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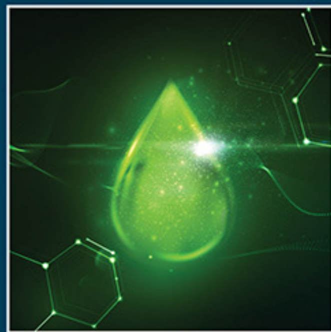

Bioenergy with Carbon Capture and Storage

Using Natural Resources for Sustainable Development

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CHAPTER

6

Role of the ocean in climate stabilization

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6.1 Introduction: the ocean's role in climate regulation

In 2015 world leaders gathered at the end of the United Nations Framework Convention on Climate Change 21st Conference of Parties to sign the most comprehensive and ambitious climate accords in history: the Paris Agreement. Goals set in this landmark climate agreement were based on the findings of the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report (AR5), which summarized current understanding of anthropogenic climate change and its impacts on natural and human systems. Specifically, the 195 signatories would strive to "[hold] the increase in the global average temperature to well below 2°C above pre-industrial levels and [pursue] efforts to limit the temperature increase to 1.5°C above pre-industrial levels" [1]. To this end, parties submitted Nationally Determined Contributions that described their individual capacities to curb greenhouse gas emissions and contribute to climate change mitigation. The Paris Agreement additionally notes "the importance of ensuring the integrity of all ecosystems, including oceans, and the protection of biodiversity" as integral to climate stabilization. The only ecosystem named in this clause is by many measures the most significant player in climate stabilization: the ocean.

The ocean's climatic interactions within the Earth's system are complex. Its high heat capacity and sheer mass make it a leading determinant of Earth's heat balance [2,3]. Unbounded by national borders but nonetheless responsive to societal actions, the world's oceans have absorbed greater than 90% of ($33 \pm 14 \times 10^{22}$ J in the upper 700 m) anthropogenic warming that has occurred during the industrial era [4,5]. As the primary reservoir of this excess heat, the ocean reflects planetary energy imbalances in advance of changes to mean planetary temperature [6]. Levitus et al. [2] examined ocean temperature measurements, concluding that mean heat content of the world ocean increased by $0.4 \times 10^{22} \pm 0.05$ J/year between 1969 and 2008 [2], or about 10 W year/m^2 between 1955

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and 1998, compared with 1 W year/m^2 for the Earth as a whole [7]. Regional heat content in the Atlantic, Pacific, and Indian oceans was found to be increasing by 7.7, 3.3, and 3.5×10^{22} J/year, respectively, between 1955 and 2003 [8]. An average of 85% of heat content was shown to be stored above 750 m within a range of 78% and 91% [6].

By capturing this excess heat, the ocean has buffered society from the full consequences of greenhouse warming. The full climate feedbacks in response to changes in heat content and the global carbon cycle demonstrate a significant time lag; thus many of the effects of increased atmospheric CO_2 concentration from past emissions will likely emerge in the late 21st century, posing challenges to climate stabilization [9]. The inertial persistence of climate impacts even in a carbon-neutral world is referred to as warming *in the pipeline* and depends on heat exchange rates between the surface mixed layer and deep ocean. The level of climate disequilibrium varies regionally; where climate sensitivity is approximately 0.25°C/W/m^2 of forcing, lags can be as short as a decade. In ocean areas that are less well-mixed and have climate sensitivities of 1°C/W/m^2 or larger, this overturning process can take up to a century or longer [6]. Estimates of forcing not yet reflected in the mean global temperature are approximately 0.75 W/m^2 during the first decade of the 21st century. Although detected global warming between 1880 and 2003 was 0.6°C−0.7°C, this average represents only 1 W/m^2 of a total 1.8 W/m^2. An estimated 0.6°C of warming *in the pipeline* was added during this period because of the linked relationship between ocean and atmospheric dynamics. This imbalance of 0.85 W/m^2 is considerable relative to the average over Earth's history [6].

Despite its important role in slowing the effects of greenhouse warming thus far, a changing ocean presents great risks to human society. Anthropogenic warming is linked to thermal expansion of the ocean, which is the leading cause of sea-level rise. This feedback will persist under further warming and, when combined with melting glaciers, ice sheets, and permafrost, sea level is expected to rise by at least 0.5−8 m rise is expected by 2100 [5,10−12]. In addition to low-lying island nations, many coastal megacities, especially those in Asia, might soon be at risk of inundation from sea-level rise [13−16a].

The ocean's capacity to maintain healthy ecosystems is also threatened by anthropogenic greenhouse emissions. As a result of increased uptake of CO_2, the ocean's pH has decreased by 0.1 since the beginning of the industrial era—a value that, because it is on a logarithmic scale, represents a 25% increase in acidity [16b]. This change has already impacted a number of calcifying marine organisms, including many shellfish and planktonic species, especially in high-latitude ecosystems [17]. Combining ocean warming and acidification with other anthropogenic influences, such as overfishing, nutrient runoff from land, and point-source pollution, the ocean's capacity to buffer human society from the consequences of its actions is declining. In some areas, such protection may even be reversed [18]. For example, as discussed later in this chapter, some studies suggest that the ocean's mean rate of heat and carbon uptake may decline or show greater variability under intensified anthropogenic warming [19,20].

Its high heat capacity, depth, surface area, and dynamic mixing allow the ocean to play a critical role in regulating the earth's climate system [21]. The ocean's ability to play this role, however, must be preserved and even enhanced if ambitious climate stabilization targets are to be met. In addition, because natural carbon storage is vulnerable to reversal,

society cannot rely solely on these processes to stabilize the climate system. IPCC projections of warming under the 2°C and 1.5°C stabilization targets assume sophisticated negative emissions strategies to complement emissions reductions. Although a number of such methods and technologies exist, they remain underutilized and often lack the necessary support for research and development. If society hopes to preserve ocean systems, action must be taken swiftly in all sectors. Although the ocean presents society with a number of options that could be used in tackling the climate problem, it also faces acute risks if such actions are not taken. This chapter reviews the ocean's potential role in international climate stabilization, and how its natural processes can be used to further support such actions. Given the breadth of topics covered, sections are meant to introduce relevant strategies and provide the reader with a general understanding of the research that has been conducted to date. They are not intended to be comprehensive reviews of all relevant literature, although many topics introduced here will be covered in greater detail in subsequent chapters. Because the ocean's capacity to serve many functions is at risk in a warming world, this chapter also discusses the consequences society might face if climate stabilization actions are not prioritized globally.

