IV. Geoengineering with Macroalgae

Macroalgae or seaweed, refers to several species of macroscopic, multicellular, marine algae. The term includes some types of Rhodophyta (red), Phaeophyta (brown) and Chlorophyta (green) macroalgae. **Seaweed grows quickly**. Seaweed species such as kelps provide essential nursery habitat for fisheries and other marine species and thus protect food sources.

Since aquaculture of macroalgae may avoid the considerable cost involved in fertilization of microalgae and many of the above objections to fertilization-based microalgae geoengineering, macroalgae deserve examining for possible use in carbon sequestration.

Macroalgae Aquaculture and Carbon Sequestration

Approach/rationale Macroalgal aquaculture is performed in the nearshore environment, to supply a range of products from food to nutraceuticals. It is a well-established industry globally (Pereira and Yarish, 2008), and in particular in China, Japan and S. Korea (Chung et al., 2011). In this Asia-Pacific region, macroalgal cultivation already may account for ~0.8 Mt organic carbon accumulated annually (Sondak et al., 2017), this compares with estimates of the natural and ongoing sequestration of macroalgae in the deep ocean and sediments of ~170 Mt C per year (Krause-Jensen and Duarte, 2016). There has been debate about whether this aquacultural approach can be extended onto larger scales to produce biomass that could potentially be sequestered (Chung et al., 2011; Duarte et al., 2017; Moreira and Pires, 2016; Raven, 2017). Macroalgal material could be stored in containers placed on the deep ocean seabed e.g. the geosynthetic containers, but the costs of such an approach may make it impractical. Sondak et al. (2017) advocated that cultivated macroalgae could mainly play a key role as a ‘carbon donor’ for biomass conversion into biogases and/or biofuels.

Underlying principles The large amount of carbon biomass that is harvested from macroalgal cultivation in nearshore waters (Sondak et al., 2017) has been used to demonstrate the potential of this approach for CO_2 sequestration geoengineering (Chung et al., 2013). The term ‘**ocean afforestation**’ was introduced by N’Yeurt et al. (2012) and this led to discussion about the role of macroalgae as ‘blue carbon’ (usually associated with sediment-linked biota such as seagrasses, mangroves and saltmarshes). Chung et al. (2013) pointed out that the lack of a sediment-substratum link for kelp would probably prevent macroalgal carbon being sequestered on long timescales and that their potential role lay in biofuels. Sondak et al. (2017) reached a similar conclusion with respect to their main role being “carbon donors’.

Evidence of concept from the natural world A recent study has highlighted the potential of macroalgae to currently play a significant role in the oceans biological pump (Krause-Jensen and Duarte, 2016, see below) and hence challenges the above assertion by Chung et al. (2013). The authors collate reports of the sequestration of macroalgae in the deep ocean and also marine sediments and use this as the basis to develop a global budget for macroalgal carbon sequestration, along with propagation of error analysis. Krause-Jensen and Duarte (2016) report that **macroalgae have the potential (without enhanced cultivation) to sequester ~170 Mt C annually** (c.f. 5-10 Gt C per year by the phytoplankton driven oceanic biological pump). Most of the macroalgal sequestration is through export to the deep-sea (90%) with the remainder buried in coastal sediments.

Direct/indirect sequestration Direct C sequestration via burial in sediments and export to the deep ocean (Krause-Jensen and Duarte, 2016), and indirect sequestration if used for biofuels (Chung et al., 2013; Sondak et al., 2017).

Proposed deployment zones and potential scale of use Current deployment zones are in the **coastal ocean** (Pereira and Yarish, 2008) and based on the natural C sequestration budget of (Krause-Jensen and Duarte, 2016) and/or the estimates from intensive aquaculture (Sondak et al., 2017) would have to be expanded into more nearshore areas and/or moved offshore (Buck et al., 2004) to achieve a significant scale of additional sequestration. There has also been debate about using hybrid approaches such as permaculture (Flannery, 2017) in which macroalgal cultivation takes place alongside other forms of aquaculture within 1 km length scale submerged to 25 m depth, to avoid navigational issues. This approach is also termed **IMTA (Integrated Multi-Trophic Aquaculture**), (Troell et al., 2009; Buck et al., 2018). Other hybrid approaches (proposed for offshore waters) include macroalgal farms in conjunction with wind farms (Buck et al., 2004).

Duration of deployment The deployments would likely be long-term (years, sustained, ongoing) as this approach is CDR geoengineering (see National Research Council, 2015a).

