Chapter 5

Seaweed: A Powerful Tool for Climate Change Mitigation That Provides Various Ecological Services

Md. Simul Bhuyan, Md. Nazrul Islam, Abu Sayeed Muhammad Sharif, Md. Mohidul Islam, Md. Shafiqul Islam, and Md. Enamul Hoq

Abstract Seaweed production (both culture and natural) has increased compared with in the past. It occupies a strong position in the food supply and meets global food demand. Seaweed emerges as a powerful tool to mitigate and adapt to climate change. It acts as a carbon sink by sequestrating carbon from the atmosphere into the ocean. It can reduce the carbon emission from agricultural fields by improving the soil quality. It also minimizes the emissions of methane gas when mixed in cattle food. Seaweed increases the pH of water thus reducing the ocean acidification phenomena. As a result, aquatic organisms such as finfish, shellfish, corals, and invertebrates find a suitable place to live in. It produces trace gas (e.g., volatile brominated and iodinated halocarbons) that deplete the ozone. Seaweed dampens wave energy during storms and protects the coast as climate change adaptation. Seaweed provides oxygen to the ocean water, which minimizes the issue of de-oxygenation. It offers

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M. S. Bhuyan (✉)
Faculty of Marine Sciences and Fisheries, University of Chittagong, Chittagong, Bangladesh

Bangladesh Research Consultancy Firm, Dhaka, Bangladesh

M. N. Islam
Department of Geography and Environment, Jahangirnagar University, Savar, Dhaka, Bangladesh
e-mail: nazrul_geo@juniv.edu

A. S. M. Sharif
Bangladesh Oceanographic Research Institute, Cox's Bazar, Bangladesh

M. M. Islam
Marine Fisheries and Technology Station, Bangladesh Fisheries Research Institute, Cox's Bazar, Bangladesh

M. S. Islam
Faculty of Marine Sciences and Fisheries, University of Chittagong, Chittagong, Bangladesh

M. E. Hoq
Bangladesh Fisheries Research Institute, Mymensing, Bangladesh

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habitats and food for important components of the marine ecosystem that have a great impact on the climate. Seaweed provides biofuels, fertilizer, medicine, and food for human consumption. In this review, we emphasize the role of seaweed in climate change mitigation and adaptation. Seaweed cultivation can be optimized to get maximum climate benefits and increase the livelihood status of the seaweed farmer.

Keywords Seaweed · Climate change · Mitigation and adaptation · Ecological services · Emission

5.1 Introduction

According to FAO, about 131.4 million tonnes of fish, aquatic animals, and aquatic plants produced worldwide in 2014 (FAO 2016a). Seaweed, marine aquatic plants contribute over 20% of this total production, with a growth of 8% per year over the past decade (FAO 2016a). Seaweed is regarded as an important component of marine aquaculture, which will be the main weapon to meet global food security over the next 30 years (Langton et al. 2019). As the world population is increasing rapidly, it will be a challenge to feed this huge population (Hasselström et al. 2020). The cultivation of seaweed is dominated by Asian countries although European countries (Ireland, Spain, Scotland, Norway, and Denmark) have started seaweed culture over the last 15–20 years (Kraan et al. 2000; Kerrison et al. 2015; Peteiro et al. 2016).

Seaweeds or marine macroalgae are commonly known as a vital source of ocean primary productivity (Mann 1973; Dayton 1985; Okey et al. 2004; Ruiz and Wolff 2011), which comprises 8000–10,500 species. There are three main categories of seaweed (i.e., green, red, or brown algae) (Lüning 1990; Thomas 2002; Hurd et al. 2014). Seaweed provides various ecological services and is regarded as the most diverse and productive habitat on earth (Mann 1973; Dayton 1985; Boden et al. 2017). The ecological services include habitat (feeding, breeding, and nursery ground), biodiversity, food web subsidy, nutrient cycling, and removal of excess nutrients, carbon sequestration and shore protection, environmental restoration and nursery grounds, and protecting juvenile invertebrates and fish from predators (Smale et al. 2013; Langton et al. 2019).

The provision of habitat is a great ecological service of seaweed. It provides physical structure, habitat, shading, and acts as good a source of food (Arsenault 2018). Seaweeds are the primary producers of the ocean and support secondary productivity and three-dimensional habitat structure for many commercially important marine organisms (invertebrates, fish, and marine top-predators, such as seabirds and sea mammals) (Lorentsen et al. 2010; Arsenault 2018). Seaweed is a significant biological resource as their detritus is exported to other habitats; this process increases the productivity of that particular area (Arsenault 2018). Seaweed takes up necessary nitrogen, phosphorus, and carbon dioxide required for its growth and production of energy storage products (Kim et al. 2017).

Climate change mitigation is an important role of seaweed (Langton et al. 2019). The impact of climate change on seaweed abundance, distribution, and quality is a global concern (Straub et al. 2016). Seaweed has a certain degree of resilience to global climate change (Krumhansl et al. 2016), and its biomass availability can vary on a spatial basis (Bell et al. 2015; Boden et al. 2017). Seaweed acts as a sponge for carbon dioxide and reducing ocean acidification (Duarte et al. 2017). *Gracilaria tikvahiae* (red seaweed) and *Saccharina latissima* (brown seaweed) assimilate carbon rapidly in Long Island Sound and the Bronx River Estuary of New York (Kim et al. 2014, 2015a). Bjerregaard et al. (2016) reported that if 0.03% ocean surface area can be cultured then it will be able to remove about 135 million tons of carbon from the ocean water. That means it will remove approximately 3.2% of carbon annually inputted to ocean water from the atmosphere.

Uptake of excess nitrogen, phosphorous, and some toxic chemical by seaweed reduces coastal eutrophication and pollution (Kim et al. 2014; Marinho et al. 2015; Rose et al. 2015). That reduces the harmful algal blooms such as red tides (Imai et al. 2006). For example, it was reported that the richness index of the red tide species *Skeleton emacostatum* declined from 0.32 to 0.05 during the growing season of *Porphyra yezoensis* in the Jiangsu Province in China (Wu et al. 2015). Thirty percent of the introduced nitrogen can be removed if 0.03% of the ocean surface area can be brought under seaweed culture (Bjerregaard et al. 2016; Kim et al. 2017). This way, seaweed can remove inorganic nutrients from ocean water and have a great impact on the mitigation of adverse environmental impacts (Neori et al. 2004, 2007; Corey et al. 2012, 2014; Kim et al. 2013, 2014, 2015b; Rose et al. 2015; Wu et al. 2017).

Overharvesting or degradation of marine algae habitat can be detrimental to marine biodiversity (Arsenault 2018). It will bring important changes into the benthic community structure. This phenomenon will decrease the functional diversity and overall productivity of the ocean (Bodkin 1988; Graham 2004; Lilley and Schiel 2006). Moreover, it will cut the amount of "*blue carbon*" stored in submerged marine habitats. Consequently, it will change the global weather patterns that will have negative impacts on the coastal residents, their livelihoods, and food security (Nelleman et al. 2009; Byrnes et al. 2011). The losses of seaweed also affect marine biodiversity such as manatees, dugongs, and green turtles who are herbivores (West et al. 2017).

