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Assessment of Carbon Sequestration Capacity of Seaweed in Climate Change Mitigation

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Abstract: Carbon (C) cycling is being influenced by global climate change, which is altering the primary productivity and the rate at which carbon is fixed, released and stored in vegetation systems on Earth. Carbon sequestration is recognised as the storing of carbon dioxide (CO_2) and other kinds of carbon for a long time. A selective atmospheric carbon-based anthropic enrichment causes an environmental catastrophe, which necessitates methods of mitigation. Algal primary production (which includes cyanobacterial algae, microalgal, and macroalgal) is a key pathway for C biosequestration in the ocean. Many scientists and environmental professionals are concerned about the rise in global temperatures and climate change. Increased quantity of carbon that can be absorbed from the atmosphere by exploiting the ability of plants, particularly seaweed, to use CO_2 in process of photosynthesis is one of the key solutions being given to prevent the earth's rising temperature at a faster rate. The ability of ocean plants to act as a carbon sink from anthropogenic sources (also recognised as "Blue Carbon") has piqued people's interest. Marine primary producers are responsible for at least half of the earth's carbon uptake and up to 71 percent of all C storing. Seaweeds have important roles in the elemental cycles of coastal ecosystems, mostly through the export of organic matter to neighbouring communities and the accumulation of carbon and nutrients in the sediment.

Keywords: Climate change; Seaweed; CO_2 sequestration; Blue carbon; Ocean.

Introduction

Global warming is one of the global environmental issues that has been broadly studied by environmental specialists (Mashoreng et al., 2019; Azeez, 2021) in recent years. A rise in the amount of supposed greenhouse gases (mostly carbon dioxide), which traps extra heat and warms the globe, in the air is the primary driver of global heating (Trenberth et al., 2007). This rising temperature affects a wide range of industries, both directly and indirectly (Islam et al., 2020; Bhuyan et al., 2020, 2021).

Humans can apply two fundamental methods to slow the rate of global warming (Mashoreng et al., 2019). To begin, reduction of C released from human activities and the usage of C origin that can raise CO_2 levels in the atmosphere, like forest fires, fossil fuel energy use, and so on. Second, increasing atmospheric carbon sequestration by promoting vegetation's or plants' ability to utilise and absorb CO_2 through the photosynthesis process (Mashoreng et al., 2019). In addition to natural flora in seaside locations, seaweed culture has spread around the world. Cultivated seaweeds can absorb CO_2 through photosynthesis (Hill et al., 2015; Pajusalu et al., 2016; Duarte et al., 2017; Sengupta et al., 2017).

Seaweed and other plants contribute to the absorbance of CO_2 from the atmosphere (Table 1). Since the industrial revolution, the ocean has absorbed 25% of

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Table 1: Estimation of biomass, yearly CO_2 absorption, and other ecosystems' potential CO_2 capture

Ecosystem	*Area (km^2)*	*C assimilation ($t\ km^{-2}$)*	*CO_2 sequestration ($t\ km^{-2}$)*	*References*
Mangrove	139170	139-7210	510-24460	Duarte et al. (2005); Siikimaki et al. (2012)
Saltmarsh	22000-400000	≥218180	≥800060	Chmura et al. (2003)
Seagrass	319000	6270	22988	Siikimaki et al. (2012)
Forest				
Temperate	10400000	n/a	5096	Schlesinger (1997)
Boreal	13700000	n/a	3599	Zehetner (2010)
Tropical	19622846	n/a	4000	

N.B. n/a: not available

carbon emissions and is now suffering the repercussions (GETF, 2020). Seaweed has the possibility to play an important role in combating climate related impacts by absorbing C emissions (Godin, 2020). Kelp has the ability to absorb a considerable amount of CO_2. By 2050, the goal is to "re-wild" the ocean and trap millions of tonnes of CO_2 (Azeez, 2021). Massive volumes of seaweed are buried at the ocean's bottom, where they can store carbon for thousands of years (NPR, 2021). However, the introduction of seaweed in the international platform as a C balancing approach to prevent climate change remains a concern. If seaweed is not used correctly, the benefits of CO_2 sequestration can be undone. If seaweed is produced just to collect carbon and is not harvested, it will decompose, and emit the CO_2 it has absorbed into the atmosphere (Godin, 2020).