6.2 The ocean carbon sink

In addition to absorbing heat the ocean plays another equally important role in modulating the Earth's climate system by absorbing approximately 40% of society's carbon dioxide emissions. These emissions stem primarily from fossil fuel combustion, cement production, and land-use change, such as deforestation [16b,22,23]. IPCC AR5 estimated the oceanic anthropogenic carbon (C_{ant}) to be 569 Pg $CO_2 \pm 20\%$ at an annual uptake rate of 3.67−11.74 Pg CO_2/year. This represents 50 times more carbon than the atmosphere contains [16b,24]. The ocean's circulation transports carbon from the surface to the deep ocean, where it can be stored for decades to millennia. This system is often referred to as the "solubility pump," which relies on ocean circulation and the CO_2's solubility in seawater for efficient carbon sequestration. It is estimated that this solubility pump has strengthened compared with the preindustrial era [25].

Carbon storage in the lowest layers of the ocean can be weakened and/or overturned, however. In the 1990s, upper ocean overturning circulation intensified, leading to increased outgassing of CO_2, thus weakening the effects of the ocean carbon sink. During the following decade, this process reversed; overturning circulation was dampened, and the strength of the carbon sink was restored [25a]. In the near future, weakened upper ocean overturning may transport larger quantities of natural CO_2 to the deep ocean for storage. However, increased atmospheric CO_2 from human sources will likely weaken ocean ventilation and thus diminish oceanic carbon uptake [25a]. Randerson et al. [9] modeled future ocean contributions to the climate-carbon feedback and found that they increased considerably over time and could exceed terrestrial contributions as early as 2100. They additionally found that ocean carbon's sensitivity to climate change is proportional to changes in ocean heat content. This is primarily a consequence of heat altering transport pathways for anthropogenic CO_2 inflow and solubility of dissolved inorganic

carbon. As a result, oceanic carbon uptake could be reduced by 1211 Pg CO_2, from 5175 Pg CO_2 this decade to 3964 Pg CO_2 as early as 2300 [9].

The rate of oceanic CO_2 uptake is not uniform but rather varies over time and space. The Southern Ocean is understood to be the ocean's most prominent region in anthropogenic CO_2 uptake because of its expansiveness: 30% of total global surface area [26]. Located south of 30°S, the Southern Ocean accounts for approximately 40% of the global ocean's CO_2 uptake [20,27,27a]. Between the 1980s and 2000s, however, a stagnation or even reduction in Southern Ocean CO_2 uptake was observed [20]. Because this ocean region is a dominant site for the surfacing of deep ocean water, it can prove a major source of CO_2 previously stored in the deep ocean [26]. Westerly winds, which are important for ocean mixing, intensified and shifted poleward during the latter decades of the 20th century, contributing to a more positive regional signal of the Southern Annular Mode. This, in turn, resulted in enhanced upwelling of deep ocean waters that contained high concentrations of dissolved inorganic carbon. The addition of this carbon further saturated the Southern Ocean and led to anomalously strong fluxes of CO_2 from the ocean to the atmosphere, reducing the global ocean's role as a net CO_2 sink. Despite this period of reversal, the Southern Ocean's carbon uptake rebounded by 2012, returning to the levels expected based on increased atmospheric CO_2 [20].

Ultimately, it remains unknown how future warming will affect ocean carbon uptake. However, research has underscored the ocean's sensitivity to changes in climate. It is likely that a warming planet will drive changes in ocean circulation that will slow and/or weaken its ability to transport carbon to the deep ocean for storage [28]. In the absence of human influence, carbon fluxes are highly variable and not fully understood. Therefore although it is critical to consider the role oceans play in carbon uptake, their natural processes alone provide unreliable insurance against climate disruption. Humanity is currently benefiting from a reinvigoration of the Southern Ocean's carbon sink; however, under future changes these benefits may be lost, resulting in an accelerated accumulation of atmospheric CO_2 [20]. Although this phenomenon is most pronounced in the Southern Ocean, given its preeminence in carbon uptake, other regions of the ocean face similar threats. Persistent uptake of atmospheric carbon will most likely remain the ocean's most important contribution to climate stabilization; therefore threats to this uptake capacity will require further research and, where possible, intervention.

6.3 Ocean fertilization

In recent decades, ocean fertilization has featured prominently in the debate over "geoengineering"—manipulating Earth processes for large-scale climate intervention [25]. Climate intervention refers to a suite of actions taken to stabilize the Earth's climate system. It has received greater attention in recent years with the realization that cutting emissions alone cannot stabilize climate below 1.5°C or 2°C above preindustrial levels [29,30]. Carbon dioxide removal (CDR) is an increasingly popular method of climate intervention that, as the name suggests, removes carbon from the atmosphere for utilization in materials or for storage in deep geological formations [13]. Since 1750, human activities, especially fossil fuel combustion and cement production, have led to emissions of over 400 Gt of

carbon. Of fossil fuel emissions, over half are attributed to the period from the late 1980s through present day. In 2014 alone, a record-breaking 10 Gt of carbon were emitted, representing a 0.8% increase from 2013 emissions. Reducing atmospheric carbon dioxide concentration after decades of intensive emissions will be no mean feat. Drawing down the concentration at a rate of 1 ppm/year would require removal and storage of about 18 Gt CO_2/year. At the larger scales necessary for high-impact climate intervention, drawdown of CO_2 by 100 ppm would rely on removal and storage of close to 1800 Gt CO_2—approximately equivalent to all anthropogenic CO_2 emissions from 1750 to 2000 [30a].