5.2 Methodology

Related articles were collected from different databases, including Scopus, Web of Knowledge, Google Scholar, Dimension, and PubMed, using the keywords "Climate change mitigation by seaweed" or "Role of seaweed in climate change mitigation and adaptation" or "Ecological services of seaweed" or "Ecosystem services of seaweed" or "Carbon sequestration by seaweed" or "Carbon absorption by seaweed" or "Role of seaweed in reducing ocean acidification" or "Nutrients removal by seaweed" or "Uptake of nutrients by seaweed" or "Role of seaweed in reducing

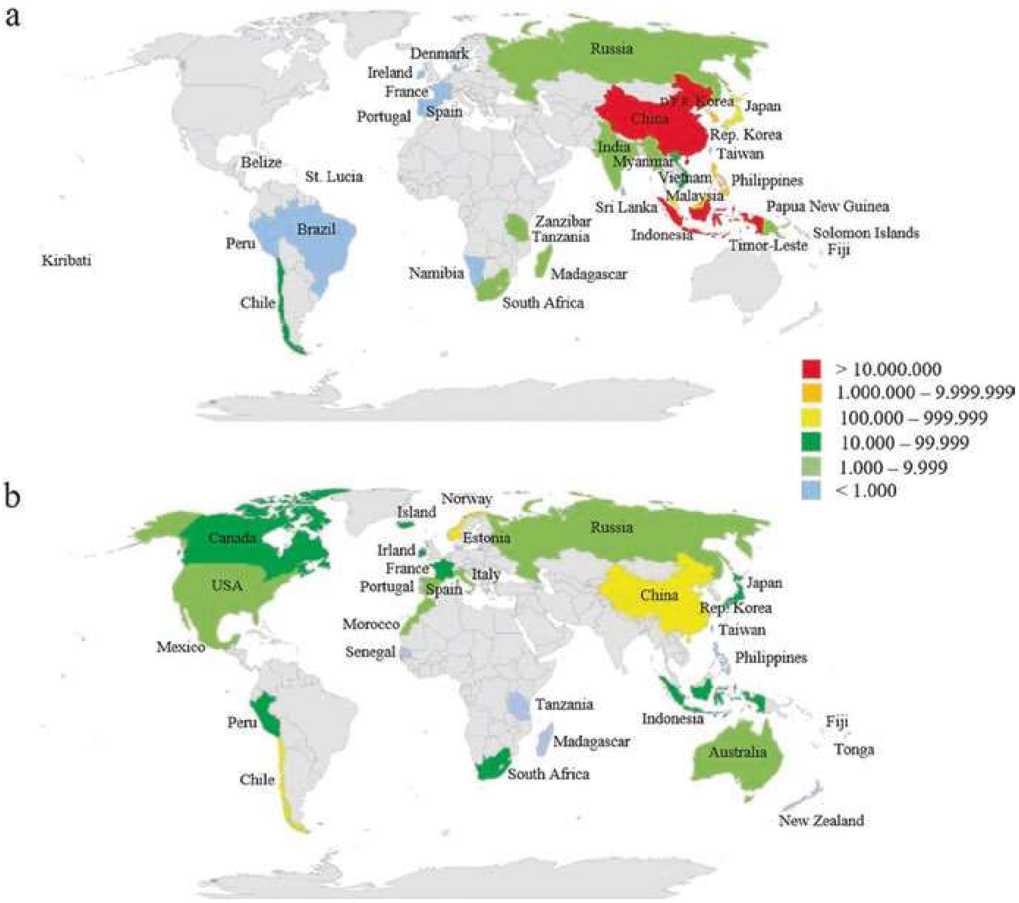

Fig. 5.1 Seaweed production in 2018 by different countries of the world. (**a**) Culture and (**b**) capture. Color scale in wet metric tonnes. (Source: FAO 2018)

eutrophication" or "Trace gases produced by seaweed" or "Shore protection by seaweed," "Dampening wave energy by seaweed" or "Absorption of heavy metals by seaweed" or "Bioabsorption of heavy metals by seaweed" or "Oxygen production by seaweed" or "Seaweed acts as best primary producer" or "Regulation of biogeochemical cycle by seaweed" (Fig. 5.1).

5.3 Worldwide Seaweed Production Status

In the past, seaweed production was higher from the wild than from culture. Production from culture increased in the 1960s (FAO 2018). Brown seaweed was the most abundant followed by red seaweed and green seaweed respectively (Fig. 5.2).

Now, seaweed contributes to 27% of the total marine aquaculture production (FAO 2016a). In 1984, income from brown seaweed was US$737,400.90 whereas it was US$5,944,093 in 2017 (FAO 2018). In the case of red seaweed, US$751,614.6

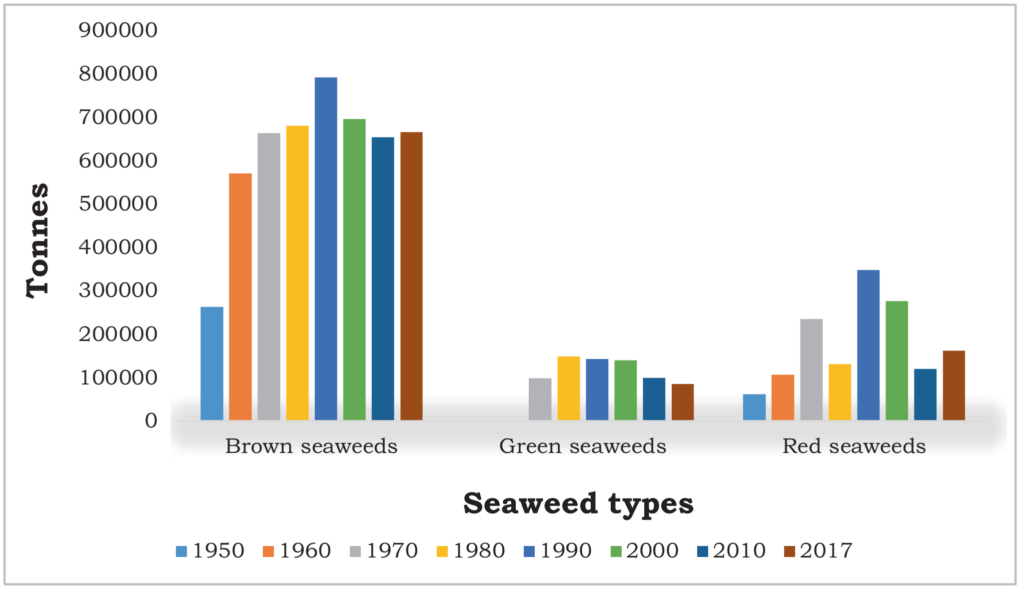

Fig. 5.2 Global capture of production of seaweed (tonnes). (Source: FAO 2018)

was made, while this figure converts into US$5,272,332 in 2017 (FAO 2018). Recently world, red seaweed has become the target species for the extraction of valuable chemicals (e.g., agar, carrageenan). Consequently, red seaweed production has increased and has surpassed the production of brown seaweed (Fig. 5.3).

5.4 Role of Seaweed in Climate Change Mitigation and Adaptation

Climate change mitigation is the process of cutting down or limiting greenhouse gas emissions to reduce future global warming. Mitigation can be done using new technologies, making available technologies more energy efficient, using clean energy sources, and changing people's behavior (IPCC 2014). The term climate change adaptation is different than the term climate change mitigation. According to IPCC (2014), climate change adaptation is the process of adjustment to the actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities, whereas in natural systems it refers to human intervention to facilitate adjustment to the expected climate and its effects. Seaweed is the ideal candidate for climate change mitigation and adaptation. We emphasize seaweed as it has been providing a service for many years as a natural shield against violent storms. It protects coastal regions and provides human food. It also acts as a natural buffer (reducing ocean acidification and ocean deoxygenation) and restores the vulnerable ecosystems. The climate change benefits of cultivation are briefly described in Fig. 5.4.