To gather vital information, the potential for C uptake by seaweed must be thoroughly investigated. Negotiations for a blue carbon trade-in have so far been hindered by a shortage of data on the C sequestration capacity of sea resources. Furthermore, associated parties require this information for the maintenance of ocean resources. The goal of the current research was to assess seaweeds' C sequestration capacity and overall carbon sequestration. In order to achieve such goals, it is important to focus on resources to monitor seaweed habitat trends and conserve existing seaweed resources as an act to attenuate the causes of seaweed loss and develop knowledge to revert ongoing seaweed decline.

Methodology

Related articles were found using the keywords "Carbon sequestration by seaweed," "Carbon sequestration by kelp," "Carbon sequestration by macroalgae," "Climate change mitigation by seaweed," and "Role of seaweed in climate change mitigation and adaptation" in databases such as Google Scholar, PubMed, Dimension, Scopus, Web of Knowledge, and others.

Recent Emission Trend of CO_2

People are living at a time when atmospheric CO_2 amounts are increasing at a rate that has never been seen before in geological history. CO_2 emissions by different countries in the world are tabulated in Table 2. Annually, fossil fuel combustion and cement manufacture emit 7.2 Pg C (1 Pg=1015 g), but forest destruction and rapid change in land-use produce 1.6 Pg C/year (Denman et al., 2007). The seas have been a key sink for anthropogenic CO_2 emissions since the Industrial Revolution, accounting for 48 percent of total emissions (Sabine et al., 2004). The annual oceanic CO_2 sink, according to Behrenfeld et al. (2002), is 2±0.8 Pg C, withal a further 1.8 Pg C missing sink element containing both oceanic and terrestrial biosphere elements.

Despite the turndown from these abiotic and biotic ocean activities, the air CO_2 pool is rising at ~4.1 Pg C/year (Denman et al., 2007). CO_2 concentrations in the atmosphere have risen dramatically in the previous ~200 years, from 280 parts per million (28 Pa) in 1800 to 385 parts per million (38.5 Pa) now. The last 100 years have seen most of this increase (Denman et al., 2007). Depending on the CO_2 emissions growth, the most likely scenario is for a 2- to 3-fold increase in air CO_2 levels during the next 100 years (Meehl et al., 2007).

CO_2 Sequestration by Seaweed

According to Krause-Jensen and Duarte (2016), total global carbon sequestration by seaweed is projected to be 173 Mt C/yr (Figure 1). In a recent UK study, out of

Table 2: Comparison of CO_2 emissions, present seaweed harvest, and possible for C uptake withal made better use of coastline for seaweed cultivation in the top 10 algae harvesting countries

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	698529	209559	5010169	1366410	0.0153	14500	48.2	826500	1.18	0.02	0.17
Korea	138499	41550	465643	126994	0.0327	2413	57.4	138499	1.00	0.03	0.34
Japan	123074	36922	1257962	343081	0.0108	29751	4.1	1695807	13.78	0.15	5.00
Chile	109308	32792	62418	17023	0.1926	6435	17.0	366795	3.36	0.65	7.54
Norway	40632	12190	87602	23891	0.0510	25148	1.6	1433436	35.28	1.80	29.5
Philippines	46218	13865	80511	21958	0.0631	36289	1.3	2068473	44.75	2.83	42.5
Indonesia	26894	8068	378250	103159	0.0078	54716	0.5	3118812	115.97	0.91	64.1
France	16762	5029	37392	101916	0.0049	3427	4.9	195339	11.65	0.06	4.0
USA	15330	4599	6049435	1649846	0.0003	19924	0.8	1135668	74.08	0.02	23.3
Mexico	10205	3062	438021	119460	0.0026	9330	1.1	531810	52.11	0.13	10.9

(Data source: Zemke-White and Ohno, 1999) http://mdgs.un.org/unsd/mdg/)

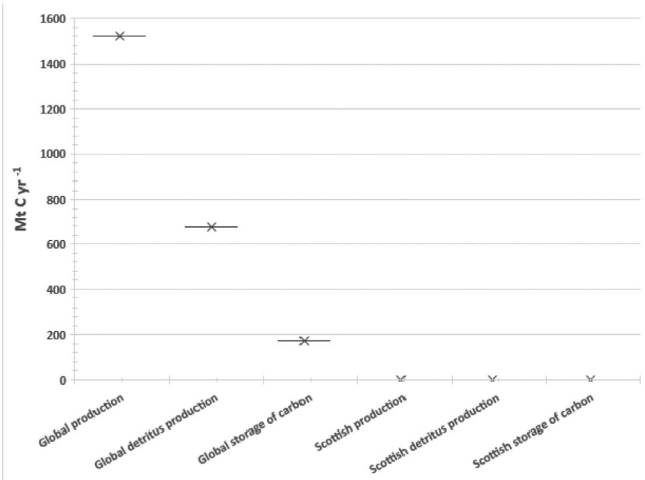

Figure 1: In comparison to global figures, production of seaweed and detritus, and carbon storage in Scotland. (Data source: Krause-Jensen and Duarte, 2016)