Beginning in the 1990s, studies have examined the potential for human manipulation of natural ocean processes to maximize uptake and long-term storage of carbon. The primary means for natural oceanic carbon uptake are the "solubility pump," which relies on ocean circulation and the solubility of CO_2 in seawater as discussed in earlier sections, and the "biological pump," which relies on phytoplankton primary production and export of particulate organic carbon (POC) to the deep ocean (Fig. 6.1) [29]. In much of the global ocean, biological productivity is limited by nutrient availability, especially in the euphotic zone where sunlight is in sufficient supply [25]. In particular, phytoplankton growth requires macronutrients, such as phosphate and nitrate, which typically occur at relatively high concentrations in the global ocean, and micronutrients, such as iron and zinc, which typically occur at much lower concentrations [31]. These nutrient constraints on the biological pump have led some scientists to recommend nutrient additions as an intervention to enhance primary production and the export of POC to the deep ocean.

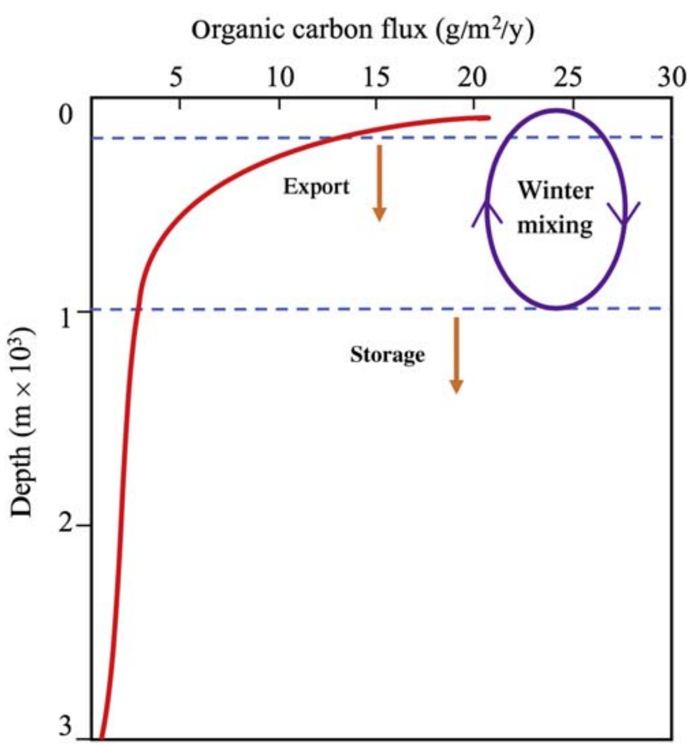

FIGURE 6.1 Organic carbon flux as a function of ocean depth. Carbon storage becomes more secure with depth, especially below mixed layers. Source: *Adapted from R.S. Lampitt, E.P. Achterberg, T.R. Anderson, J.A. Hughes, M.D. Iglesias-Rodriguez, B.A. Kelly-Gerreyn, et al., Ocean fertilization: a potential means of geoengineering? Philos. Trans. R. Soc. London, Ser. A: Math. Phys. Eng. Sci., 366 (1882) (2008) 3919–3945, which draws on Martin, J.H., Knauer, G.A., Karl, D.M., Broenkow, W.W., 1987. VERTEX: Carbon cycling in the northeast Pacific. Deep-Sea Res. A 34 (2), 267–285.*

Scientists have been especially interested in exploring the potential of ocean iron fertilization in the high-nutrient low-chlorophyll (HNLC) areas of the global ocean. In these HNLC regions, including the subarctic and equatorial Pacific Ocean, as well as the Southern Ocean, iron has been found to be the limiting nutrient, and its addition can induce diatom-dominated phytoplankton blooms. If a significant fraction of these diatom blooms sinks into the deep ocean as large, carbon-rich particles, then this export of organic carbon can lead to carbon sequestration on decadal to millennial timescales [32]. Long-term sequestration potential is critical if CDR options are to be pursued, and the [33] synthesis report notes that carbon removed must remain out of contact with the atmosphere for a century or longer to be effective in reducing anthropogenic warming [33]. To be most effective, the POC must settle below winter mixing depths (Fig. 6.1) [25].

Ocean iron fertilization may show promise for increased carbon sequestration, transporting carbon to depths below 1000 m for storage of up to centuries. Models of the Southern Ocean indicate a potential for sequestration of up to 367−826 Gt CO_2, or 50 to just over 100 ppm of atmospheric CO_2, under business-as-usual IPCC projections [33a]. Based on existing models, it is likely this would only amount to 1 GtC/year and thus would not meaningfully contribute to meeting the Paris climate stabilization goals [29]. Model patchiness and variable output also leave questions about how effective such actions would prove to be [33a]. Finally, in order to maintain drawdown, the entire Southern Ocean would need to be fertilized with large quantities of iron (and other limiting nutrients, such as zinc and silica)—in perpetuity. The investment required for such an undertaking—in human, infrastructural, and financial capital—makes fertilization unrealistic for long-term climate action [29].

In addition to its potentially limited benefits, ocean iron fertilization poses a number of risks. Large-scale alteration of primary production in any large marine ecosystem has the potential to affect higher trophic level species in that ecosystem and other downstream ecosystems. In particular, changes to phytoplankton communities can have direct consequences for nutrient cycling, light penetration, zooplankton grazing, and the availability of organic material to benthic systems [32]. Because ocean ecosystems are often highly connected, such changes can spread via advection to downstream ecosystems, even ones quite distant from the site of fertilization [34]. These impacts as might be expected are shown to be strongest in ocean regions with naturally low productivity [32]. Certainly, large influxes of any nutrient can and usually do have broader impacts. Field experiments of iron fertilization show differing effects from nitrogen or phosphorus fertilization [25,34]. Although additional research may prove useful in understanding potential benefits and risks, the National Academy of Sciences concluded that conducting ocean iron fertilization at the scales necessary to stabilize the climate system poses more risks than benefits. As a result, many scientists have excluded ocean fertilization when discussing the ocean's current and future roles in mitigating climate change [34a].