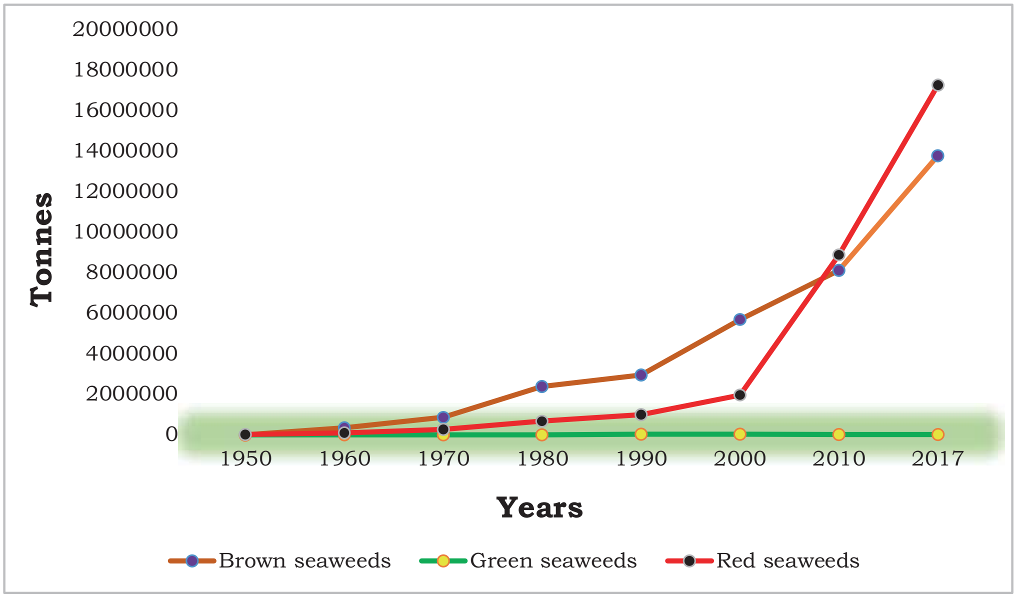

Fig. 5.3 Global culture production of seaweed (tonnes). (Source: FAO 2018)

Fig. 5.4 Benefits of seaweed farming in climate change mitigation and adaptation (Source: Reproduced from Duarte et al. 2017)

5.5 Ecological Services of Seaweed

Seaweed provides various ecological services. Supporting and regulating services fall under the term ecological services (Table 5.1). Ecological services are crucial for climate change mitigation and adaptation. Although there are some

Table 5.1 Ecosystem services provided by seaweed

Ecosystem services		Motivating factors for status classification
Supporting	S1. Biogeochemical cycling	Oxygen cycle, nutrient status, carbon cycle (low pH).
	S2. Primary production	Elevated phytoplankton concentrations, loss of eelgrass, and macroalgae.
	S3. Food web dynamics	Fish populations, bottom fauna, and habitats.
	S4. Biodiversity	Habitats, species abundance.
	S5. Habitat	Biological oxygen demand, bottom fauna, physical disturbance
	S6. Resilience	Observed regime shifts, loss of habitats, and biodiversity.
Regulating	R1. Climate and atmospheric regulation	Marine regulation of climate has good potential, but not sufficient given human greenhouse gas emissions.
	R2. Sediment retention	Pressures from bottom trawling and shipping, coastal zone vegetation.
	R3. Regulation of eutrophication	Coastal and pelagic nutrient concentration.
	R4. Biological regulation	Deterioration of top-down food web dynamics increased transport of parasitic microorganisms from agricultural land to marine systems due to climate change (precipitation patterns).
	R5. Regulation of toxic substances	Seafloor activities release embedded toxic substances, observed concentrations in commercial fish species, and sea birds.
Provisioning	P1. Food	Current status of commercial fish species abundance.
	P2. Raw material	Current status of commercial fish species abundance (e.g. for feed).
	P3. Genetic resources	Genetic material from within and between species biodiversity. Potential supply exceeds demand.
	P4. Chemical resources	Resources e.g. pharmaceuticals and food ingredients. Potential supply exceeds demand.
	P5. Ornamental resources	Current use is mainly sustainable. Potential supply exceeds demand.
	P6. Energy (from biomass only)	Current production is mainly sustainable. Potential supply exceeds demand.
	P7. Space and waterways	Space is currently abundant but increased competition expected.
Cultural	C1. Recreation	Eutrophication status, the abundance of recreational fish species, the satisfaction of recreationists (survey), bathing water quality.
	C2. Aesthetic values	Litter abundance, probability of oil spills.
	C3. Science & education	Increasing scientific interest in marine environments.
	C4. Cultural heritage	Loss of culturally important activities in coastal villages.
	C5. Inspiration	Inspiration to e.g. culture. Loose connection to water quality.
	C6. Natural heritage	Related to current water quality status.

Sources: Swedish EPA (2008), Bryhn et al. (2015), and Hasselström et al. (2018)

environmental risks associated with seaweed farming, these are much lower than ecological services it provides (Knox et al. 2015; Cabral et al. 2016; Kim et al. 2017; Walls 2017; Campbell et al. 2018; Lotze et al. 2019).

5.6 Supporting Services

Supporting services include biogeochemical cycling, primary production, food web dynamics, biodiversity, habitat, and resilience. All cycles are linked. For example, the photosynthetic conversion of CO_2 and other inorganic nutrients dissolved into organic material and oxygen by primary producers, such as algae, has a bearing on several of the cycles. A seaweed farm could influence the dynamic food web interactions that organisms have with the ecosystem. The long-term ability to cope with a changing environment is reflected in the resilience of an ecosystem. It is expected that resilience is affected by biodiversity in terms of, for example, species richness (Tilman et al. 1998).

5.7 Feeding, Breeding, Nursery Ground of Marine Organisms

Habitat-forming species such as seaweeds are popularly known as biological engineers (Jones et al. 1994). Seaweed modifies the existing ecological features (light, nutrients, sediments, physical scour, and water flow, etc.) and resources to make them favorable for other species (Jones et al. 1994; Bertness and Callaway 1994; Jones et al. 1997). Almost 8000 individual macroinvertebrates were found in a single kelp plant (Christie et al. 2003).

Holdfast, stipe, and lamina of seaweed provide a primary habitat (Rinde et al. 1992), whereas epiphytes (*Palmaria palmata*, *Phyllophora* spp., *Delesseria sanguinea*, *Polysiphonia* spp., *Ceramium* spp. *Lithothamnion* spp., etc.) provide secondary habitats for the colonization of organisms (Whittick 1983; Teagle et al. 2017). Holdfast traps sediment/detritus, is a good source of food, and provides a stable environment for the fish and invertebrates (Moore 1972; Schaal et al. 2009).

Holdfast is regarded as the most diverse species habitat, which supports 30–70 macrofaunal species per holdfast (Edwards 1980; Christie et al. 2003; Blight and Thompson 2008). Most of the organisms were found in the holdfasts than in other parts of the seaweed (Jones 1972; Moore 1972; Thiel and Vásquez 2000; Teagle et al. 2017). Epiphytes support highly diverse and abundant species that vary spatiotemporally (Christie et al. 2003).

Seaweed beds are the most productive habitats on Earth and provide three-dimensional habitats for many organisms in the coastal sea (Mann 1973, 2000; Graham 2004; Reed et al. 2008; Christie et al. 2009; Bustamante et al. 2014).

Seaweed habitat is vital for the promotion of species diversity. Macrocystis algae provide habitats in California that support genetic diversity. A 19-year observation study in the Channel Islands National Park showed that 90% of species were common in the giant kelp regions (Graham 2004).

Laminaria hyperborean is a canopy-forming species that supports huge species diversity in the northeast Atlantic (Smale et al. 2013). Approximately 130 species and 8000 individual species were recorded on a single *Laminaria hyperborea* sporophyte in Norway (Christie et al. 2003). Canopy plays an important role in the richness of species diversity. More than 40 species were regularly found under the kelp canopies (Maggs 1993). The elimination of canopy-forming *Cystoseira* species in the Mediterranean reduced the number of invertebrate species that relied on it (Benedetti-Cecchi et al. 2001; Bulleri et al. 2002; Mangialajo et al. 2008). Eriksson et al. (2006) reported that species diversity was higher beneath a canopy of *Fucus* in the Baltic Sea. Lilley and Schiel (2006) also showed that 36–44% of biological diversity declined because of the removal of the canopy of the *Hormosera banksii* species. Seventy-seven percent of the commercial species use seaweed beds as their habitat. Many commercial fish species rely on the seaweed beds as a nursery and feeding ground. These productive habitats increase the fish survival rates, hence increasing the yield of fish (Smale et al. 2013; Seitz et al. 2014).