whole particulate C absorption rate of 58.74 gC/m/yr in soil at a given site, just organic C uptake off seaweed was 8.75 gCm^2/yr on average (Queirós et al., 2019). Burrows et al. (2014) calculated the Scottish seaweed NPP to be 1.73 Mt C yr^{-1}. In Scotland, C absorption by seaweed is predicted to be 11.4 percent of NPP at 0.2 Mt C/yr when the outcomes of the 2016 examination are applied to this count.

Kaladharan et al. (2009) investigated marine-algae CO_2 assimilation and established that standing macro-algae biomass crops along the Indian Coast can consume 9052 tons of carbon dioxide per day, reporting an 8867 t CO_2 gross daily credit for an emission rate of 365 tons of carbon dioxide. Because of their abundance and massive biomass, Chlorophytes, such as *Ulva lactuca*, were assessed to have the maximum CO_2 absorption capability among the diverse taxa, after Phaeophytes (*Sargassum polycystum*) and Rhodophyta's (*Gracilaria corticata*) (Kaladharan et al., 2009). Chlorophyta, Phaeophyta and Rhodophyta played a great role in primary production, that is carbon sequestration (Figure 2). Enormous-scale cultivation of marine macroalgae, particularly commercially important species, has been shown to lower CO_2 levels in the atmosphere (Table 3) while also generating vast amounts of useable biomass for biofuels and phycocolloid manufacturing (Migliore et al., 2012; Chung et al., 2013).

Macroalgal beds have a greater Net Ecosystem Productivity than other types of oceanic vegetation, like phytoplankton and seagrass beds (Kim et al., 2015). In terrestrial, freshwater, and marine ecosystems, biomineralisation of atmospheric CO_2 as $CaCO_3$ is prevalent (Ridgwell and Zeebe, 2005). In the oceans,

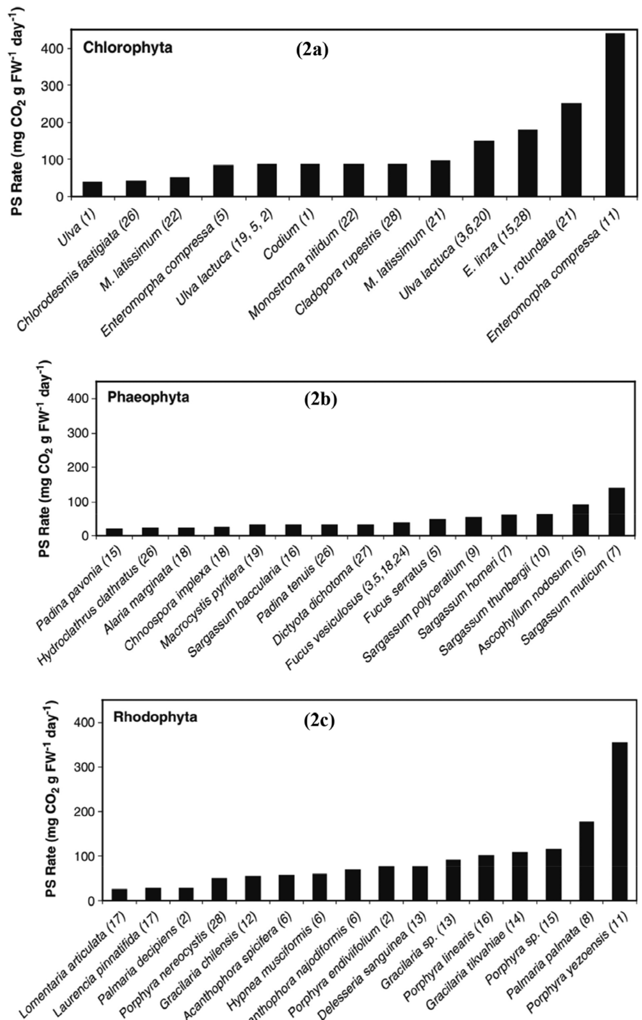

Figure 2: Rates of primary production for different types of seaweed: 2(a) Chlorophyta; 2(b) Phaeophyta and 2(c) Rhodophyta. (Source: Chung et al., 2011)

the majority of biomineralisation occurs by biological mechanisms (Jansson and Northen, 2010). In this sense, calcifying macroalgae play a significant role.

