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The Environmental Impacts of the Carbon Dioxide Problem on Coral Reefs

Introduction

Presently, our world runs on fossil fuels, producing massive amounts of carbon dioxide and other gases trapping heat in our atmosphere, termed greenhouse gases, which cause atmospheric temperatures to rise. Fossil fuels, industrial processes, and land-use are all sources of anthropogenic—or human-caused—greenhouse-gas emissions, which negatively impact human and environmental health (Doney et al., 2020). The presence of greenhouse gases in the atmosphere is natural, but their rapidly increasing rates of production are not. About 10 billion metric tons of carbon are emitted into the atmosphere per year, with an annual increase of 0.5% (Doney et al., 2020). Today's growth rate of carbon dioxide is unprecedented in the history of the last 55 million years, and the amount of carbon dioxide in our atmosphere is almost 50% higher than were preindustrial concentrations (Doney et al., 2020). This means our current atmospheric carbon dioxide levels are the product of an accelerating emission rate caused by human activity, with known and unknown consequences for the environment.

Why the focus on carbon dioxide? It is one of the most abundant greenhouse gases in the atmosphere, with a wide range of environmental effects. This is partially due to the fact that it is used and involved in natural processes. An imbalance in the level of carbon dioxide present in an ecosystem can disrupt the ecosystem itself, in a variety of ways. The ocean, especially tropical marine ecosystems, have felt and will continue to suffer from an elevated atmospheric carbon dioxide level.

Historically, the ocean has acted as a natural cooling agent, absorbing atmospheric carbon dioxide and thus cooling the atmosphere. In the past 200 years, the ocean has soaked up one-third of all anthropogenic carbon dioxide, helping to keep our climate stable (Fabry, 2008). However, as more carbon dioxide is produced, more is absorbed by the ocean. Therefore, an excess amount of carbon dioxide in the atmosphere means the ocean is becoming an even bigger carbon sink, absorbing that much more carbon dioxide, to the point where it is adversely affecting marine life and ecosystems. This is quite noticeable in two aspects of the ocean's carbon dioxide problem: ocean acidification and warming (Andersson et al., 2015).

Ocean acidification and warming are interrelated. Their effects on marine life overlap and are often compounded, intensifying the other's damage to cause a snowball effect on individual organisms and whole ecosystem dynamics. These carbon dioxide disruptions are of major consequence to not only individual organisms, but also entire communities, ecosystems, food webs, human populations, and their connectivity (Andersson et al., 2015). Anthropogenic carbon dioxide emissions are increasing the rate of ocean acidification and warming, thus changing the structure of marine communities and threatening the biodiversity, resilience, and survival of populations and ecosystems, most noticeably those of coral reefs.

What is Ocean Acidification?

The ocean's absorption of anthropogenic carbon dioxide alters the chemical composition of seawater (Fabry, 2008). As carbon dioxide is absorbed, it reacts with water to form bicarbonate and hydrogen ions, which subsequently reduces the concentration of carbonate ions, as these bond with the hydrogen ions produced to form more bicarbonate (Hardt & Safina, 2008).

The production of hydrogen ions is what makes seawater more acidic, reflected by its lowered pH value, thus causing ocean acidification (Bates et al., 2014). There has been a decline in pH by 0.1 units—equivalent to a 30% increase in surface-ocean acidity—in the past 200 years, since industrialization began (Kerr, 2010). Decreased levels of carbonate also have adverse impacts on marine life that uses carbonate ions to form their calcium carbonate skeletons (Hardt & Safina, 2008).

The shifts in ion concentrations and decreasing pH corresponding to ocean acidification disrupt the balanced chemical systems to which marine organisms are adapted, in a variety of ways. They can slow the growth and decrease the resilience of carbonate-based organisms such as certain corals and mollusks, and both directly and indirectly affect the mortality rates of populations unable to survive in acidifying regions.

What is Ocean Warming?

When elevated levels of atmospheric carbon dioxide and other greenhouse gases increase the temperature of air directly above the ocean, the temperature of the surface water increases as well. Just as marine organisms are suited to the chemical composition of seawater with quite small margins of variation, they are also suited for *certain temperatures* within a narrow margin.

Today, ocean temperatures are warmer than they have been in the last 420,000 years, and the global average temperature has been increased by 0.74 degrees Celsius due to human carbon dioxide emissions in the 20th century alone (Hoegh-Guldberg et al., 2007). Such a rapid increase has reverberating effects on marine life and ecosystems.

