Chapter 6
Diatom Algae for Carbon Sequestration in Oceans

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Abstract Diatom algae are responsible for about 20–25% of primary production on Earth. They are said to have evolved ~200 million years ago (mya). Diatoms have a unique feature—a silica exoskeleton, giving them an advantage over the other phytoplankton. Diatoms play a vital role in regulating the nitrogen cycle in oceans and freshwater bodies. However, anthropogenic activity has adversely impacted diatom production and water ecology over the past 250 years. Their production may have decreased by as much as 40% in the last 50 years. The invention of mechanized trawlers enabled fishing on an industrial scale since these trawlers and other support vessels could travel long distances and spend more days out in the ocean. Thus, fish stocks plummeted, which directly affected the diatom population. Growing diatom algae is also considered the best solution to eutrophication. Diatoms take in CO_2 and nutrients like nitrogen and phosphorus, produce oxygen, and are also consumed by zooplankton and fish. Planting forests is considered a carbon sequestration solution. Similar is growing macroalgae in coastal waters. Diatoms in coastal waters keep it clean, enabling mangroves and sea grasses to grow. Dead diatoms sink to the depths of the ocean, together with other organic matter, and sequester carbon into the depths. This is called the ocean's biological pump. However, growing microalgae/phytoplankton is currently not being considered as a valid carbon sequestration solution. What is required is a thorough research into the world of oceans to understand in further detail the role of diatoms in increased ocean productivity and carbon sequestration.

Keywords Blue carbon · Carbon sequestration · Climate change · Diatom · Eutrophication · Fish carbon · Fisheries · Ocean biological pump · Whales

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6.1 Introduction

Bacillariophyceae/diatom algae are the most prolific phytoplankton on Earth, responsible for about 20–25% of primary production (Marella et al. 2016). This accounts for 40–50% of primary production in the oceans (Fox et al. 2020). Annual diatom production has been estimated to be approximately 23 GtC/yr (Mann 1999). This may be compared to the tropical rainforest production of ~18 GtC/yr, agriculture production of ~8 GtC/yr, and anthropogenic carbon emissions of ~10 GtC/yr (Mann 1999). Thus, diatoms may be considered the most important photoautotrophs on Earth (Amin et al. 2012).

Diatoms are said to have evolved ~200 million years ago (mya) (Benoiston et al. 2017). Thus, they are the last phylum of phytoplankton to have evolved. *Cyanobacteria* evolved over 2400 mya and *Chlorophyceae* ~1700 mya. Dinoflagellates and coccolithophores evolved after that. Diatoms have a unique feature—a silica exoskeleton (Marella et al. 2016). This gives them an advantage over the other phytoplankton and is perhaps the reason for their evolutionary success. Diatoms are more nutritious and easier to digest than other phytoplankton forming the preferred diet for zooplankton and newborn fish. Diatoms are grown in shrimp hatcheries to feed the post larval shrimp for the first 3 days (Tam et al. 2021). Thus, the survival of newly hatched fish depends on diatom availability. We may conclude that diatoms are the most important phytoplankton/microalgae in oceans (Fox et al. 2020).

Dr. Bostwick Ketchum of Woods Hole Oceanographic Institute, USA, is quoted to have said, "***All fish is Diatom***." (Barber and Hiscock 2006)

Diatoms are also more complex than other phytoplankton. They require silica and micronutrients such as iron, zinc, boron, etc., for their complex metabolism (Marella et al. 2018). So, when the availability of silica and micronutrients reduces in absolute terms or in relation to the availability of macronutrients, the production of diatoms declines.

6.2 Advent of Technology and Decline in Diatom Production

Anthropogenic activity has adversely impacted diatom production and water ecology over the past 250 years, ever since the Industrial Revolution (IPCC 2018). This impact has accelerated in the past 100 years or so, and diatom production may have decreased by as much as 40% in the past 50 years. Industrial whaling and fishing, eutrophication due to flow of nutrients into the oceans, and building of dams, in addition to other activities, are the main reasons for the decline in diatom production (IPCC 2022).