The reaction(s) that occur during calcification are depicted in equations (2) and (3):

$$Ca^{2+} + 2HCO_3^- \rightleftharpoons CaCO_3 + CO_2 + H_2O \text{ (Reaction 1)}$$

$$Ca^{2+} + CO_3^{2-} \rightleftharpoons CaCO_3 \text{ (Reaction 2)}$$

The fall in the pH of sea water is triggered by rising CO_2 concentrations, a phenomenon known as "*Ocean Acidification*" (Doney et al., 2009). Even though lower pH is a reason for interest in the survival of calcifying seaweed, *in situ* works on *Padina* sp. have shown that the seaweeds are more abundant under high CO_2 levels (Johnson et al., 2012), pointing out that photosynthesis

Table 3: Carbon sequestration rate by seaweed

Types of seaweed	*Ecosystems*	*Carbon sequestration rate*	*References*
Kappaphycus alvarezii	Marine	0.660 $mgCO_2.gdw^{-1}.h^{-1}$	Mashoreng et al. (2019)
Eucheuma spinosum	Marine	11.997 $mgCO_2.gdw^{-1}.h^{-1}$	Mashoreng et al. (2019)
Gracilariaverrucosa	Marine	0.286 $mgCO_2.gdw^{-1}.h^{-1}$	Mashoreng et al. (2019)
Caulerpa lentillifera	Marine	0.927 $mgCO_2.gdw^{-1}.h^{-1}$	Mashoreng et al. (2019)
Laminaria hyperborea	Marine	11.49 Tg C $year^{-1}$	Pessarrodona et al. (2018)
Seaweeds	Marine	173 Tg C $year^{-1}$	Krause-Jensen and Duarte (2016)
Macroalgae	Marine	-1 PgC $year^{-1}$	Chung et al. (2011)
Kelp	Marine	7.50 Tg C $year^{-1}$	Reed and Brzezinski (2009)
Seagrass and macroalgae	Marine	-1 PgC $year^{-1}$	Schippers et al. (2004)
Marine macroalgae	Marine	3×10^{-5} PgC $year^{-1}$	Gao and McKinley (1994); Jackson (1987); Muraoka (2004)
Kelps (*Macrocystis* sp. and *Laminaria* sp.)	Marine	$>3 \times 10^{-12}$ PgC $year^{-1}$	Gao and McKinley (1994)
Macrocystis integrifolia	Marine	1.3×10^{-8} PgC $year^{-1}$	Wheeler and Druehl (1986)
Laminaria japonica	Marine	2.2×10^{-8} PgC $year^{-1}$	Chao-yuan et al. (1984)

and calcification are intertwined (Okazaki et al., 1986). Furthermore, enhanced photosynthesis due to higher CO_2 concentrations partially offsets increased $CaCO_3$ dissolution caused by low pH (Johnson et al., 2012). While lower $CaCO_3$ deposition in *Padina* sp. tissues was observed as a result of habitat water acidity and larger macroalgal biomass was anticipated to result in higher $CaCO_3$ precipitation and, as a result, higher C sequestration in the intertidal zones.

The massive growth of macroalgae, frequently as mats of moving, littoral, benthic, or epiphytic seaweed, are common in estuarine habitats. However, it has been proven that these have a deleterious impact on microbenthic communities (Sundbäck et al., 1990, 1996), different benthic biotas (Den Hartog, 1994), and macrofauna (Norkko and Bonsdorff, 1996; Sundbäck et al., 1990, 1996). IA rise in the C substance of the soil is discovered by shifting some of the C, which is absorbed through the growth of sediments underneath them (Corzo et al., 2009). Pyrolysis of wild or commercially farmed seaweed is a different and focused way of C biosequestration using seaweed. Bird et al. (2012) found that pyrolysis of seaweed biomass yields biochar, which increases nutrient retention while lowering N_2O emissions from agricultural soils (Cayuela et al., 2013). As a result, the use of biochar for both soil C absorption and the rehabilitation of barren sediments has been recommended (Roberts et al., 2015). Seaweed DNA was found in the garbage on the ocean bottom, and this data suggested that 70% of the seaweed analysed had sunk to a depth of 1000 meters. This conclusion is critical for CSS since it implies that any carbon collected by seaweed is released into the atmosphere.