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments There have been a range of pilot studies, perhaps best exemplified by the CCRB (Coastal CO_2 Removal Belt) off South Korea (Chung et al., 2013). The 0.5 ha CCRB pilot farm (with perennial brown macroalgae on a midwater rope-culture framework for grazer avoidance) has removed 10 t CO_2/ha/y as measured using net community production and time-series of dissolved inorganic carbon (Chung et al., 2013). Prospects for the use of macroalgae for fuel in Ireland and the UK have been evaluated, informed by stakeholder interviews (Roberts and Upham, 2012). They found considerable practical obstacles to the technology, amplified as operations move offshore, leading to skepticism among stakeholders that an offshore industry could develop. However, a Norwegian study on the opportunities and risks of seaweed biofuels in aviation indicated large coastal area potentially available for seaweed production (Andersen, 2017).

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate) There is little evidence, so far, of assessment of side-effects from either macroalgal cultivation or IMTA pilot studies (Chung et al., 2013). There is also little discussion of the need for, and implications of, upscaling cultivation, either in nearshore and/or offshore waters, to increase the magnitude of C sequestration, or how to detect and attribute sequestration. Clearly, modelling simulations could be used to further develop this debate.

Several studies have recently examined the wider ecological or societal implications of macroalgal cultivation for geoengineering (Aldridge et al., 2012; Cottier-Cook et al., 2016; Wood et al., 2017). Cottier-Cook et al. (2016) produced a policy brief which considers and debates "how the production of seaweed affects and impacts our alternate source of safe food and nutrition supplement or our surrounding environment, with respect to pollution of coasts, our indigenous biodiversity, disease outbreak (food safety standard-pet food, chocolate and toothpaste), climate change mitigation, fair trade and blue economy". Wood et al. (2017) have recently raised a range of policy-relevant issues around the licensing of further work into this potential marine geoengineering approach.

Natural Macroalgae as a carbon sink.

The previous section discussed the use of macroalgae aquaculture for carbon sequestration. However, this approach is unlikely to be very efficient when used a fuel. Although it does prevent the use of fossil fuels, when burned the carbon is returned to the atmosphere as CO_2. It is carbon neutral and does not pull CO_2 from the atmosphere. Other techniques will still need to be used to actually remove CO_2 from the atmosphere. The same holds when the macroalgae is used for food. Again, the C is returned to the atmosphere as CO_2 after the food is eaten. For these reasons, the report of Krause-Jensen and Duarte (2016) on the use of macroalgae for **marine carbon sequestration** was of considerable interest. The following is taken virtually verbatim from that report.

Macroalgae export about 43% of their production (Duarte & Cebrián, 1996) both as particulate organic carbon (POC) (Krumhansl & Scheibling, 2012); Filbee-Dexter & Scheibling 2014) and dissolved organic carbon (DOC) (Hill, R. et al. 2015; Barron, et al 2014; Barrón & Duarte, 2015; Reed, et al 2015). Some of this carbon may reach depositional areas and be sequestered in sediments, or reach the deep sea, where the carbon is locked away from exchange with the atmosphere. Macroalgae can thereby act as carbon donors to sink reservoirs located elsewhere (Smith, 1981; Duarte & Cebrián, 1996). In 1981 Smith (1981) stated:

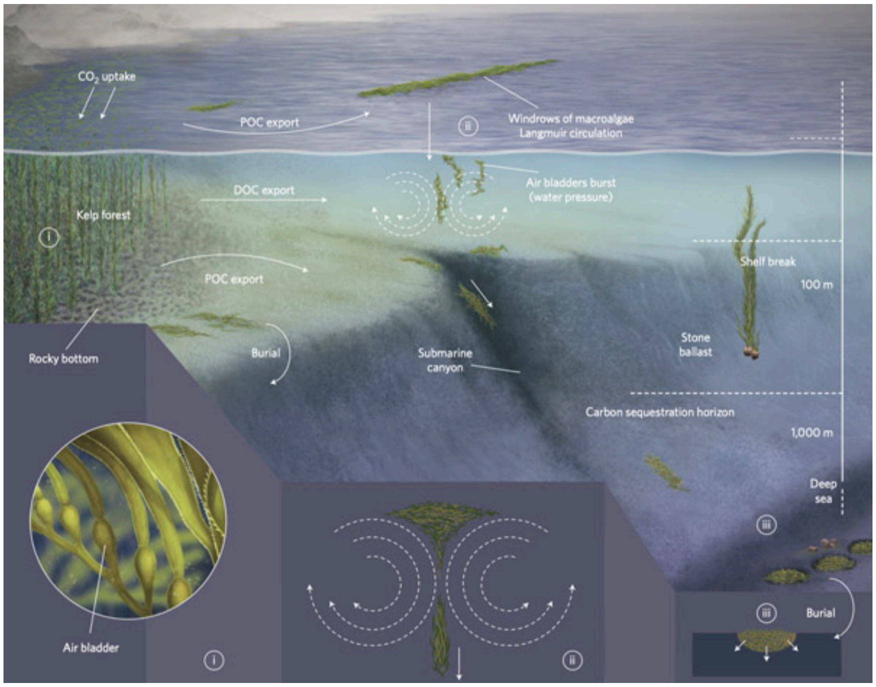
> “Marine macrophyte biomass production, burial, oxidation, calcium carbonate dissolution, and metabolically accelerated diffusion of carbon dioxide across the air-sea interface may combine to sequester at least 10^9 tons of carbon per year in the ocean.”