6.4 Storage of terrestrially captured carbon in deep ocean

Many scientists point out the potential of land management for enhanced carbon uptake. Certainly, strategies such as reforestation, afforestation, and improving

agricultural practices are important to climate stabilization. However, terrestrial carbon sinks may pose higher risks than their marine counterparts. Despite terrestrial biomass being a dominant reservoir for carbon storage, this reservoir can be easily drained [35] as fire, respiration, decomposition, and changes in land management can quickly release stored carbon back into the atmosphere [13,36]. Practices must be maintained over the long-term for such strategies to be effective, and even so are vulnerable to unexpected events. In addition, warming temperatures may reduce or possibly reverse aboveground carbon sequestration, especially in urban forests [37]. Under intensified climate change, rates of photosynthesis may decrease while rates of forest die-back and fire risk increase. As a result, terrestrial carbon uptake may become an increasingly less reliable approach to achieve sequestration goals [38].

While their reliability for long-term carbon sequestration is uncertain, terrestrial ecosystems are often easier to manage than marine ecosystems. Effective strategies for carbon drawdown could link terrestrial and marine processes, such as storing terrestrial biomass in the ocean. This would entail compacting biomass from land and sinking it into the deep ocean in areas of low oxygen. If the return time of the carbon from this sunken biomass is sufficiently long, comparable to the residence time of CO_2 in the atmosphere, then long-term storage is achieved [38a,b]. Dead and dying biomass would be good candidates, as they would otherwise off-gas stored CO_2 during decomposition. In particular, management practices might target agricultural waste and forest residues [13]. If combined with alkalinization techniques, described later in this chapter, ocean storage potential could be greatly increased. Adapting methods in this way could also help counter ocean acidification [34a].

As discussed in earlier sections, the deep ocean may be an effective storage site for carbon. However, the deep ocean hosts a diversity of life sensitive to environmental change that is poorly understood compared with benthic systems. Research suggests, however, that these ecosystems may be more sensitive to disturbance and slower to rebound than their shallower counterparts. Already, a number of deep-sea fishes meet International Union for Conservation of Nature criteria for “critically endangered” classification, and are challenged in recovery by late maturation, low fecundity, slow growth, and longevity [39,40]. Loading deep ocean ecosystems with nutrients, as discussed in previous sections, would likely have repercussions, which may be long-lasting, such as depleted oxygen availability, changes to species composition and richness, physiological processes, among others [25,40a]. Mass carbon storage in deep-ocean sediments from terrestrial sources could pose threats to deep-ocean life, even if unaccompanied by the influx of other nutrients. Given the lack of understanding of such impacts—not only on deep-ocean life but also the systems they interact with, including those closer to and at the surface—there is great need for further research before mass-scale deployment of such strategies.

6.5 Microalgae: biofuels, nutrition, and negative emissions

Marine microalgae can assist in advancing the goal of climate stabilization while simultaneously addressing the challenges of energy, food, and negative emissions [41,42]. Humanity currently relies on fossil fuels for approximately 80% of its energy use [43].

Although the share of fossil fuels in global energy portfolio is projected to level off and then fall as electrification of the light-vehicle fleet expands and renewable sources of electricity proliferate, the IPCC has reported that the rate of substitution is insufficient. In order to achieve global decarbonization and limit global warming to "well below 2°C" compared with preindustrial averages, the energy transitions required by 2040 must be accelerated considerably [44]. If current rates of population growth and energy demand continue on their current trajectories then global energy use could increase by up to 80% by 2050, committing the planet to catastrophic warming if fossil emissions are not curtailed [45]. The 2018 IPCC special report on 1.5 degrees projects that at current rates of energy consumption, the world will exceed 1.5°C and possibly 2°C thresholds by 2040 [44].

Eventually, society may actualize a global transportation sector that does not rely on liquid fossil fuels; however, this transition will more than likely be phased. Oil represents approximately 90% of the global energy mix for transportation [46]. The light-vehicle subsector is expected to continue rapid electrification, which will ease reliance on fossil fuels. This electricity will increasingly be sourced from alternative energy systems that already exist and are capable of meeting electric and light-vehicle fuel needs [47]. However, no such viable alternative exists for the heavy-vehicle, shipping, and aviation subsectors. Thus they will rely on energy-rich liquid fuels into the foreseeable future. Liquid fuels that are fossil carbon neutral are necessary [41,42]. The contributions of these transportation subsectors to total CO_2 emissions are projected to increase from 6% to 40% by 2050, representing a serious threat to climate stabilization efforts. The markets for such fuels (over 8 billion tons per year) and relevant infrastructure are considerable, presenting an exciting economic opportunity. In addition, these fuels may be used as back-up energy sources for renewables-powered electric grids, which can be intermittent according to time of day, weather patterns, etc. [48]. Recent studies have shown that algal biofuels have the potential to meet the existing global transportation fuel demand. By expanding algal biofuel production to cover approximately 1.92 million km^2, equivalent to around 21% of US land area, 100% of global liquid fuel needs, as of 2015, could be met [41,42].

In addition to alternative energy sources, sustainable sources of nutrition will be necessary for a growing population. Projections estimate that by 2050, the planet may be home to almost 10 billion people [49]. This will pose a greatly increased demand for food production, and, based on current agricultural practices, substantial growth in the requirements for arable land and freshwater. Research points to the deleterious effects of commercial agriculture, especially animal agriculture. A report found that the world's five leading dairy and meat producers are responsible for greater greenhouse gas emissions than the oil-giants Exxon, Shell, and BP [50]. Despite a growing share of global GHG emissions, animal products only represent 37% of global protein and 18% of total caloric intake [50a]. As global consumption trends increasingly mirror those of the United States, especially in rapidly developing countries, intake of animal-based protein may rise from 25.5 kg per person in the late 1990s to 37 kg by 2030 [51]. Barring drastic changes to all stages of production, such growth could lead to significant increases in global emissions [50a]. Perhaps equally important to sustainable fuels is the need for scalable protein production that aligns with sustainable land- and water-use practices. Here, too, large-scale production of marine microalgae could contribute to climate stabilization. As discussed above, global liquid fuel needs could be met with 1.92 million km^2 of marginal land for

algae "farming." Biofuel production at this scale is estimated to jointly produce 2.40 Gt of protein [42], which would more than meet current protein demand for the global population. It would also likely meet total future protein demand given population projections to 2050 [49,52,53]. Already, 24 million tons of algae (mainly macroalgae) are farmed globally, representing a $7.5 billion enterprise [52]. Commercially viable opportunities for scaling up the production of microalgae for commodity nutritional markets, either for animal- and aqua-feeds or for direct human nutrition, already exist [53a,54]. This alternative approach to food production has a much smaller footprint, in terms of arable land and freshwater, providing a more environment friendly and sustainable source of nutrition for the world's growing population[41,52,55].