Mechanized ships and boats were invented in the late eighteenth century and commonly used after the invention of the diesel engine in the 1890s. This enabled large-scale hunting of whales. By 1960, their population had already plummeted when an embargo on whaling was imposed by the United Nations. The International Whaling Commission had been set up in 1946 as the global body responsible for management of whaling and conservation of whales. Ever since, whaling was banned in the 1960s; whale stocks have recovered a little. (IWC 2022).

About 100 years ago, human population was ~2 billion. Now, it has reached ~8 billion. Back then, we grew enough food to feed the-then population, whereas, today, we are bound to grow food to feed this fourfold increase in population. This 400% increase in food production has been achieved utilizing new techniques like irrigation by building dams, fertilizers such as urea, phosphates, introducing hybrid varieties, modern machinery, efficient pesticides, etc. Agriculture production is about 8000 million tons per year as of now (Fakhr-ul-Islam and Karim 2019).

The invention of mechanized, i.e., diesel engine powered, trawlers enabled fishing on an industrial scale, since these trawlers and other support vessels could travel long distances and spend more days out in the ocean. Wild fish catch is estimated at about 100 million tons per year, whereas aquaculture production adds another 100 million tons. Investments in wild fisheries are a fraction of investment in agriculture and forests (IPCC 2018).

Industrial fishing depleted fish stocks in the oceans. Many species of fish were at risk of becoming extinct. However, measures are being taken to conserve the ocean fauna, such as fishing holiday during the spawning season, limits of catch, limits on the size of fish that may be caught, type of fishing gear that may be used, etc.

6.3 Interdependence in the Ocean Ecosystem

A key question is the impact of decline in whales and fish population on production of phytoplankton and zooplankton. Does the reduction in numbers of the predators increase or decrease the production of their prey? The first impression would be that when predator numbers are reduced, prey can grow rapidly. However, contrary to the first impression, reduction in predator population actually results in decrease in production of prey (Smetacek 2014). Predators digest and retain the carbon in the prey but excrete most of the macronutrients, like nitrogen and phosphorus, and micronutrients, like iron and zinc (Buskirk and Yurewicz 1998). These nutrients are the input required by the phytoplankton and is called the nitrogen cycle in water (Amin et al. 2012).

Thus, when the predator numbers decline in the oceans, nutrient cycling too slows down. As such, the nitrogen cycle rate decreases. Phytoplankton can grow based only on the fresh input of nutrients from land sources or physical upwelling of nutrients in the oceans. This is one of the reasons for decline in primary production in oceans, and most of this is related to the production of diatom algae (Benoiston et al. 2017).

In the twentieth century, there was an increase in the input of macronutrients into water bodies due to untreated and treated sewage, fertilizer runoff, animal dung, stormwater, etc. Increase in human and farm animal population resulted in increase in the production of sewage and dung. Growth in agriculture and in use of chemical fertilizers, mainly NPK fertilizers, also resulted in a splurge of macronutrients into lakes, rivers, and oceans (USEPA 2022).

Construction of dams across rivers, on the other hand, resulted in the reduction in the flow of water and silt into oceans. Dams divert water from the river to fields for agriculture, while silt is held back. Silt contains silica and micronutrients, like iron, zinc, and the rest. So, reduction in silt inflow in the oceans resulted in the decline in diatom production (Humborg et al. 2000).

6.4 Eutrophication

Eutrophication of coastal waters due to nutrient input from wastewater, both treated and untreated, fertilizer runoff, and stormwater is a major problem. Eutrophication is causing a decline in the amount of carbon sequestered in coastal water. Prevention of eutrophication will help increase quantum of carbon stored in coastal waters. (Jiang et al. 2018).

6.5 Carbon Sequestration in Oceans

How much carbon is sequestered in the oceans and the annual flux have not been quantified in any of the IPCC reports, such as the Report of WGIII AR6—Mitigation of Climate Change or the Report of WG1 AR5 Chapter 5: Changing Ocean, Marine Ecosystems, and Dependent Communities or Chapter 6: Carbon and Other Biogeochemical Cycles. (IPCC 2018).