The evidence required to estimate this contribution of macroalgae has been published under a range of research fields. For instance, macroalgal export has been studied because of its consequences for the dispersal of species and genes (Fraser, 2016; Macaya, E. C. et al (2016), the relocation of rocks across the seafloor (Garden & Smith, 2015), connectivity among habitats and the stimulation of secondary production in adjacent and distant habitats (Krumhansl & Scheibling 2012; Filbee-Dexter & Scheibling 2014) including the supply of food to deep-sea fauna (Wolff, 1962) and carbonate to the deep sea (Fabry & Deuser,1991).

Macroalgal specific markers such as stable carbon isotopes coupled with lipids, sterols and carotenoids have been used to trace the contribution of macroalgae to sediments (Hardison, et al., 2013; Chikaraishi, 2014) and food webs (Renaud, et al, 2015). This suggests two modes of transport: bed-load transport of drift material and sinking fluxes of negatively buoyant macroalgal detritus (Palanques, A. et al., 2002). This ability to drift, in combination with their relative unpalatability due to phenols and refractory carbon compounds such as fucoidan (Trevathan-Tackett, et al. 2015), explain their prevalent role as carbon source in deep sediments. The diagram below illustrates the mechanism.

The gas vesicles characteristic of many brown algae (pneumatocysts, see figure) favor the formation and long-distance drift of floating aggregates of macroalgae (Fraser, 2016; Macaya, et al, 2016). Drifting rafts of giant kelp may occur at very high densities, with 39,000 to 348,000 rafts identified in the Southern California coast alone, exporting the kelp more than 300 km offshore (Hobday2000). Drifting surface mats of Sargassum are also abundant (Rowe & Staresinic, 1979).

A number of mechanisms have been identified for the delivery of drifting macroalgae to marine sediments. Langmuir circulation consists of a series of shallow, slow, counter-rotating vortices at the ocean's surface aligned with the wind. These circulations are developed when wind blows steadily over the sea surface. Wind induced Langmuir circulation can entrain floating macroalgal fragments at depth, where pressure can collapse their gas vesicles, rendering the macroalgae negatively buoyant and removing them from surface organisms.



Conceptual diagram of the pathways for export and sequestration of macroalgal carbon. Air bladders are common among brown algal taxa and facilitate their long-range transport (i). Langmuir circulation forms windrows of macroalgae (ii) and can force the algae to depths where water pressure makes the air bladders burst and the algae then sink. Macroalgal carbon can be sequestered either via burial in the habitat or by transport to the deep sea where it is sequestered whether buried or not (iii).(Krause-Jensen and Duarte, 2016)