Over the last 60+ years, a considerable amount of research has been conducted on the seaweed-associated biodiversity in the northeast Atlantic (Ebling et al. 1948; Sloane et al. 1957; Jones 1971; Moore 1971, 1973; Norton et al. 1977; Norderhaug et al. 2002; Christie et al. 2003; Blight and Thompson 2008; Walls et al. 2016, 2017; Teagle et al. 2017).

5.8 Habitat for Fish

Seaweed habitats are very favorable for the increase in diversity and abundance in fishes (Bodkin 1988). The complication of rocky substratum act as a suitable habitat for reef fishes to protect themselves from the predators (Quast 1968a,b; Miller and Geibel 1973; Russell 1977; Ebeling et al. 1980; Wheeler 1980; Bodkin 1988; Larson and DeMartini 1984; Stephens et al. 1984; Norderhaug et al. 2002). The structure of the substratum appears nearly flat, with little three-dimensional structure to large rocky outcrops. High vertical relief and complex structures are also available in the substratum (Bodkin 1988). Larson and DeMartini (1984) reported that low relief of seaweed beds is favorable for the increase in assemblage of fishes. The substratum structure plays a vital role in the increase in fish in the seaweed vegetated area (Stephens et al. 1984). Laur et al. (1988) reported that a huge amount of fishes found in the kelp-dominated regions of southern San Luis Obispo. Ebeling and Laur (1988) mentioned that fish diversity or species richness is high in the seaweed-dominated area of Santa Barbara, California. Murphy et al. (2000) found massive species richness in the filamentous algae-dominant regions of Alaska. *Sargassum* provides a vital habitat for many species and serves as a nursery ground for larvae and juveniles (Coston-Clements et al. 1991).

Seaweed beds or kelp forests are suitable spawning and reproduction grounds for many fishes (Gordon 1983; Schultze et al. 1990). Fishes use algae to make their habitats where they lay their eggs. Some fish species lay sticky eggs that stick to the seaweed or substratum. Gordon (1983) reported that spherical holdfasts of *Saccorhiza polyschides* are a favorite nesting place for headed clingfish (*Apletodon microcephalus*) and two-spotted gobies (*Gobiusculus flavescens*). The eggs of *Agonus cataphractus* are found in the rhizoid of *Laminaria* (Schultze et al. 1990). *Labrus bergylta* (Ballan wrasse) and *Ctenolabrus rupestris* (Goldsinny wrasse) feed on kelp-associated invertebrates (Norderhaug et al. 2005). Sardines, grunts, barracuda, and sharks were found in the seaweed bed of the Caribbean and Pacific coasts of Costa Rica (Langton et al. 2019).

Besides nesting and breeding grounds, seaweed beds are also used as a nursery ground for the growth of juvenile fishes (Carr 1983; Shaffer 2003; Lorentsen et al. 2004). Juvenile gadoids, cod (*Gadus morhua*), lumpsucker (*Cyclopterus lumpus*), striped sea snail (*Liparis liparis*), shore rockling (*Gaidropsarus mediterraneus*), Goldsinny wrasse (*Ctenolabrus rupestris*), and Montagu's sea snail (*Liparis montagui*) used seaweed beds as a nursery ground (Schultze et al. 1990; Fossa 1995; Borg et al. 1997; Sjøtun and Lorentsen 2003). Juvenile fishes have been found in the benthopelagic zone and canopy (*Sebastes* sp.) of seaweed (Carr 1983; Murphy et al. 2000). On the coast of Washington, juvenile salmon (i.e., *Oncorhynchus tshawytscha*) and forage fish (i.e., *Hypomesus pretiosus*) use kelp habitat (Shaffer 2003). *Macrocystis pyrifera* and *Nereocystis* spp. found on the western coast of the USA and Canada are suitable sites for fish to live in (Quast 1968a, b; Miller and Geibel 1973; Russell 1977; Leaman 1980; Ebeling et al. 1980; Ebling and Laur 1988; Laur et al. 1988). The compilation of Norwegian kelp forest species was conducted by Hoeisaeter and Fossa (1993).

Worldwide, a large number of studies have been carried out on the comparison between seaweed vegetated and non-vegetated fish assemblage and the effects of seaweed removal on the fish diversity (Limbaugh 1955; Moore 1972, 1973; Abbott and Perkins 1977; Perkins et al. 1978; Gordon 1983; Larson and DeMartini 1984; Stephens et al. 1984; Bodkin 1988; Schultze et al. 1990; Erwin et al. 1990; Fossa 1995; Murphy et al. 2000; Shears and Babcock 2003; Sjøtun and Lorentsen 2003; Burrows 2012).

5.9 Habitat for Invertebrates

Seaweed habitat is regarded as the most dynamic and biologically diverse habitat on the planet (Birkett et al. 1988). Seaweed slows down or prevents suspended particles from transportation from the overlying water column to the sea bed (Eckman et al. 1989). Seaweed beds are a hub/habitat for a large number of invertebrates (e.g., gastropod mollusks, crustaceans, and echinoderms), which are of great ecological and economic importance (Jones and Kain 1967; Kitching and Thain 1983; Christie et al. 2003). Seaweed/kelp creates microniches that support large decapods such as lobster and crayfish. Amphipods and gastropods are the most diverse and dominant invertebrate groups found on the seaweed bed (Christie et al. 2003; Wagge-Nielsen et al. 2003).

Polychaetes are also found in the kelp bed, as reported by Healy and McGrath (1998). Edwards (1980), Ball et al. (1995), and Healy and McGrath (1998) recorded various types of invertebrates from or within the holdfasts of seaweed off the coast of Ireland. Christie et al. (2003) and Wagge-Nielsen et al. (2003) made a checklist of invertebrates found in the Norwegian laminaria. Birkett et al. (1988) listed 1260 invertebrate species, of which 173 species belong to polychaetes. *Saccharina latissima* and other seaweed provide habitat where gastropods and crabs have been observed feeding on the seaweed. Hydrozoans (*Obelia* spp.) and harpacticoid copepods were recorded in farmed kelp in the spring (Peteiro and Freire 2013). Caribbean spiny lobster (*Panulirus argus*) pueruli post-larvae complete metamorphosis into the seaweed-associated substrate (Acosta and Butler 1999). Seaweed provides a surface for algicidal bacteria that can mitigate eutrophication (Imai et al. 2006).

Holdfast, stipe, and fronds of seaweed support different invertebrate organisms. Three-dimensional holdfast, with its internal spaces, provides a suitable habitat for moving species of polychaetes (e.g., *Anaitides*, *Eulalia*, *Harmothoe*, *Hediste*, *Kefersteinia*, *Lagisca*, *Lepidonotus*), crustaceans (e.g., *Bodotria*, *Idotea*, *Apherusa*, *Jassa*, *Melita*, *Porcellana*), and echinoderms (e.g., *Amphipholis*, *Asterina*, *Ophiothrix*, *Asterias*, *Psammechinus*, *Pawsonia,* and *Ocnus*) (Christie et al. 2003; Jørgensen and Christie 2003). The lower part of the stipe also supports polychaetes (e.g., *Amblyosyllis*, *Brania*, *Pionosyllis*, *Trypanosyllis*), crustaceans (*Caprella*, *Pariambus*, *Ammothelia*, *Anoplodactylus*), mollusks (*Onoba*, *Tricolia*, *Elysia*), and echinoderms (e.g., *Echinus*, *Psammechinus*, *Henricia*) (Kelly 2005).