One way to quantify the gross carbon sequestered on Earth is with reference to the oxygen in the atmosphere. All the oxygen in the atmosphere is produced during photosynthesis. There is no other natural process that produces oxygen on a large scale. UV radiation and lightning may cause some of the water vapor in the atmosphere to split. This releases some oxygen; however, some of it becomes ozone. So, these processes do not have a net impact on the amount of oxygen in the form of O_2 in the atmosphere. The mass of oxygen is ~23% of the total mass of the atmosphere. This is 1,200,000 Gt of oxygen. The ratio of carbon in the organic carbon produced during photosynthesis to the oxygen produced is 1 atom of C to 1 molecule of O_2. So, in terms of mass, it is 12:32, based on the atomic mass of C and O. Thus, for 1,200,000 Gt of oxygen, the carbon in organic carbon on land and oceans is ~450,000 GtC. The IPCC reports do not mention this figure, since no peer-reviewed papers have been published on this subject, and IPCC reports are based entirely on peer-reviewed papers.

The role of trees, especially tropical rainforests, such as the Amazon jungles, in sequestering carbon on land is well-known (Butler 2020). There is, unfortunately, less information and discussion on the role of diatoms in carbon sequestration in the oceans.

6.6 Role of Diatoms in Carbon Sequestration

Growing diatom algae is the best solution to eutrophication. Diatoms consume CO_2 and nutrients like nitrogen and phosphorus, produce oxygen, and are consumed by zooplankton and fish. So, carbon enters the food chain, and oxygen remains in the water, keeping it clean. This is the best solution to eutrophication. Diatoms out-compete the other algae, such as cyanobacteria (blue-green algae) and dinoflagellates (red tides). Therefore, algal blooms are prevented (Marella et al. 2016).

BGA and red tides are not good food for zooplankton and fish, whereas diatoms are the best natural food for these (Mann 1999).

Diatoms play a vital role in regulating the nitrogen cycle in oceans and freshwater bodies (Marella et al. 2016). They are the best feed for zooplankton, such as copepods, krill, etc.; small herbivore fish, such as Clupeidae family of fish, herring, sardines, and menhaden; and all the *oily fish,* such mackerel, anchovies, etc. These small fish are the feed for bigger fish, whales, etc. All animals in water that feed on diatoms recycle silica, nutrients, and micronutrients (Tam et al. 2021). Once biomass increases to a sustainable level, it will sustain itself. So, the cost of growing diatoms in oceans may have to be incurred for 25 to 50 years only.

Growing forests on land is considered a carbon sequestration solution. Similar is growing macroalgae in coastal waters (Fox et al. 2020).

Phrases such as ***Blue Carbon*** and ***Fish Carbon*** have been coined to describe sequestration in coastal waters using mangroves, sea grasses, corals, and growing fish in pens and cages, respectively. Dead diatoms also sink to the depths of the ocean, together with other biological/organic matter, and sequester carbon into the depths. This is called the ***Ocean Biological Pump*** (Honjo et al. 2014). However, growing microalgae/phytoplankton is currently not being considered as a valid carbon sequestration solution.

6.7 Organic Carbon in Oceans

There are no peer-reviewed papers on the estimates of total stock of organic carbon in the oceans. This would include live, dead, and fossilized biomass, i.e., bacteria, phytoplankton, zooplankton, fish, crustaceans, corals/dead corals, whales, hydrocarbons, methane, methane hydrates, etc. (Sigman and Hain 2012).

Gross biomass on land is estimated at ~450 to 600 GtC, by IPCC reports. It may be possible that a similar biomass exists in the oceans.

6.8 Blue Carbon

Growing diatoms in coastal waters keeps it clean, enabling mangroves and sea grasses to grow. Shallow waters are the spawning and nesting ground for fish and amphibians. They lay eggs in the shallow waters, and diatoms are the best feed for the newly hatched fish and tadpoles. Blue carbon is the carbon stored in shallow coastal waters by mangroves, sea grasses, and macroalgae (Macreadie et al. 2019).

6.9 The Way Ahead

The questions that remain are not hard to answer. However, what is required is a thorough research into the world of oceans. These massive water bodies supporting a rich biodiversity, biogeochemical cycles occurring within or out, nutrient transfer, historical peak and its theoretical maximum limit need to be understood in further detail so as to easily comprehend the role of diatoms in increased ocean productivity and carbon sequestration.

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