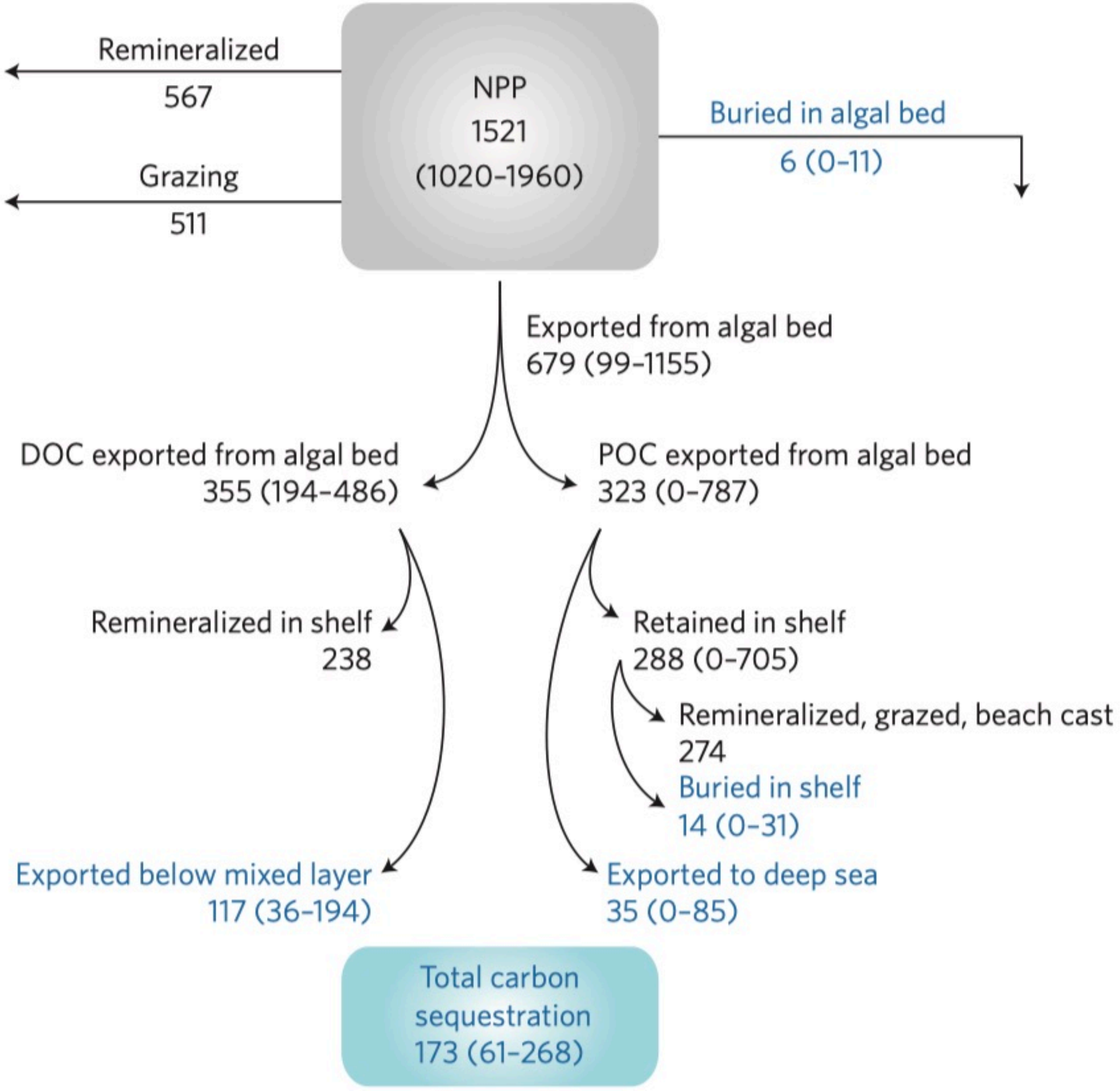
Another delivery mechanism is the ballasting of floating macroalgae by the stones dislodged by excessive drag forces — a phenomenon of global geological relevance that results in deep sea soft sediment plains being paved with stones (Garden & Smith (2015). The growth of calcifiers on macroalgal surfaces can also add to their density and contribute to their subsequent sinking (Fabry & Deuser, 1991).

The offshore export of macroalgal fragments from the coastal zone fuels a potentially large flux of macroalgal carbon to the deep sea. There are reports of 16.5 gC m^2/d of giant kelp being exported through the Carmel Canyon, California (Harrold, et al (1998) and of 0.4 gC m^2/yr of Sargassum reaching 3,600 m depth in the Northwest Atlantic (Rowe & Staresinic, 1979). These fluxes can also be highly episodic, such as the estimated input in excess of 7×10^{10} gC (49 million tons) potentially reaching the seafloor at 1800 m depth off the Bahaman shelf (Dierssen, et al (2009) during a storm.

Global carbon sequestration by macroalgae

Macroalgae are the dominant primary producers in the coastal zone with a global **net primary production** (NPP) of 1,521 TgC/yr) over an estimated area of 3.5 million km^2 (range: 2.8–4.3 million km^2. Together these findings yield a first order estimate of the contribution of macroalgae to carbon sequestration of about 173 TgC/yr (range: 61–268), of which about 88% is sequestered in the deep sea (see figure below). This estimate exceeds that for carbon buried in angiosperm based coastal habitats (111–131 TgC/yr) and provides **evidence of the importance of macroalgae in biological CO_2 sequestration**.