A third potential contribution of large-scale microalgae production to climate stabilization comes in the form of a novel approach to bioenergy carbon capture and storage (BECCS). Recent reports make clear that carbon-neutral energy alternatives and emissions reductions will be insufficient to prevent a warming of greater than 1.5°C or 2°C [1,44]. The recent IPCC special report on achieving the 1.5 °C climate stabilization target [44] heavily underscored the need for negative emissions technologies and resource management methods that remove carbon from the atmosphere [13]. BECCS has become popular among IPCC modelers and policymakers as a means for achieving negative emissions. However, at the large scales needed to drawdown sufficient amounts of atmospheric CO_2, BECCS becomes a major competitor with agriculture for land, freshwater, and nutrients. Given these demands, BECCS may also impact biodiversity, making surrounding social and natural systems less resilient to anthropogenic change [54]. Because of their high rates of primary productivity, marine microalgae can alter the BECCS framework and greatly diminish the requirements for arable land and freshwater [41,56,57]. Beal et al. [54] developed a model to explore the potential benefits of algae with BECCS, or what the authors called algal-based biomass energy with carbon capture and storage (ABECCS).

The modeled ABECCS system had a total areal extent of 2800 ha and included a 2680-ha, purpose-grown eucalyptus forest on land that was formerly soy cropland, a combined heat and power electricity generation plant, an amine-based carbon capture and geological sequestration system, and a 121-ha advanced algae production facility that utilized the captured CO_2. The analysis was not geographically explicit but rather assumed the colocation of algae production and suitable geologic storage with a BECCS facility. Model results from this ABECCS system were promising. The 2800-ha integrated eucalyptus, algae, and combined heat and power system with carbon capture and storage yielded a comparable amount of protein, ~2770 t/year, as the soy produced from the same 2800 ha, while simultaneously generating 61.5 TJ of electricity and producing negative emissions of 29,600 t CO_2/year. More energy was generated than consumed, while the freshwater footprint was roughly equal to that for soy. Roughly two-thirds of the biogenic carbon contained in eucalyptus biomass was available for geological sequestration, even after providing the CO_2 required for growing the algae. Commercial viability could be achievable for realistic prices of algae-based aquafeeds, electricity prices, and carbon credits. Finally, a sensitivity analysis demonstrated that significant reductions to the cost of negative emissions were possible; especially if eucalyptus and algal productivity rates could be increased, the cost of biomass could be decreased, and/or the algae cultivation costs could be decreased [54].

The IPCC special report on achieving the 1.5°C climate stabilization target [44] specified that in order to meet climate stabilization goals without overshoot, CDR of up to 1000 Gt would be required over the 21st century. As a thought exercise, installation by 2025 of the modeled ABECCS infrastructure scaled up to remove the entire 1000 Gt CO_2 in 75 years would require ~12.6 million km^2 of land, slightly less than the land areas of China and India combined. Of this total land area, 544,500 km^2 would be cultivated with algae and the remaining, approximately 12 million km^2, would supply the required terrestrial bioenergy. This staggering amount of land is consistent with the requirements of any BECCS system, and while ABECCS offers the benefits of simultaneous protein production, it is unlikely to be the silver bullet solution to climate stabilization.

Solutions that simultaneously address the nexus of energy, food, and negative emissions are critical to climate stabilization but remain largely unexplored. Despite a growing body of research, detailed investigations of algal production for fuels, food, and negative emissions are lacking for future energy and nutrition scenarios. In order to capitalize on the potential benefits of large-scale algae production, including ABECCS, investment in research and development is needed. Scaling up and commercialization of marine microalgae production for commodity markets will be an essential first step in enabling this technology's contribution to climate stabilization.

6.6 Artificial ocean alkalinization

CO_2 is naturally extracted from the atmosphere and stored via weathering reactions that bind carbon in its mineral phase [24,48]. These reactions with Mg- and/or Ca-rich minerals usually take centuries or millennia, so the natural processes are not immediately useful in drawing down anthropogenic carbon from the atmosphere. However, the reactions can be accelerated artificially to occur on timescales from hours to months. The majority of CO_2 emitted to the atmosphere will dissolve in ocean water as bicarbonate ions and ultimately be transported to the sea floor as carbonate sediments. The transition between these states relies on carbonate and silicate weathering reactions that occur in soil or ocean sediments. One proposed form of CDR draws on this process, accelerating weathering reactions to store CO_2 in the ocean [13]. Artificial ocean alkalinization (AOA) refers to adding alkaline substances to surface seawater, enhancing CO_2 uptake and reversing ocean acidification. The process weathers minerals through chemical reactions that raise concentrations of carbonate ions while reducing concentrations of hydrogen ions. These reactions occur naturally and have been critical to modulating Earth's climate. They function on geological timescales but can be sped up artificially to aid in near-term climate action [58]. Alkaline materials necessary for this CDR method are usually extracted from terrestrial minerals or synthetic chemical sources. Some ocean materials, such as waste shells could also be compelling candidates [34a]. Natural biological and physical processes distribute mineral dissolution products, a large portion of which are transported to coastal areas and the open ocean. The influx of bicarbonate increases alkalinity in these systems, thus partially counteracting ocean acidification and aiding in stabilization of the ocean's carbonate chemistry. In addition to bicarbonate, elements such as silicon, phosphorus, and potassium would be released. These elements could enhance biological productivity, thus contributing to

greater atmospheric CO_2 removal [34a,58a]. In many cases, weathering reactions yield rapid, near-complete conversion from CO_2 to carbonate minerals [48]. Dissolved inorganic carbon has an ocean residence time of 100,000−1,000,000 years so are considered "permanent" solutions [24].