Conclusion

Carbon sinks have been detected in vegetated coastal ecosystems. Marine seaweed has been largely ignored in discussions of marine C sinks, compared to other ocean ecosystems (e.g., salt marshes, seagrass, and mangroves). Although seaweeds are considered as the key producers in the coastal ecosystem, they rarely flourish in environments that are thought to store considerable amounts of organic C. The decline of seaweed bed ecosystems has resulted in significant changes in the coastal area's species richness, fertility, and sediment equilibrium. Therefore, planning/steps to restore seaweed is very important for sustainable sea resources. However, seaweed carbon has been found in the deep-sea region, where it can effectively suck carbon out from the atmosphere. According to these findings, seaweed could be a significant carbon-storing component of the marine ecosystem. Policy makers should give emphasis to the huge expansion of seaweed cultivation considering its carbon-reducing capacity.

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References

Azeez, W., 2021. These 4 start-ups are using seaweed to help save the planet. https://www.weforum.org/agenda/2021/05/startups-seaweed-farming-ocean-planet-climate/

Behrenfeld, M.J., Esaias, W.E. and Turpie, K.R., 2002. Assessment of primary production at the global scale. *In:* Phytoplankton Productivity: Carbon Assimilation in Marine and Freshwater Ecosystems, pp. 156-186.

Bhuyan, M.S., Sharif, A.S.M., Islam, M.M., Mojumder, I.A., Monika Das, M. and Islam, M.S., 2020. Blue economy and the prospect of seaweed in Bangladesh. *Journal of Marine Science Research and Oceanography*, **3:** 1-2.

Bhuyan, M., Islam, M.M., Sharif, A.S.M. and Hoq, M.E., 2021. Seaweed: A Powerful Tool for Climate Change Mitigation That Provides Various Ecological Services. Bangladesh II: Climate Change Impacts, Mitigation and Adaptation in Developing Countries, pp. 159-192. Springer Climate. Springer, Cham. https://doi.org/10.1007/978-3-030-71950-0_5

Bird, M.I., Wurster, C.M., de Paula Silva, P.H., Paul, N.A. and De Nys, R., 2012. Algal biochar: effects and applications. *Gcb Bioenergy*, **4(1):** 61-69.

Burrows, M.T., Kamenos, N.A., Hughes, D.J., Stahl, H., Howe, J.A. and Tett, P., 2014. Assessment of carbon budgets and potential blue carbon stores in Scotland's coastal and marine environment.

Cayuela, M.L., Sánchez-Monedero, M.A., Roig, A., Hanley, K., Enders, A. and Lehmann, J., 2013. Biochar and denitrification in soils: When, how much and why does biochar reduce N_2O emissions? *Scientific Reports*, **3(1):** 1-7.

Chao-yuan, W., Yan-xia, Z., Ren-zhi, L., Zuo-sheng, P., Ying-fang, Z., Qing-chen, L., ... and Xiao, F., 1984. Utilization of ammonium-nitrogen by Porphyrayezoensis and Gracilariaverrucosa. *In:* Eleventh International Seaweed Symposium (pp. 475-477). Springer, Dordrecht.

Chmura, G.L., Anisfeld, S.C., Cahoon, D.R. and Lynch, J.C., 2003. Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles*, **17(4)**.

Chung, I.K., Beardall, J., Mehta, S., Sahoo, D. and Stojkovic, S., 2011. Using marine macroalgae for carbon sequestration: A critical appraisal. *Journal of Applied Phycology*, **23(5):** 877-886.

Chung, I.K., Oak, J.H., Lee, J.A., Shin, J.A., Kim, J.G. and Park, K.S., 2013. Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean Project Overview. *ICES Journal of Marine Science*, **70(5):** 1038-1044.

Corzo, A., Van Bergeijk, S.A. and Garcia-Robledo, E., 2009. Effects of green macroalgal blooms on intertidal sediments: Net metabolism and carbon and nitrogen contents. *Marine Ecology Progress Series*, **380:** 81-93.