Climate change leads to the loss of kelp forests near their southern distribution limit (Wernberg, et al, 2011; Smale, et al, 2013), but may favor their poleward expansion into the Arctic (Poloczanska, et al. 2013; Krause-Jensen & Duarte, 2014) and may change macroalgal NPP and detrital export in the future (Duarte, C. M. (2014).



Pathways for the **sequestration of macroalgal carbon in the ocean**. Each step of the carbon flow from global macroalgal **net primary production** (NPP) to carbon sequestration (in blue) is supported by the literature or inferred by a difference between a total and subcomponents supported by literature. All values are in TgC/yr. One trillion grams = 1.1 million tons. Thus **173 TgC =193 million tons**

Conclusion Re: Suitability of the Use of Macroalgae as a NET for the Comings Foundation.

In the above sections we conclude that that Macroalgae as reviewed is unlikely to provide us with a useful technique for the sequestering of large amounts of CO_2. Why? First, the use of macroalgae aquaculture is unlikely be useful – i.e. when used to produce fuel or food, all the C is readmitted to the atmosphere in the form of CO_2.

In addition, despite the exciting review of Krause-Jensen and Duarte, (2016), showing that huge amounts of carbon are sequestered to the ocean bottom by macroalgae, it is likely we need to simply leave that to natural processes. The only apparent way to use macroalgae as a CO_2 sink, beyond what is currently happening, is to a) find ways to get aquaculture grown macroalgae to the bottom of the ocean. The one published idea was to bind it up in bundles and weigh them, so they sink. This was deemed too expensive. Not only does it preclude the commercial use of the macroalgae, studies would be needed to trace the fate of the bundles. For example, would they simply produce large amounts of methane that was eventually released to the atmosphere? As to the Krause-Jensen and Duarte (2016) report, it is not clear how it would be possible to artificially increase the growth of macroalgae. Does that simply get us back to ocean fertilization, but this time for macroalgae? We think this deserves some discussion and research, since the fertilization of macroalgae might evoke fewer objections than the fertilization of microalgae.

There is, however, one simpler and exciting option - Take our emphasis off the sequestration of CO_2 and put it instead on land-based aquaculture of red algae and the use of that algae to add to cattle feed **to prevent cattle from belching and farting methane**. Since methane is up to 80 times more potent of a greenhouse gas, eliminating this element of global warming would be a very powerful contribution. The following explores this option. But first, a few things about red algae.

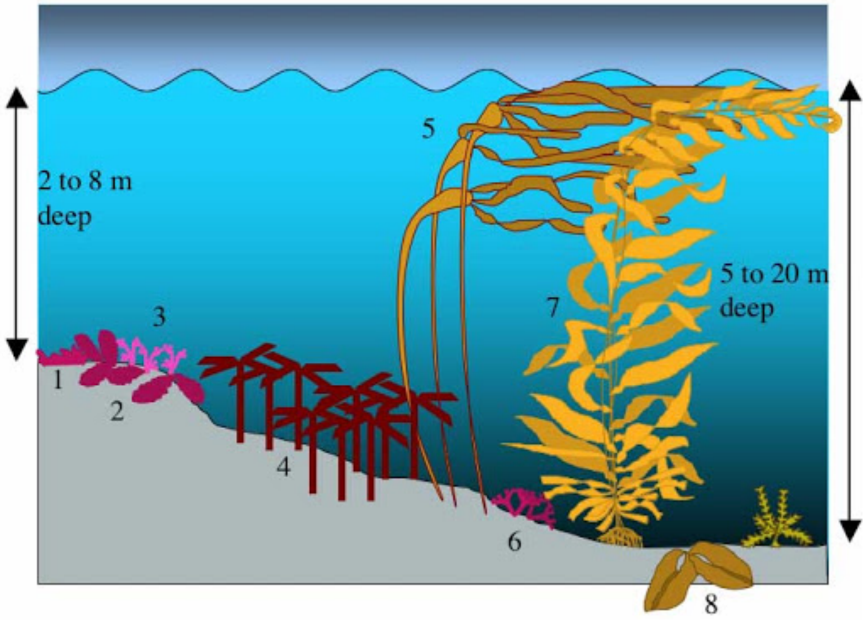
Red Algae

Why Red Algae? The concept of using red algae to supplement cattle food for the purpose of preventing the production of atmospheric methane by cattle, is discussed on the Comings Foundation web site under Negative Emission Technology – methane.

