with terrestrial crops for farm land. Biomass

from macroalgae promises to provide environmentally and economically feasible alternatives to fossil fuels. Nevertheless, the techniques and technologies for growing macroalgae on a large-scale and for converting feedstocks to energy carriers must be more fully developed for the potential to be realized.

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