Using an Earth system model that includes climate-carbon feedbacks, Lenton et al. [58] estimated global potential for AOA under different emissions pathways. Under the fixed addition of 0.25 Pmol ALK/year, AOA weathering led to reduced atmospheric CO_2, reduced ocean acidification, and cooler global mean temperatures for the period 2020−2100. Global emissions reduction proved important in parallel with AOA. Under representative concentration pathway (RCP) 8.5, AOA was able to reduce atmospheric carbon concentrations by 16%; however, given the magnitude of the emissions and warming, it had a small impact on climate stabilization. Under RCP 2.6 (low-emission scenario), however, AOA only drew atmospheric CO_2 down by 58 ppm (roughly 60% of levels under RCP 8.5) but was successful in aiding the return to 2020-level mean temperatures and ocean pH by 2100. The relative success of AOA under a low-emission scenario emphasizes the importance of rapid emissions reductions to complement negative emissions strategies.

Alkalinization is another method that can integrate terrestrial and marine CDR. Agriculture, especially on an industrial scale, routinely requires application of fertilizer and lime. Therefore annual application of weatherable minerals (e.g., basalt) is feasible using existing farm equipment, even at large scales. Mass additions of these substances could greatly enhance soil-based weathering, the products of which are often transported to the ocean via aquifers. In addition to accelerating soil uptake of carbon, basalt could additionally restore degraded soils, adding financial incentives for farmers. Although fast-weathering, olivine-rich minerals have many benefits, experiments indicate they can rapidly release bioavailable nickel. Large additions of this element to soils can suppress calcium uptake in plants and introduce harmful metals into food and ecosystems. It may therefore be more advantageous to use limestone for weathering purposes, which does avoid most of the associated risks. However, regardless of which mineral is used, particles that are produced often get washed into the ocean. Although carbonate mineral storage is advantageous in the ocean given its residence time, increased concentrations may also increase turbidity and sedimentation, which could adversely affect marine ecosystems [24].

Terrestrial-marine CDR methods, such as agricultural liming, remain in progress but hold great promise. Another method undergoing research and development is direct ocean capture (DOC). DOC aims to separate CO_2 from ocean brines using CO_2-brine membranes and/or ocean alkalinity enhancement. As with other forms of weathering and mineralization, these processes produce carbonate minerals as byproducts, which could be incorporated into sediments or used as building materials. However, for these methods to be effective, novel deployment strategies are needed, such as separation reactors, which prevent microbial biofouling on technological components. In addition to providing timely contributions to climate stabilization, techniques that directly separate CO_2 from seawater may also present solutions to ocean acidification [48]. Overall, enhanced weathering solutions require additional research, especially on their potential negative consequences. Alkalinization in the ocean may be promising when combined with emissions reductions and could be paired with terrestrial, soil-based weathering. To reiterate a major point of

this chapter the ocean's contributions to climate stabilization are most likely to be effective when a variety of different strategies operating on different geographical and time scale are considered.

6.7 Ocean thermal energy conversion and other ocean-based renewable energy sources

The ocean holds great potential for renewable energy production given its natural temperature gradients. Technological advances are making ocean energy increasingly viable compared with its terrestrial counterparts, which have traditionally attracted greater investment. Of ocean-based renewable energy, Ocean Thermal Energy Conversion (OTEC) may offer the ocean's greatest potential contribution. Basically, OTEC relies on the ocean's storage of solar energy in the form of heat, which produces thermal gradients. OTEC plants draw warm water from the surface and cooler water from greater depths and then pass them through water condensers and heat exchangers. This process drives a turbine that produces electricity [58b]. A closed-cycle OTEC plant relies on warm water of about 25°C (77°F) to vaporize a working fluid, usually ammonia, which has a lower boiling point than water. Open-cycle OTEC plants using water as the working fluid have been tested but are considered less efficient. As the working fluid expands, it turns the turbine responsible for electricity generation. The cooler water, about 5°C (41°F), then condenses the vapor to return it to its liquid state for reuse in the cycle. In addition to producing electrical energy, OTEC technology can synergistically produce nutrients for aquaculture as well as freshwater. It also can be used in seawater cooling systems to air condition buildings and greenhouses [58b,59]. OTEC systems are constrained by the available temperature gradient. Because the technology's efficiency depends on a steep, year-round temperature gradient between the warm surface waters and cooler deep waters, OTEC is only considered viable in tropical regions. While OTEC has this inherent geographical limitation, there is a great need for reliable, renewable energy access throughout the tropics [60]. In these areas, OTEC shows great promise in producing electricity. However, the system's energy conversion efficiency is quite low [59]. Despite a low theoretical Carnot efficiency (~6%–8%), OTEC takes advantage of a vast, consistently available resource that is not consumed by the system but rather cycles through it. Therefore OTEC is potentially scalable to meet local, national, and even global needs [61].

As with most renewable energy sources, OTEC may pose risks to adjacent ecosystems. Notably, discharge water from OTEC is generally cooler, denser, and higher in nutrients than the surface waters it is released into. It is unclear what effects, if any, this might have on near-shore ecosystems and the marine life that inhabits them [62]. Similarly, the water entering OTEC plants is typically treated with chlorine. For US plants, discharge is regulated by standards outlined in the Clean Water Act; in other countries, discharge would be held to standards defined by similar legislation. Although OTEC discharge may pose some negative environmental impacts, the benefits of this technology are still thought to exceed its potential risks. OTEC's estimated capacity for baseload energy production is between 3 and 5 TW—about twice the current global demand for electricity. Given the efficiency of near-shore circulation, OTEC will

likely have limited ecological repercussions compared with energy sources such as hydropower [62]. In addition to energy production, offshore OTEC may present opportunities for negative emissions. Using an H_2 energy carrier, CO_2 can be converted to ocean alkalinity, which could counteract ocean acidification [58b]. Negative-emissions OTEC (NEOTEC) remains in research stages; therefore it is not yet deployable. However, models indicate that for every gigawatt of continuous electricity produced by NEOTEC, up to 13 GW of heat could be transported from shallow to deep water, and up to 5 Mt of CO_2 removed from the atmosphere per year [58b].