What are Red Algae? Red algae, or Rhodophyta from Ancient Greek (rhodon), meaning 'rose', and (phyton), meaning 'plant'), are one of the oldest groups of eukaryotic algae. The Rhodophyta also comprises one of the largest phyla of algae, containing over 7,000 currently recognized species with taxonomic revisions ongoing. The majority of species (6,793) are found in the Florideophyceae (class), and mostly consist of multicellular, marine algae, including many notable **seaweeds**. Approximately 5% of the red algae occur in freshwater environments, rest are marine algae (Wikipedia, 2020).

The red algae form a distinct group characterized by having eukaryotic cells without flagella and centrioles, chloroplasts that lack external endoplasmic reticulum and contain unstacked (stroma) thylakoids, and use phycobiliproteins as accessory pigments, which give them their red color. Most red algae are multicellular, macroscopic, marine, and reproduce sexually. The coralline algae, which secrete calcium carbonate and play a major role in building coral reefs.

The red algae of interest here are BF - Bangiophyceae and Florideophyceae, which are found in both marine and freshwater environments. The BF are macroalgae, seaweed that usually do not grow to more than about 50 cm in length. Most rhodophytes are marine with a worldwide distribution and are often found at greater depths compared to other seaweeds. This is illustrated figure which shows the depths at which the different macroalgae reside.



1= red turf algae
2= *Chondracanthus corymbiferus*
3= erect coralline algae (red)
4= *Pterygophora californica* (brown)
5= *Nereocystis luetkeana* (brown)
6= *Rhodymenia* spp. (red)
7= *Macrocystis pyrifera (brown)*
8= *Dictyoneuropsis reticulata / Dictyoneurum californicum*
9= *Cystoseira osmundacea* (brown)

The red (found at medium to deep depths), green (found near the surface and shallow depths) and brown seaweeds (found at medium to deep waters). Red algae can be found at depths up to 120m.

Red algae have a long history of being utilized as an important source of food ingredients and pharmaceutical substances. Many of the edible red algae are a rich source of antioxidants, have high amount of protein content, minerals, trace elements, vitamins and essential fatty acids. Traditionally red algae are eaten raw, in salads, soups, meal and condiments. Several species are important food crops, in particular members of the genus *Porphyra*, variously known as nori (Japan), gim (Korea), or laver (Britain). Dulse (*Palmaria palmata*) is another important British species. In Hawaii 70% of the algal species are in the Rhodophyta.

The rhodophyte are easily grown; for example, nori cultivation in Japan goes back more than three centuries. Some of the red algal species like *Gracilaria* and *Laurencia* are found to be rich in polyunsaturated fatty acids (eicopentaenoic acid, docohexaenoic acid, arachidonic acid) and have protein content up to 47% of total biomass. Where a big portion of world population is not getting insufficient amount of daily iodine intake, a 150 ug/day requirement of iodine is obtained from a single gram of red algae. Red algae, are also known for their industrial use for phycocolloids as a thickening agent, textiles, food, anticoagulants, water-binding agents etc. Dulse (*Palmaria palmata*) is one of the most consumed red algae and is a source of iodine, protein, magnesium and calcium. China, Japan, Republic of Korea are the top producers of these seaweeds. Nori, popularized by the Japanese is the single most valuable marine crop grown by aquaculture with a value in excess of US$1 billion.

In summary, red algae are of great ecological importance. They form a vital part of the food chain and are also involved in producing about 40 to 60 per cent of the total global oxygen for both terrestrial habitats and aquatic habitats. The list below summarized the ecological and commercial importance of red algae.