5.10 Habitat for Birds

Seaweed provides foraging habitat for birds as the seaweed bed and its associated habitat are rich in diverse fishes and invertebrates. Furthermore, seaweed can dampen the wave energy (e.g., storms) and protect the shore, as well providing sheltered foraging habitat for the birds. Kelp Forests are underwater ecosystems formed in shallow water by the dense growth of several different species known as kelps. Though they look very much like plants, kelps are actually extremely large brown algae. Generally speaking, kelps live further from the tropics than coral reefs, mangrove forests, and warm-water seagrass beds, so kelp forests do not overlap with those systems. Like those systems, though, kelp forests provide important three-dimensional, underwater habitat that is home to hundreds or thousands of species of invertebrates, fishes, and other algae. Some species aggregate and spawn in kelp forests or utilize these areas as juvenile nursery habitat. Besides, a kelp forest acts as a natural barrier from the surge effects of waves, particularly in the case of storms, and therefore provides a more sheltered foraging environment for birds.

Seaweed provides three types of foraging habitats for birds (Foster and Schiel 1985):

- Living attached plants associated with rocky substrata (kelp forests).
- Drift kelp floating in the open sea.
- Wrack-detached kelp washed up on the shoreline

5.11 Food Provider/Primary Production

Seaweed is the best primary producer of marine ecosystems in the world with net production of 1521 Tg carbon/year. This amount of primary production by seaweed requires an area of over 3.5 million km^2 (Smith 1981; Steneck et al. 2002; Duarte et al. 2005; Krause-Jensen and Duarte 2016; Langton et al. 2019). Seaweed productivity largely depends on the availability of nutrients, temperature, wave exposure, light, and disturbance (Reed et al. 2008; Langton et al. 2019). Seaweed primary production is always greater than phytoplankton productivity. Seaweed primary production in the Atlantic regions is estimated to be over 1000 g C/m^2/year (Mann 1973; Smale et al. 2013), whereas phytoplankton production in the temperate areas is between 100 and 300 g C/m^2/year (Mann 2000). The primary production of cultivated seaweed is lower than that of the wild seaweed as cultivated seaweed grows only in summer and there is no further production once harvested (Yoshikawa et al. 2001). Estimated primary production by seaweed in different zones of Strangford Lough is summarized in Table 5.2.

Through the photosynthesis process, seaweed produces organic matter required for the growth and energy metabolism of higher trophic level organisms (Langton et al. 2019). Seaweed biomass is directly taken by herbivorous fish and invertebrates such as the blue-rayed limpet (*Patella pellucida*) (Langton et al. 2019). A very small amount is taken by herbivores and most of the seaweed biomass (>80%) enters the carbon cycle as detritus or dissolved organic matter (Gili and Comma 1998; Christie et al. 2009; Krumhansl and Scheibling 2012; Krumhansl and Scheibling 2012). This seaweed detritus settles locally or is transported to the adjacent or remote areas where detritus used as an ideal food source for benthic invertebrates and some other organisms (Duggins et al. 1989, 1990; Fredriksen 2003; Norderhaug et al. 2003; Norderhaug et al. 2003; Vanderklift and Wernberg 2008; Tallis 2009; Schaal et al.

Table 5.2 Primary production as tonnes of carbon in Strangford Lough

	Intertidal	Sub-tidal <10 m	>10 m	Total
Intertidal macroalgae	24,098			24,098
Subtidal macroalgae		68,582		68,582
Phytoplankton	812	5952	3394	10,158

Source: Kelly (2005)

2012; Leclerc et al. 2013a). Carbon derived from seaweed is used by suspension feeders, detrital grazers (i.e., limpets and *Littorina littorea*), and deposit feeders (Bustamante and Branch 1996; Leclerc et al. 2013b). Seaweed-derived carbon provides food for gastropod grazers, benthic suspension feeders, fish, and seabirds (Fredriksen 2003). Most of the seaweed biomass releases about 43% of its production in the water as particulate organic matter (POM; detritus) and dissolved organic matter (DOM) (Duarte and Cebrian, 1996; Krumhansl and Scheibling 2012; Filbee-Dexter and Scheibling 2014; Barron et al. 2014; Barrón and Duarte 2015; Hill et al. 2015). Organic matter derived from kelp provides more than 30% of the diet of kelp-associated organisms and is used as the ideal habitat for over half a million organisms/m^2 (Kaehler et al. 2000; Christie et al. 2009).

5.12 Food Provider of Fish

The seaweed bed is a hub of food for many fishes. Many moveable macrofauna (e.g., crustaceans and mollusks) are abundant in the kelp forest (*Laminaria hyperborea*). The macrofauna occupies an important place in the fish diet (Nelson 1979; Kennelly 1983, 1991; Holmlund et al. 1990; Nordeide and Fossa 1992; Hoeisaeter and Fossa 1993; Fossa 1995; Føsne and Gjøsaeter 1996; Jorgensen and Christie 2003; Christie et al. 2003). The abundance of the macrofauna in the kelp forest makes the habitat a vital source of prey for many top-down predatory consumers (Jorgensen and Christie 2003; Christie et al. 2003). Christie et al. (2003) reported that the average density of the macrofauna in the Norwegian *Laminaria hyperborea* kelp forest could be 100,000 ind/m^2.

Amphipods and gastropods are dominant in the Norwegian kelp forest and these are the favorite food of many fishes (Moore 1972, 1973; Gordon 1983; Schultze et al. 1990; Fossa 1995; Fossa et al. 1998; Christie et al. 1998, 2003; Norderhaug et al. 2002; Fredriksen 2003). Spatio-temporal variation in the prey species in the kelp bed also changes the availability of food and fish species dependent on them (Deady 1995; Deady and Fives 1995a, b; Varian 1998; Zemke-White and Clements 2004). Moreover, the occurrence and abundance of macroinvertebrates also rely on the age and size of the seaweed (Schultze et al. 1990). The number of invertebrates increased with the increase in seaweed age and size (Rinde et al. 1992). Consequently, the number of fishes in the kelp bed increases with the increase in seaweed age.

5.13 Food Provider of Invertebrates

Seaweed is directly used as a food source for invertebrates, gastropods (e.g., *Patella* and *Helicon*), and some echinoderms (e.g., *Echinus* and *Psammechinus*). Gastropods *Patella pellucida* and *Lacuna vincta* directly graze on seaweed for their food. Sea urchins *Strongylocentrotus droebachiensis* and *Paracentrotus lividus* also rely on seaweed for their food (Steneck et al. 2002; Molis et al. 2010; Leclerc et al. 2013b). In the northeast Atlantic, common limpet *Patella vulgata* feeds on drift kelp. An indirect form of seaweed (i.e., particulate organic matter) is used by the suspension and deposit feeders as their food (Dugan et al. 2003). Sponges, terebellids, sabellids, serpulids, spirorbids, bivalves, cirripeds, bryozoans, holothurians, crinoids, and tunicates used particulate organic matter for their growth and energy metabolism. Seaweed is also used as the food source for cnidarians, scale worms, syllids, hesionids, phyllodocids, nereids, isopods, lobster, and crab, etc. Along the coast, seaweed roots provide organic matter for the amphipods *Malacoceros* and *Capitella*.

5.14 Food Provider of Birds

Seaweed provides food for birds indirectly. In the seaweed bed food chain, kelp detritus inputs organic matter into the nutrients in poor coastal regions (particularly sandy beaches). Seaweed detritus provides nutrients that are a suitable habitat for many intertidal macroinvertebrate communities (secondary production) and fishes. These macroinvertebrates and fishes of the seaweed bed are regarded as prey/food for birds (Duggins et al. 1989).