Although OTEC variants show the greatest potential for energy production at low ecological risk, other ocean-based methods of energy production exist—some of which are already being deployed. Included in these are ocean tidal, osmotic, and wave energy sources [63]. Potential energy production estimates for these innovative technologies are approximately 800 TW h for tidal energy, 2000 TW h for osmotic energy, and somewhere between 8000 and 80,000 TW h for wave energy. Together with OTEC, ocean-based renewable energy could exceed current and likely even future global demand for electricity [61]. Despite demonstrating immense potential to meet global energy demands, these technologies will require further research and development for large-scale deployment.

6.8 Coastal ecosystem services and conservation priorities

Vegetated coastal ecosystems cover less than 0.5% of seafloor but are highly productive [64]. Coastal ecosystems store large amounts of carbon in their sediments, soils, living biomass aboveground and belowground, and nonliving biomass [65]. In particular, seagrass, tidal marsh, and mangrove ecosystems are important for carbon sequestration, earning them special recognition as "blue carbon" sinks. Together, these blue carbon ecosystems span approximately 490,000 km^2 and provide a variety of ecosystem services, including providing nursing grounds for fisheries, protecting coasts from erosion, and filtering out pollutants. In the short term (decadal to centennial timescales), this carbon is stored in biomass, and in the long term (millennial time scale) in sediments [66]. Unlike terrestrial sinks, which are prone to reversal, carbon can be fixed securely in large quantities [65]. Blue carbon ecosystems cover one to two orders of magnitude less area than terrestrial forests but contribute much greater long-term carbon storage per area [67]. This has led many scientists and practitioners alike to promote blue carbon management as an effective negative emissions strategy. Although restoration of these ecosystems is important, their total carbon sequestration potential remains quite low relative to global needs. Degradation and loss of coastal wetlands leaves estimates of their contributions as low as 0.13 Gt CO2/year. Current and future management of these areas could increase this capacity, however [68]. Therefore although this should remain a conservation priority for the varied ecosystem services offered by vegetated coastal systems, they cannot be relied upon for large-scale climate stabilization.

Total blue carbon storage is difficult to measure. Despite uncertainty, a number of studies present estimates. Together, blue carbon sinks likely store approximately 1.5 Gt carbon per year globally [66,69−72]. Human activities pose risks to blue carbon sinks,

often reversing the carbon storage process [73]. Each year, destruction and degradation of these ecosystems release approximately 0.15−1.02 Gt of CO_2. The United Kingdom, for comparison, emits approximately 0.45 Gt CO_2/year. The decline of these ecosystems results in an estimated US$6−42 billion in global economic losses. Compared with terrestrial analogs, emissions are roughly 3%−19% of those from global deforestation annually despite only covering 2%−6% of tropical forest area [74]. In addition to direct human threats, such as coastal development, blue carbon ecosystems are also endangered by climate change impacts. Mangrove forests and saltmarshes are particularly sensitive to sea-level rise. Modeling indicates that 50 cm of sea-level rise by 2100 could lead to a 46%−59% reduction in coastal wetland area, and up to 78% under an 110 cm rise [75]. Seagrass meadows are vulnerable to ocean warming itself, as seagrasses rely on stable thermal regimes. In tropical and mid-latitude waters, seagrass assemblages may decline in diversity, geographic extent, and overall health [76]. Conservation and restoration of blue carbon sinks may be the most cost-effective negative emissions strategy of all marine and terrestrial options. Although coastal blue carbon can play a minor role in climate stabilization, its effects are mainly local and regional in scale. Taillardat et al. [77] estimate that blue carbon ecosystems only sequestered the equivalent of 0.42% of global fossil fuel emissions in 2014. This low value is primarily due to the limited geographic extent of suitable habitats for coastal vegetation. While expanding blue carbon ecosystems within their geographic range should remain a priority, it must be emphasized that blue carbon storage will play a small role on a global scale [77].

An ecosystem's worth cannot and should not be solely determined by its potential to capture and store carbon. Marine ecosystems—and indeed, ocean systems more broadly—are vital for human wellbeing. The ecosystem services they provide range from fisheries for food and livelihood to cultural and religious significance [78]. Coral reefs and high-latitude ecosystems, especially those in the Arctic, face the gravest threats under climate change, both in severity and imminence [34a,78]. The potential loss of coral reefs poses serious threats to the many ecosystems that maintain synergistic relationships with reefs, as well as to human society. For example, coral reefs play a significant role in sheltering lagoons from wave action and thus facilitating the growth of seagrass meadows. As sea-levels rise, deepening water over corals could allow high-energy waves to pass into lagoons, threatening seagrass ecosystems [79]. Arctic ecosystems face similarly dire threats, especially those that are dependent on sea ice. Arctic sea ice is rapidly decreasing in areal extent, volume, and cohesion, denying biota the critical resources of shelter, nutrition, and mating habitat that they have evolved to use [80].

Although climate change threatens all marine ecosystems, some are inherently at greater risk than others. Limited management resources and policy bandwidth should focus on those ecosystems with the highest present-day risk, so as to preserve global biodiversity. In addition, blue carbon stores should be prioritized in the short term. Other ecosystems will face increasing climate pressures and should be incorporated into long-term planning. Many ecosystems, especially coastal systems, present a number of cost-effective solutions to anthropogenic climate stabilization. Ecosystems such as mangroves and salt marshes contribute to the health of connected ecosystems and provide coastal populations with services, such as storm-surge protection and erosion-hardy coasts. They are also efficient systems for capturing and storing atmospheric carbon. In sum, reforestation and

TABLE 6.1 Overview of potential ocean-based climate solutions is discussed in this chapter. Carbon storage potential is provided where data exist. Associated cobenefits, limitations, and risks are also compared.