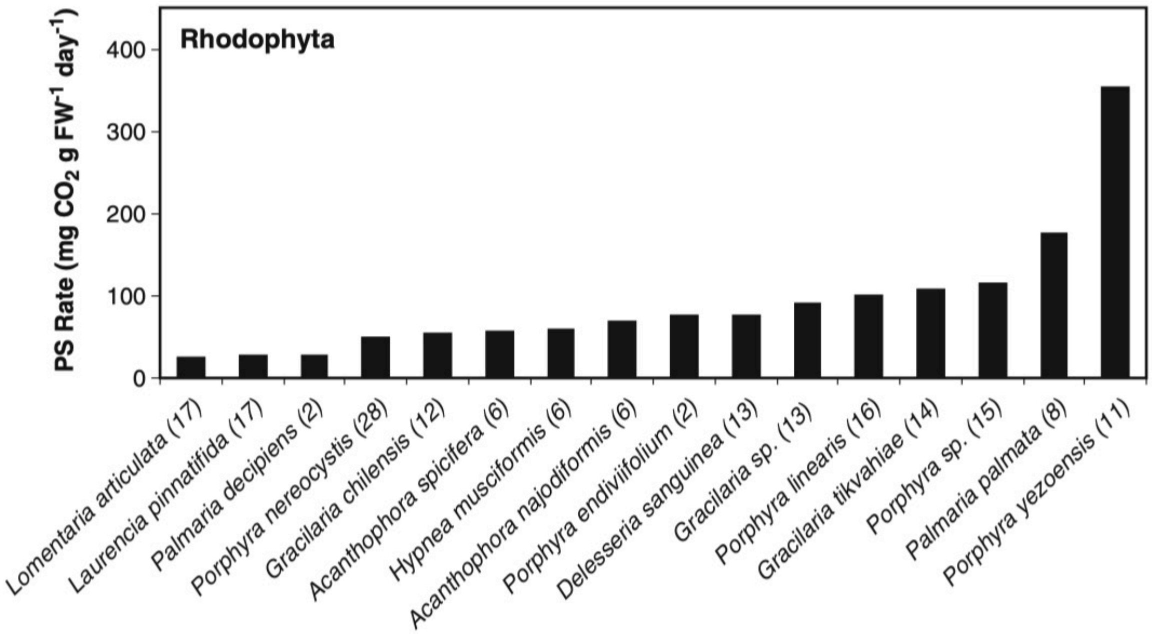
- They provide natural food for fish and other aquatic animals.
- Red alga is the most important commercial food in Japan and in the region of North Atlantic.
- Agar or agar-agar, a jelly-like substance is used in puddings, dairy toppings and other instant food products is extracted from Red algae.
- Red algae are used as the source of food for thousands of years as they are high in vitamins, minerals, a rich source of calcium, magnesium, and antioxidants.
- They are sources of dietary fiber as they have the ability to promote healthy circulation, lower bad cholesterol and regulate blood sugar levels.
- They are also involved in products that nourish your skin, boost the immune system and contribute to bone health.

Coralline Algae precipitate calcium carbonate in their outer wall layers. This forms a rigid extracellular matrix that contributes to the formation of Coral Reefs.

Genome sequencing shows that *Porphyra* and other red algae have minimal structural elements in their cytoskeletons compared to other types of multicellular organisms. This may explain why the multicellular red algae tend to be relatively small. The extremely resilient, flexible walls of *Porphyra* cells allow them to dramatically change their volume as they lose water when they are baking in the sun and drying in the winds, and to withstand the forces of beating waves.

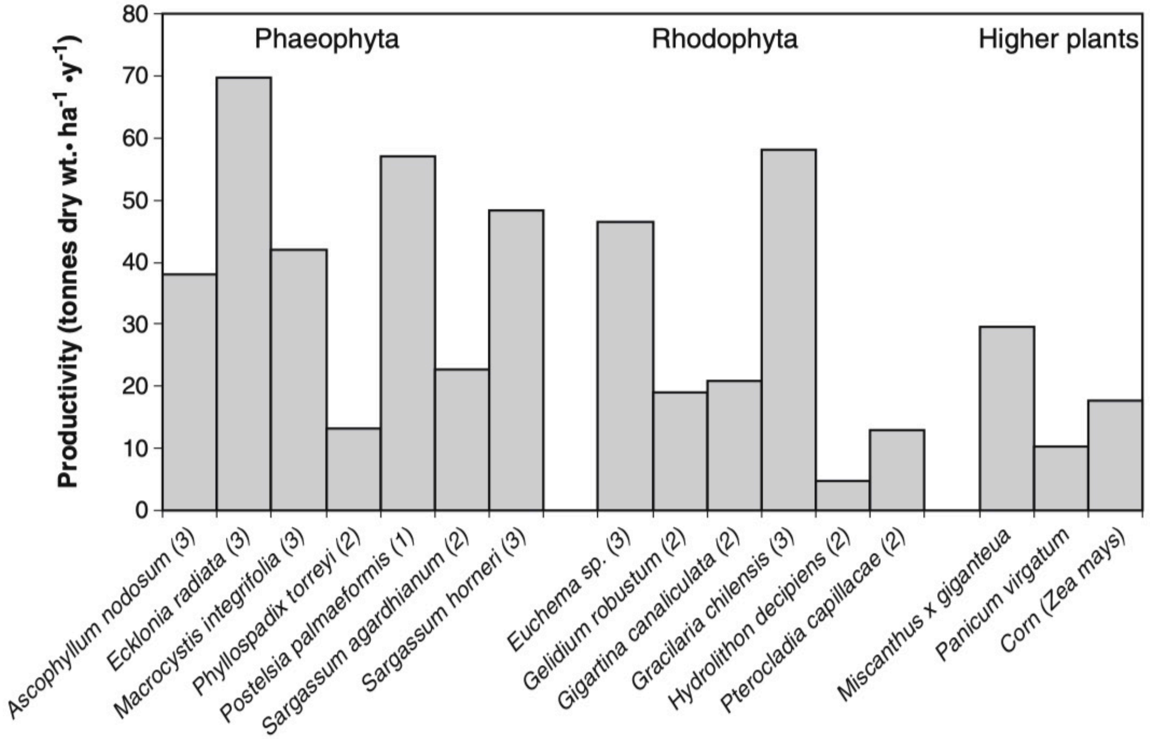
Red Algae are Strong Carbon Dioxide Absorbers