Den Hartog, C., 1994. Suffocation of a littoral Zostera bed by *Enteromorpha radiata*. *Aquatic Botany*, **47(1):** 21-28.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P.L., Wofsy, S.C. and Zhang, X., 2007. Couplings between changes in the climate system and biogeochemistry. *In:* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.). Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Doney, S.C., Fabry, V.J., Feely, R.A. and Kleypas, J.A., 2009. Ocean acidification: The other CO_2 problem. *Annual Review of Marine Science*, **1:** 169-192.

Duarte, C.M., Middelburg, J.J. and Caraco, N., 2005. Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences*, **2(1):** 1-8.

Duarte, C.M., Wu, J., Xiao, X., Bruhn, A. and Krause-Jensen, D., 2017. Can seaweed farming play a role in climate change mitigation and adaptation? *Frontiers in Marine Science*, **4:** 100.

Gao, K. and McKinley, K.R., 1994. Use of macroalgae for marine biomass production and CO_2 remediation: A review. *Journal of Applied Phycology*, **6(1):** 45-60.

Global Environment & Technology Foundation (GETF), 2020. Oceans 2050 Leads Global Effort to Quantify Seaweed Carbon Sequestration. https://www.3blmedia.com/News/Oceans-2050-Leads-Global-Effort-Quantify-Seaweed-Carbon-Sequestration

Godin, M., 2020. The Ocean Farmers Trying to Save the World with Seaweed. https://time.com/5848994/seaweed-climate-change-solution/

Hill, R., Bellgrove, A., Macreadie, P.I., Petrou, K., Beardall, J., Steven, A. and Ralph, P.J., 2015. Can macroalgae contribute to blue carbon? An Australian perspective. *Limnology and Oceanography*, **60(5):** 1689-1706.

Islam, M.M., Hoq, M.E., Ali, M.Z., Hasan, S.J., Sharif, A.S.M. and Bhuyan, M.S., 2020. Diversity and occurrence of seaweeds from the south-eastern coast of Bangladesh. *Indian Journal of Geo Marine Sciences*, **49(8):** 1-10.

Jackson, G.A., 1987. Modelling the growth and harvest yield of the giant kelp *Macrocystis pyrifera*. *Marine Biology*, **95(4):** 611-624.

Jansson, C. and Northen, T., 2010. Calcifying cyanobacteria-the potential of biomineralization for carbon capture and storage. *Current Opinion in Biotechnology*, **21(3):** 365-371.

Johnson, V.R., Russell, B.D., Fabricius, K.E., Brownlee, C. and Hall-Spencer, J.M., 2012. Temperate and tropical brown macroalgae thrive, despite decalcification, along natural CO_2 gradients. *Global Change Biology*, **18(9):** 2792-2803.

Kaladharan, P., Veena, S. and Vivekanandan, E., 2009. Carbon sequestration by a few marine algae: Observation and projection. *Journal of the Marine Biological Association of India,* **51(1):** 107-110.

Kim, J.H., Kang, E.J., Kim, K., Jeong, H.J., Lee, K., Edwards, M.S. ... and Kim, K.Y., 2015. Evaluation of carbon flux in vegetative bay based on ecosystem production and CO_2 exchange driven by coastal autotrophs. *Algae*, **30(2):** 121-137.

Krause-Jensen, D. and Duarte, C.M., 2016. Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience*, **9(10):** 737-742.

Mashoreng, S., La Nafie, Y.A. and Isyrini, R., 2019. Cultivated seaweed carbon sequestration capacity. *In:* IOP Conference Series: Earth and Environmental Science, **370(1):** 012017. IOP Publishing.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M.,. Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J. and Zhao, Z.-C., 2007. Global climate projections. *In:* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B. Tignor, M. and Miller, H.L., (eds.). Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Migliore, G., Alisi, C., Sprocati, A.R., Massi, E., Ciccoli, R., Lenzi, M. ... and Cremisini, C., 2012. Anaerobic digestion of macroalgal biomass and sediments sourced from the Orbetello lagoon, Italy. *Biomass and Bioenergy*, **42:** 69-77.

Muraoka, D., 2004. Seaweed resources as a source of carbon fixation. *Bulletin-Fisheries Research Agency Japan*, 59-64.

Norkko, A. and Bonsdorff, E., 1996. Rapid zoobenthic community responses to accumulations of drifting algae. *Marine Ecology Progress Series*, **131:** 143-157.