5.15 Shore Protection

Seaweed acts as a buffer against various natural calamities (i.e., flood, storm surges, extreme wind, etc.) (Smale et al. 2013). It is a bioengineering structure in the nearshore or coastal areas such as salt marshes and mangroves. During flooding and storm events, the seaweed structure changes the water motion and dampens breaking wave velocity, protecting shore or coastal areas from possible damage (Lovas and Torum 2001). It protects the shore from erosion by sediment retention (Mork 1996; Lovas and Torum 2001). Seaweed beds are very important where climate change phenomena such as sea-level rise and storms are frequent. There is little information about the storm protection capability of seaweed beds. The magnitude of wave or storms is site specific and species dependent (Firth et al. 2016). The degree of water flow largely depends on the assemblage, density, and morphology of the seaweed (Eckman et al. 1989; Gaylord et al. 2007). *Laminaria hyperborea* beds reduced the height of the waves in Norway by 60% (Mork 1996). Similar findings were observed in the UK and Ireland in the case of shore protection. The importance of seaweed cultivation or naturally growing seaweed will increased soon as the climate is changing rapidly.

Besides, fronds and stipes are exposed to faster water currents and greater effects of wave action. Kelp stipe is often colonized by highly abundant and diverse flora and fauna, which varies considerably spatio-temporally (Christie et al. 2003).

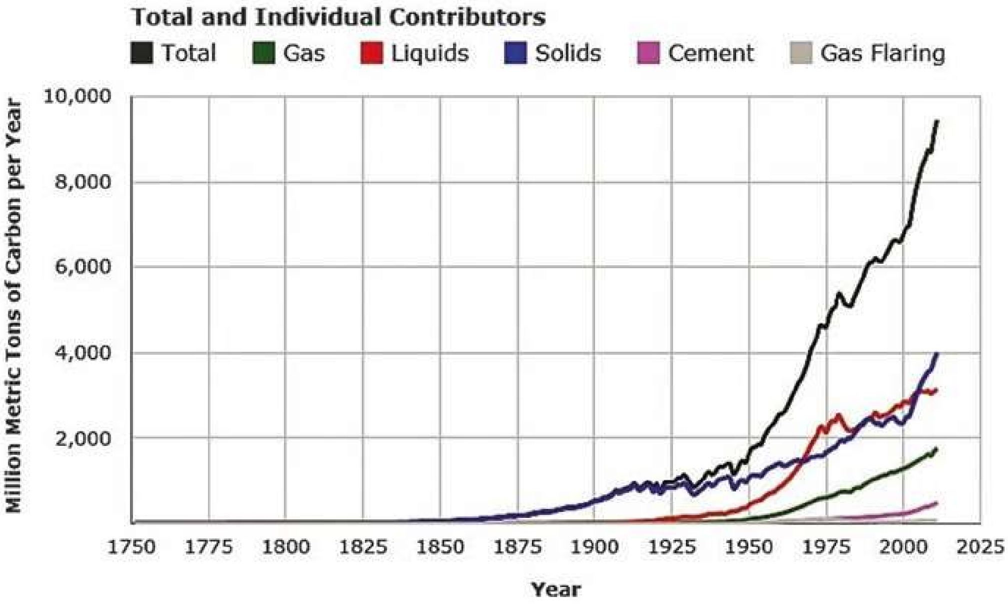

Fig. 5.5 Different contributing factors in the global carbon production trend (Source: Modified from Boden et al. 2017)

5.16 Carbon Sequestration and Climate Change Regulation

"Blue Carbon" is the carbon that is sequestered by both living and non-living biomass in the ocean and coastal habitats and provides many ecological services (Nellemann et al. 2009; Howard et al. 2014; Vierros 2017; Queirós et al. 2019). Worldwide carbon production is increasing at an alarming rate (Fig. 5.5). The average CO_2 concentration increased from 315 ppm to 380 ppm over 47 years (1960–2007). Worldwide, there has been an estimated 35% increase in CO_2 emission since 1990 (IPCC 2007). The ocean acts as a hub for the sink of carbon dioxide (Arsenault 2018; Froehlich et al. 2019; Ortega et al. 2019). Seaweed, phytoplankton, and seagrasses remove CO_2 from the atmosphere (Zou 2005; Kaladharan et al. 2009; Arsenault 2018). Seaweed is the permanent or long-term sequester of carbon dioxide (Nellemann et al. 2009; McLeod et al. 2011; Hughes et al. 2012a, b). By reducing CO_2 from the seawater it minimizes the issue of ocean acidification (Arsenault 2018). Seaweed stabilizes the pH concentration of the ocean water by taking CO_2 and by releasing oxygen during the photosynthesis process. The process that converts CO_2 into seaweed biomass and releases oxygen into the surrounding environment is light driven (Langton et al. 2019). Seaweed converts CO_2 into organic matter (N'Yeurt et al. 2012; Chung et al. 2013; Duarte et al. 2017) and this organic carbon cannot go back into the atmosphere (Hill et al. 2015; Trevathan-Tackett et al. 2015). Seaweed respires at night, but the concentration of oxygen consumption and CO_2 production do not exceed the amount of daytime O_2 production and CO_2 absorption (Duarte and Cebrian, 1996; Langton et al. 2019).

Seaweed cultivation showed a net increase in pH and oxygen levels (Liu et al. 2009). Shellfish (e.g., mollusks and crustaceans) respire CO_2 while seaweed receives the CO_2. This is a mutual aspect of the benefit that reduces the acidification of water (Langton et al. 2019). Excess CO_2 in the water forms carbonic acid that dissociates into bicarbonate and hydrogen ions, which lowers the pH. This lower pH largely hampers the formation of the shell (Langton et al. 2019). Lower pH changes the availability of shell-forming minerals required by corals, mollusks, and myriad microorganisms (Gatusso and Hansson 2011). Consequently, the shell-forming animals are declining. Seaweed helps in the mitigation of CO_2 and regulates the environmental impacts of climate change (Duarte et al. 2017) such as risk to human health, loss of biodiversity, increased risk of extreme weather events, and loss of agricultural productivity (Isacs et al. 2016).

An excessive volume of atmospheric carbon dioxide (CO_2) creates a serious adverse situation for marine organisms. Ocean acidification phenomena and an increase in sea surface temperatures are alarming issues (Feely et al. 2004; Meehl et al. 2007; Ciais et al. 2013). According to the IPCC (2013), CO_2 concentrations are expected to reach 1000 ppm in the atmosphere by the end of this century. This will increase dissolved CO_2 by ~2.5 fold. As a result, a decrease in pH (~0.4 units) will increase bicarbonate concentrations (by ~10%) and carbonate levels (approximately halve) (Feely et al. 2004; Raven et al. 2005). More than 30 countries have decided to increase the production of renewable resources to meet carbon emission targets (Bjerregaard et al. 2016). Seaweed cultivation plays a significant role in marine carbon sequestration (Chung et al. 2011, 2013; Duarte et al. 2017), which reduces ocean acidification and also provides human food, animal feed, and bioenergy (Kraan 2013; Krause-Jensen et al. 2015; Chen et al. 2015; Bjerregaard et al. 2016). This sequestrated carbon can be buried in sediments (Zhang et al. 2012), particularly in continental shelf sediments or in the deep sea (Krause-Jensen and Duarte 2016). A large flux of macroalgal carbon was exported to the offshore i.e., about 16.5 g carbon/m^2/day of giant kelp was exported through the Carmel Canyon, California. Approximately 7×10^{10} g carbon seaweed carbon reached a depth of 1800 m from the Bahaman shelf during a storm, while 0.4 g carbon/m^2/year of *Sargassum* reached a depth of 3600 m in the Northwest Atlantic region (Rowe and Staresinic 1979; Harrold et al. 1998; Dierssen et al. 2009). *Grypania spiralis* (the oldest dating of a multicellular organism) proved that macroalgae have contributed to carbon sequestration for over 2.1 billion years and act as a source of oil deposits (Han and Runnegar 1992; Sun et al. 2013; Xie et al. 2014). Macroalgal carbon ultimately finds its way into anoxic basins, submarine canyons, rocky shores, and the

Table 5.3 Nitrogen, phosphorus removal, and carbon rate by 500 million tonnes of dry seaweeds

Nitrogen removal	10,000,000 tons	Assumes nitrogen content to be 2% of dry weight. Equals 18% of the nitrogen added to oceans through fertilizer
Phosphorous removal	1000,000 tons	Assumes phosphorous content to be 0.2% of dry weight. Represents 61% of the phosphorous input as fertilizer
Carbon assimilation	135,000,000 tons	Assumes carbon content to be 27% of dry weight. Equals 6% of the carbon added annually to oceans from greenhouse gas emissions

Bjerregaard et al. (2016)

deep sea where sedimentation occurs (Wolff 1962; Canals et al. 2006; De Leo et al. 2010; Filbee-Dexter and Scheibling 2014; Barron et al. 2014; Renaud et al. 2015).