Method	CO_2 sequestration potential range	Cobenefits	Limitations	Risks
Ocean fertilization	367–826 Gt		• Primarily applicable in the Southern Ocean (limited efficacy elsewhere) • Requires constant maintenance to avoid resurgence of "stored" carbon • High associated costs for low carbon sequestration potential	• Nutrient loading in coastal and open ocean ecosystems • Fisheries decline and loss of associated livelihood • Limited availability of sunlight and organic materials for benthic systems
Terrestrial carbon storage in deep ocean	Unknown			• Disturbance of deep ocean ecosystems
ABECCS	2.9 Mt per facility	• Liquid fuel for heavy transport sectors • Sustainable protein-rich food and/or aquaculture feed • Does not compete with agriculture	• Optimized for regions with ample sunlight • High initial financial investment	• May have limited impacts on biodiversity
Enhanced weathering	Upwards of 660 Gt	• Counters ocean acidification	• Has little effect for climate action under high emissions pathways (requires deep global emissions cuts to be an effective strategy)	• Unknown
OTEC	5 Mt/GW of continuous electricity	• Renewable energy production • Passive cooling	• Optimized for tropics • High initial financial investment	• May have limited impacts on biodiversity
Blue carbon	0.13 Gt/year	• Shoreline protection • Biodiversity conservation • Storm-surge buffer	• Potentially little effect on global atmospheric carbon levels	• Carbon storage potentially reversible

afforestation of coastal vegetation present many cobenefits and are readily available for carbon storage when compared with the other ocean-related strategies for climate stabilization that have already been discussed. On a regional scale, protecting blue carbon makes sense even if its contribution to climate stabilization on a global scale is quite limited.

6.9 Conclusion

The methods reviewed in this chapter have received considerable attention during recent years as prospective ocean-based contributors to climate stabilization. Table 6.1 provides an overview of the potential benefits and risks associated with the methods discussed. However, it is important to note that these methods do not represent a complete list of potential ocean-based solutions. It may be easy to look at such a summary and conclude that society should divert resources to a solution with the greatest carbon sequestration potential. Certainly, the models from which these numbers are derived should help guide policy and management. However, no single ocean-based solution will provide a silver bullet for large-scale climate stabilization. Rather, the selected methods described in this chapter should be viewed as new, and potentially negative emission wedges, in the climate stabilization pie [81].

Beyond limitations, such as regional climate, physical geography, and policy landscapes, a diversified climate stabilization portfolio can often overcome a number of potential obstacles, including investment risk, market fluctuation and volatility, and risk of damage (i.e., by natural disaster) [82]. For example, ABECCS might be paired with blue carbon restoration in coastal regions. Combinations of "engineered" and "natural" solutions are especially important, because they are often vulnerable to different environmental and market forces [13]. In the example presented, ABECCS can rely on supportive economic and political landscapes. Although ecosystem restoration also involves policy, it presents additional economic incentives beyond carbon sequestration, such as coastal buffering. Blue carbon is at greater risk of carbon storage reversal where properly implemented negative emissions technologies, such as ABECCS, may not be [48]. Some solutions, such as ocean fertilization, may offer opportunities for enhanced oceanic uptake of carbon but pose risks that are too great by many standards [25,29]. The onus for presenting these risks along with the potential benefits to policymakers should fall to researchers as well as environmental and resource managers. It is also important to consider the upper and lower bounds of potential carbon sequestration and other forms of climate change mitigation. For example, although ocean fertilization could store as much as 826 Gt of atmospheric CO_2, it could also store significantly less. Taking such ranges into account through sensitivity analyses is especially important for risk assessment. Methods that pose serious risks to natural and human systems may benefit from further research. However, it is unlikely that their deployment should be counted on in developing climate action plans. For this reason, many scientific and policy circles have recommended that methods, such as ocean fertilization, be put to rest. They argue that instead of allocating resources to high-risk methods, low-risk alternatives should be emphasized [48].

It is also important to note that although the ocean is a global resource, its use in climate stabilization will require local policy support and financial investment. For example, OTEC is most viable for renewable energy production in the tropics. Therefore nations with tropical coastlines will need to make necessary adjustments to support the growth of OTEC and similar technologies. However, many countries best suited for such development may lack the necessary financial resources. The global need for climate action should compel wealthier nations to support such efforts in less developed regions. Institutions such as the Green

Climate Fund (GCF) will be indispensable. Government and industry contributions to climate action through democratic agencies, such as the GCF, can promote equitable access to resources. They can also enable knowledge-sharing for high-impact climate action and increase the likelihood of meeting the Paris global climate targets [83]. Most of the technologies to harness ocean-based processes for climate stabilization, as described in this chapter, already exist. Many may benefit from greater research and development; however, a number of these approaches can and should be implemented expeditiously. As existing solutions are being applied, new approaches are being created to supplement them. At all stages of deploying ocean-based methods for climate stabilization, it will be critical to consider the impacts they may have on marine ecosystems. These delicate ecosystems play important roles in climate modulation, as well as their other services to society; therefore they must be protected. And, finally, it should be noted that an ecosystem's capacity for carbon sequestration should not be the sole factor in prioritizing its conservation. Indeed, the ocean's ecosystems and biodiversity are worthy of conservation for their inherent value and beauty, as well as the essential services they provide to society.

Acronyms

ABECCS algal bioenergy carbon capture and storage
AOA artificial ocean alkalinization
AR5 Fifth Assessment Report (of the Intergovernmental Panel on Climate Change)
BECCS bioenergy carbon capture and storage
CDR carbon dioxide removal
DOC direct ocean (carbon) capture
GCF Green Climate Fund
HNLC high-nutrient low chlorophyll
IPCC Intergovernmental Panel on Climate Change
NEOTEC negative-emissions ocean thermal energy conversion
OTEC ocean thermal energy conversion
POC particulate organic carbon
RCP representative concentration pathway

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