The following graph from Chung et al (2011) shows that Rhodophyta are significant primary producing consumers of CO_2. As such they could play a dual role of CO_2 fixation and controlling methane production by cattle. If all the algae harvested were eaten by cattle, the fixed CO_2 would be released by respiration. However, if this project could stop the production of methane by cattle, they would more than make up for the respired CO_2.



Rates of primary production for selected members of different species of Rhodophyta (red algae).

The following figure shows that red algae are more efficient consumers of CO_2 than biomass land plants such as *Miscanthus x giganteus, Panicum virgatum* (switch grass) and corn.



Annual primary production rates of selected algae compared to those of terrestrial plants associated with biofuel production. (Chung et al, 2011).

Calcifying photosynthetic organisms, including coralline algae, can act as a CO_2 sink via photosynthesis and act as a CO_2 source during respiration and $CaCO_3$ production on short-term timescales. Long term carbon storage potential might come from the accumulation of coralline algae deposits over geological timescales.

Aquaculture of Rhodophyta

As outlined below, if we plan to combat the release of methane by feeding red algae to cattle, one approach is to utilize land-based aquaculture to grow red algae. This can avoid many of the problems associated with growth in the open ocean.

In the 1980’s, in response to the energy crisis, the Department of Energy formed a Biomass Energy Technology Division to examine the possibility of using algae aquaculture to produce fuel. In 1984 they issued a final report on this technology (Ryther, et al, 1984) summarizing the techniques they perfected.

As an alternative concept to open ocean culture they used a land-based energy production system utilizing saline waters from underground aquifers or enclosed coastal areas. A total of 42 species were grown in specially adapted vaults. These included 16 green algae (Chlorophyta), 2 brown algae (Phaeophyta), and 18 red algae (Rhodophyta). Of these, the most successful and suitable species were a strain of *Gracilaria* (a red seaweed) and *Ulva* (a green seaweed).

Gracilaria were grown in channels or raceways on land or in shallow coastal waters in tropical to semitropical latitudes. At an offshore site, the seaweed would be confined by a fence or other barrier. Within the enclosure, the culture is maintained at a density of approximately two kilograms wet weight per square meter. At this density, the algae were compacted such that normal wind and tidal action would not cause the algal mass to drift and accumulate unevenly. At brief intervals during the day, the culture was mixed and rotated by compressed $C0_2$ from pipes distributed throughout the culture systems.

Well-nourished *Gracilaria* were exposed to full sunlight. At these latitudes they doubled their biomass in 1 to 4 weeks, depending on the season, water flow, and other variables. After its biomass had doubled (i.e., from 2 to 4 kg/m^2) the incremental growth was harvested to return the crop to a starting density that will ensure continued optimal yield. The doubling of biomass was accompanied by the utilization of all stored nutrients and a reduction of elemental nutrients in the plant tissues to roughly half the initial concentrations. Enrichment of the new starting crop following harvest could be accomplished onsite at the seaweed farm, but the rapid uptake and storage of nutrients by depleted seaweeds makes possible a simpler, more efficient enrichment process, known as pulse fertilization.

Gracilaria photosynthesis correlated best with bicarbonate concentration. Aeration could be decreased twelve-fold with a minimal impact on productivity. Aeration with a one sixth duty cycle provided only during daylight hours was found to stimulate growth nearly as well as continuous aeration.

What to Do?

These reports provide many details relevant to the use of the ocean in combating climate change. The section entitled **Priority Projects** summarizes some of the answers to the question – **What to Do?**