In 2010, emissions of carbon were about 8182 Tg from anthropogenic sources (Boden et al. 2010). Large-scale seaweed culture can remove huge amounts of carbon from the coastal water (Tang et al. 2011; Hughes et al. 2012a, b). For example, 500 million tons of seaweed production would absorb 135 million tons of carbon (Table 5.3). Krause-Jensen and Duarte (2016) reported that globally, about 173 Tg carbon/year (with a range of 61–268 Tg carbon/year) fixed by seaweeds, which is a relatively small proportion of total oceanic primary production (54–59 Pg carbon/year) and the increase in atmospheric CO_2 of 4 Pg carbon/year (Denman et al. 2007). This absorption process can add carbon credit as about 3.2% of the carbon is added annually to seawater from greenhouse gas emissions (Bjerregaard et al. 2016). It is reported that the seaweed biomass of the Indian coast can utilize 9052 tCO_2/day against 365 tCO_2/day emissions. This is a clear indication of a net carbon credit of 8687 tCO_2/day (Kaladharan et al. 2009). As a result, India is the biggest beneficiary of the carbon trade, and claims about 31% of the total world carbon trade (The Economic Times 2005).

CO_2 sequestration by seaweed was not fully incorporated with the *"Blue Carbon"* concept owing to the decomposition nature of seaweed (Nellemann et al. 2009; McLeod et al. 2011; Duarte et al. 2013). However, the thinking changed after the evidence that seaweed is the contributor to the carbon sink in the ocean (Hill et al. 2015; Sondak and Chung 2015; van der Heijden and Kamenos 2015; Trevathan-Tackett et al. 2015; Moreira and Pires 2016; Krause-Jensen and Duarte 2016). The role of seaweed in the *"Blue Carbon"* service and mitigation of climate change is now well accepted. Using seaweed biomass as biofuel or a seaweed-based food system to replace fossil fuel or intense carbon production could reduce the CO_2 emission (Fry et al. 2012; Kraan 2013; Chen et al. 2015). In Korea, a *"Blue Carbon"* program has been developed, even though they contribute only 6% of global seaweed production (Chung et al. 2013; Sondak and Chung 2015; FAO 2016b). To make this *"Blue Carbon"* program successful in mitigating climate change, world-leading seaweed producers (e.g., China, Indonesia, Philippines) can come forward.

5.17 Nutrients Uptake/Mitigation of Eutrophication

Eutrophication has recently become the emerging environmental concern throughout the world (Jiang et al. 2019). Oceans, especially coastal areas, receive nutrients from both natural and atmospheric sources (Paerl 1995; Prospero et al. 1996; Jickells 1998; Baker 2003). Moreover, nutrients are added from anthropogenic sources (e.g., finfish aquaculture, agriculture, and urban wastewater) (Smith 2003; Boesch et al. 2006) through the bio-deposition of feces and pseudofeces and the release of excess feed into the coastal water (Crawford et al. 2003; Kalantzi and Karakassis 2006; Forde et al. 2015). These excess nutrients can cause harmful algal bloom or eutrophication, which exerts negative impacts on the surrounding water

Table 5.4 Total nutrient removal by seaweed aquaculture in China and the nutrient removal capacity of Chinese seaweed farms per km^2

Total for China (2014)		
Seaweed production	2.00	million tonnes Dry-Wet (DW)
Seaweed area	1250	km^2
Nitrogen concentration[a]	3.76 ± 0.92	% DW
Phosphorus concentration[a]	0.47 ± 0.19	% DW
Nitrogen removal	75,371 ± 18,423	tonnes nitrogen per year
Phosphorus removal	9496 ± 3875	tonnes phosphorus per year
Per km^2 of seaweed farm and year		
Seaweed production	1604	tonnes DW
Nitrogen concentration[a]	3.76 ± 0.92	% DW
Phosphorus concentration[a]	0.47 ± 0.19	% DW
Nitrogen removal	60.31	tonnes nitrogen per km^2 per year
Phosphorus removal	7.60	tonnes phosphorus per km^2 per year
Nitrogen input[b]	3.38	tonnes nitrogen per km^2 per year
Phosphorus input[b]	0.06	tonnes phosphorus per km^2 per year
Seaweed farm nitrogen footprint area	17.8	km^2 of coastal ocean removed of nitrogen inputs per km^2 of seaweed farm
Seaweed farm phosphorus footprint area	126.7	km^2 of coastal ocean removed of phosphorus inputs per km^2 of seaweed farm

The seaweed farm nitrogen and phosphorus footprint area refer to the km^2 of Chinese coastal waters receiving nutrient inputs equivalent to those removed by 1 km^2 of seaweed farms. [a]The average tissue nutrient concentrations of Chinese seaweed, as weighted per species. [b]Nutrient input from the inventory integrating the riverine and atmosphere resources, weighted by the area of the East China Sea and the Yellow Sea

Source: Xiao et al. (2017)

quality (Bricker et al. 2008; Jiang et al. 2014; Glibert et al. 2018; Paerl et al. 2018). This polluted water is detrimental to both pelagic and benthic marine organisms (Shumway 1990; Anderson et al. 2002; Heisler et al. 2008; Chopin et al. 2008). Nitrogen and phosphorus are the main contributing agents for coastal pollution. Removal of these nutrients can be a great approach to mitigating the eutrophication issue worldwide (Conley et al. 2009; Holdt and Edwards 2014; Kim et al. 2015a).

Seaweed is the main weapon for removing nutrients from the coastal water (Fei 2004; Kang and Sui 2010; Liu et al. 2016; Roleda and Hurd 2019; Jiang et al. 2019). Cultivation of seaweed is regarded as the most promising tool for restoring the ecological balance (Buschmann et al. 2001, 2017; Chung et al. 2002; Neori et al. 2004; Yang et al. 2015a,b; Seghetta et al. 2016; Kim et al. 2017; Xiao et al. 2017). In China, excess nutrients have been removed significantly by cultured seaweed and seaweed farms (Table 5.4). Seaweed cultivated in suspended conditions along the coast can absorb inorganic nutrients from the water and absorption increases with the growth of seaweed (Troell et al. 1999; Neori et al. 2004; Troell et al. 2009; Kerrison et al. 2015; Marinho et al. 2015). Annually, seaweed removes 297 tonnes of nitrogen and 42 tonnes of phosphorus from Xiangshan Bay of the East China Sea