NPR, 2021. Run The Oil Industry In Reverse': Fighting Climate Change By Farming Kelp. https://www.npr.org/2021/03/01/970670565/run-the-oil-industry-in-reverse-fighting-climate-change-by-farming-kelp

Okazaki, M., Pentecost, A., Tanaka, Y. and Miyata, M., 1986. A study of calcium carbonate deposition in the genus Padina (Phaeophyceae, Dictyotales). *British Phycological Journal*, **21(2):** 217-224.

Ortega, A., Geraldi, N.R., Alam, I., Kamau, A.A., Acinas, S.G., Logares, R., ... and Duarte, C.M., 2019. Important contribution of macroalgae to oceanic carbon sequestration. *Nature Geoscience*, **12(9):** 748-754.

Pajusalu, L., Martin, G., Paalme, T. and Põllumäe, A., 2016. The effect of CO_2 enrichment on net photosynthesis of the red alga *Furcellaria lumbricalis* in a brackish water environment. *PeerJ*, **4:** e2505.

Pessarrodona, A., Moore, P.J., Sayer, M.D. and Smale, D.A., 2018. Carbon assimilation and transfer through kelp forests in the NE Atlantic is diminished under a warmer ocean climate. *Global Change Biology*, **24(9):** 4386-4398.

Queirós, A.M., Stephens, N., Widdicombe, S., Tait, K., McCoy, S.J., Ingels, J. ... and Somerfield, P.J., 2019. Connected macroalgal-sediment systems: Blue carbon and food webs in the deep coastal ocean. *Ecological Monographs*, **89(3):** e01366.

Reed, D.C. and Brzezinski, M.A., 2009. Kelp forests. *In:* Laffoley, D. and Grimsditch, G., (Eds.). The Management of Natural Coastal Carbon Sinks (pp. 31-37). Gland, Switzerland: IUCN.

Ridgwell, A. and Zeebe, R.E., 2005. The role of the global carbonate cycle in the regulation and evolution of the Earth system. Earth and Planetary Science Letters, 234(3-4), 299-315.

Roberts, D.A., Paul, N.A., Dworjanyn, S.A., Bird, M.I. and de Nys, R., 2015. Biochar from commercially cultivated seaweed for soil amelioration. *Scientific Reports*, **5(1):** 1-6.

Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J.L. ... and Rios, A.F., 2004. The oceanic sink for anthropogenic CO_2. *Science*, **305(5682):** 367-371.

Schippers, P., Lürling, M. and Scheffer, M., 2004. Increase of atmospheric CO_2 promotes phytoplankton productivity. *Ecology Letters*, **7(6):** 446-451.

Schlesinger, W.H., 1997. Biogeochemistry: An analysis of global change, 2nd edn. Academic Press, San Diego.

Sengupta, S., Gorain, P.C. and Pal, R., 2017. Aspects and prospects of algal carbon capture and sequestration in ecosystems: A review. *Chemistry and Ecology*, **33(8):** 695-707.

Siikamäki, J., Sanchirico, J.N., Jardine, S., McLaughlin, D. and Morris, D.F., 2012. Blue carbon: Global options for reducing emissions from the degradation and development of coastal ecosystems. Washington, DC: Resources for the Future.

Sundbäck, K., Carlson, L., Nilsson, C., Jönsson, B., Wulff, A. and Odmark, S., 1996. Response of benthic microbial mats to drifting green algal mats. *Aquatic Microbial Ecology*, **10(2):** 195-208.

Sundbäck, K., Jönsson, B., Nilsson, P. and Lindström, I., 1990. Impact of accumulating drifting macroalgae on a shallow-water sediment system: An experimental study. *Marine Ecology Progress Series*, 261-274.

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Tank, A.K., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden, B. and Zhai, P., 2007. Observations: Surface and Atmospheric Climate Change The Physical Science Basis: Contribution of Working University Press, Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Cambridge, United Kingdom and New York).

Wheeler, W.N. and Druehl, L.D., 1986. Seasonal growth and productivity of *Macrocystis integrifolia* in British Columbia, Canada. *Marine Biology*, **90(2):** 181-186.

Zehetner, F., 2010. Does organic carbon sequestration in volcanic soils offset volcanic CO_2 emissions? *Quaternary Science Reviews*, **29(11-12):** 1313-1316.

Zemke-White, W.L. and Ohno, M., 1999. World seaweed utilisation: An end-of-century summary. *Journal of Applied Phycology*, **11(4):** 369-376.