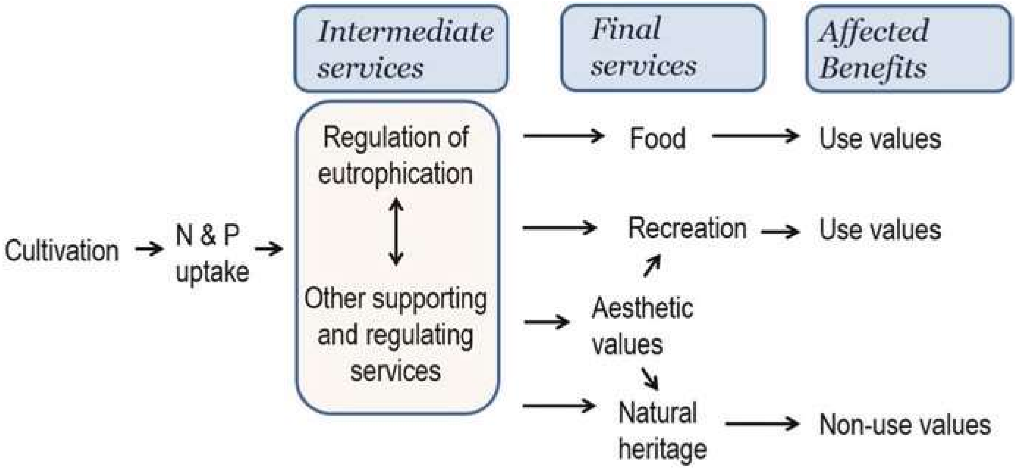

Fig. 5.6 Positive effects of removing excess nutrients from seawater through seaweed cultivation (Source: Modified from Hasselström et al. 2018)

(Jiang et al. 2019). Because of the decrease, less eutrophicated water or good-quality water has a positive impact on fish stocks and reproduction, habitat availability, and underwater vegetation (naturally growing kelp and bladderwrack density) (Kautsky et al. 1986; Paulsen 2007; Moy and Christie 2012). Furthermore, clear water is very important for the growth and succession of photosynthetic species and many other associated species (Kautsky et al. 1986; Svane and Gröndahl 1988; Jiang et al. 2019).

5.18 Nitrogen Removal

Globally, 124 million tons of nitrogen were used as fertilizer in 2014 for the growth of plants (Bjerregaard et al. 2016). But only half the amount was used by the plants and the remained unused. Finally, approximately 15–30% of the nitrogen was to find its way into the coastal water (Swaney et al. 2012; Lassaletta et al. 2014; FAO 2015). This excess nitrogen results in 245,000 km^2 of the polluted zone or biologically dead zone worldwide (Diaz and Rosenberg 2008). Removal of nitrogen is crucial because it is the main agent responsible for creating coastal eutrophication (Conley et al. 2009).

Seaweed cultivation can be a positive approach to removing this excess nitrogen from the coastal water (Bjerregaard et al. 2016). Cultivated seaweed removes nitrogen from seaweed, which exerts a positive impact on the environment (Fig. 5.6). Five hundred million tons of seaweed production would remove 10,000,000 tonnes of nitrogen (Table 5.3). Marine plants can produce 1000 tons dry weight per km^2 or 245 million tons dry weight, which can cover the dead zone area (Zhang et al. 2014; Kim et al. 2014, 2015a). In the case of dry seaweed, about 20 tons of nitrogen can be taken up per km^2 (Mišurcová 2012). It is postulated that 10 million tons of nitrogen can be removed from seawater if seaweed production could reach up to 500 million tons (Bjerregaard et al. 2016).

5.19 Phosphorus Removal

Phosphorus is not limiting nutrients in the ocean water or coastal water. Thus, the dead zone or eutrophication zone in the coastal water is less related to phosphorus (Bjerregaard et al. 2016). Removal of excess phosphorus from seawater by seaweed cultivation provides massive benefits for both aquatic organisms and humans (Fig. 5.6). The phosphorus reserve would be depleted in the next 50–100 years (Cordell et al. 2009). This nutrient reserve is declining owing to excessive use on the land and high energy production costs in manufacturing phosphate fertilizers. In 2014, 48 million tons of fertilizer was produced from phosphorus globally (FAO 2015). Phosphorus reserve in seaweed may be the best source of phosphorus for the future (Cordell et al. 2009). By-products of seaweed can be used as a potential source of phosphorus and as fertilizer or to replace the other forms of phosphorus use (Bjerregaard et al. 2016). Pechsiri et al. (2016) reported that 16 g nitrogen can be taken up by 1 kg of seaweed biomass in Sweden: 22.5–27.5 tons of seaweed (wet weight)/hectare/year can sequestrate 79.5–97 kg nitrogen/hectare/year. One million tons of phosphorus can be removed by cultivating 500 million tons of seaweed (Table 5.3).

5.20 Producer of Trace Gases

Seaweed acts as an important component that produces trace gases responsible for the depletion of ozone (Carpenter and Liss 2000). Macroalgae are global producers of trace gases that contain sulfur or halogens, such as volatile brominated and iodinated halocarbons. Various biotic and abiotic factors (i.e., physiological, mechanical, and oxidative stress) regulate the production of halogenated compounds (Mehrtens and Laturnus 1997; Manley 2002; Palmer et al. 2005; Leedham et al. 2015). Besides ozone layer depletion, trace gases are also responsible for playing an important role in global biochemical cycles, cloud formation, and the lifetime of other greenhouse gases (Laturnus 1996; Giese et al. 1999; Carpenter and Liss 2000; Leedham et al. 2013). Most of the studies are laboratory based with wild seaweed, which depends on the seasonal growth of seaweed (Zhou et al. 2005), whereas studies on farmed seaweed. Leedham et al. (2013) reported that cultured seaweed produced a low amount of halocarbons compared with naturally produced seaweed. Although Phang et al. (2015) mentioned that farmed seaweed can play a great role along with natural seaweed in terms of halocarbon production.

5.21 Nutrient Regulation and Biogeochemical Cycling

Seaweed plays a vital role in nutrient regulation and biogeochemical cycling in the coastal environment (Klinger 2015). This process is completed by nutrient assimilation, photosynthesis, and organic matter production, decomposition, and transportation (Klinger 2015). Seaweed is regarded as the best producer of the ocean. Seaweed productivity is greater than the productivity of phytoplankton, seagrasses, corals, and benthic microalgae (Mann 1973; Yokohama et al. 1987; Alongi 1998; Wada and Hama 2013). The productivity is the assimilation of carbon, nitrogen, phosphorous, silica, and other compounds from seawater. These compounds are then incorporated into organic matter. This organic matter is consumed by other organisms as POM or living tissue, used as food by herbivores and suspension feeders, and used as a substrate for microbial colonization and digestion. Finally, carbon and other nutrient content are transported into the system (Leclerc et al. 2013b; Yorke et al. 2013). Seaweed produces POM, which is higher than the production of phytoplankton (Bustamante and Branch 1996).

Seaweed also contributes to the organic matter in coastal water as DOM. Seaweed releases a considerable amount of DOM; up to 40% of seaweed production is released as DOM (Wada and Hama, 2013). DOM contributes to the organic carbon reservoir in the coastal water and fuels the microbial loop. POM and DOM export carbon in the offshore ecosystem. Seaweed plays an important role in the carbon cycle, which came into focus after the buzzword *“carbon sequestration”* was coined (Nellemann et al. 2009). Seaweed acts as a powerful tool in the context of mitigating climate change and ocean acidification.

5.22 Conclusion

From the above discussion, it can be concluded that seaweed plays a significant role in climate change mitigation and adaptation. If the culture of seaweed increased worldwide on a large scale it could be a powerful tool in controlling the climate. Ocean acidification and de-oxygenation are the effects of climate change. These issues can be minimized by seaweed cultivation. Moreover, it dampens the wave energy and protects coastal dwellers and their livelihood. It also provides food and habitat, and removes excess nutrients from the water, which is required for a healthy marine ecosystem. By reducing CO_2 from the atmosphere, people can benefit economically. Owing to the low investment required for the setup, seaweed culture gaining in popularity among the coastal people. Although some constraints are identified in the seaweed culture, climate change mitigation and adaptation features, as well as socio-economic benefits, make it a successful venture.

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