As global warming continues, the species inhabiting warmer ecosystems within and outside of the ocean, unlike most others, will be forced to develop “new environmental tolerances” in order for species survival, as there are no species better suited for warmer conditions than those already living in them (Goreau & Hayes, 1994). This could potentially be a grim fate for many tropically based marine species, as evolution is much slower in comparison to the migration of species to a new, cooler region (Goreau & Hayes, 1994).

Not only will this affect individual organisms, as they will be required to relocate and physiologically acclimate, but entire ecosystems. The inability of certain organisms to adapt to warming and its associated negative impacts causes higher rates of mortality, with direct effects on “the productive capacity and energy flow within food webs,” adding to the decline of tropical ecosystems (Lima et al., 2021, p. 2). Coral reefs, specifically, may change in terms of their structure and function, among other aspects. They are located mostly along the equator and are near the ocean’s surface, and thus are directly impacted by rising atmospheric and sea surface temperatures. Variations of just 1 to 2 degrees Celsius above the usual maximum summer temperature can cause an event known as coral bleaching, wherein the health and survival of corals is endangered (Hoegh-Guldberg et al., 2007).

Effects on Resilience and Complexity of Coral Reefs

Coral reefs are one of the most fragile ecosystems in terms of climate change effects, particularly in terms of rising temperatures (Goreau & Hayes, 1994). When the effects of warming and ocean acidification combine on coral reefs, both the biodiversity and structural complexity of the ecosystem are threatened. While it is possible for reefs to recover, their overall health may still be diminished. The ocean's carbon dioxide problem mainly affects reefs in two ways: through reduced calcification of reef-building corals and mass bleaching events. Each has its own negative impacts on reefs and the associated reliant-species, and combined, they inhibit algal overgrowth of coral communities, and thus reduce the biodiversity and structural complexity of reefs.

Effects of Reduced Calcification

Decreased calcification and growth rate of coral reefs have coincided with the chemical changes associated with ocean acidification, seen in the decreased pH and carbonate-ion concentrations of seawater (Hoegh-Guldberg et al., 2007). The increased concentrations of bicarbonate ions and hydrogen ions reduce the concentration of carbonate ions in seawater, which are extremely significant to marine life with shells or skeletons made of calcium carbonate, such as certain corals and mollusks (Kerr, 2010). A limited amount of carbonate ions means they cannot calcify as quickly, which reduces their growth rate and the health of their skeletal structures.

Between 2050 and 2100, the atmospheric carbon dioxide concentration is projected to pass 500 parts per million (ppm), exceeding the 480 ppm at which the carbonate output of reef-building corals approaches zero, or drops lower, obtaining a zero or negative net accretion value

(Hoegh-Guldberg et al., 2007). This means that reefs will enter a further state of decline and diminish in size as their coral growth rate becomes stagnant or negative, because of the lack of carbonate-ions needed to maintain their normal growth rate. Our current-day atmospheric concentration of carbon dioxide is over 419 ppm (NOAA, 2021). That concentration is nearly 100 ppm more than the maximum concentrations in the past 740,000 years, or possibly millions of years (Hoegh-Guldberg et al., 2007). The last time carbon dioxide concentrations were at this level, the sea level was nearly 80 feet higher and forests were located in areas of the Arctic, showing that atmospheric carbon dioxide levels affect much more than just the health of corals—they have the ability to change the structure and organization of ecosystems across the globe (NOAA, 2021).

The growth rate of atmospheric carbon dioxide in the past 60 years alone has increased one hundred times that of natural increases in the past (Lindsey, 2021). Currently, no type of coral has shown the ability to adapt quickly enough to such a rapid increase in atmospheric carbon dioxide concentration and subsequent acidification—neither through their genetic makeup nor physical characteristics (Hoegh-Guldberg et al., 2007). Not only are certain corals unable to keep up their growth rate, but they are also not expected to gain this ability any time soon.

It is possible for corals to keep their growth rate constant if they reduce their skeletal density, meaning they require the use of fewer carbonate ions to make their skeletons (Hoegh-Guldberg et al., 2007). However, corals that do this are frailer and more brittle, thus making them more vulnerable to grazing species and storm damage, which are responsible for reef erosion and breakage (Hoegh-Guldberg et al., 2007). Coral food-source and reef habitat loss cause subsequent effects on coral-reliant populations, food webs, and the overall health of the ecosystem. Decreased reef area also reduces breakwater quality, which helps maintain shorelines and other productive systems like mangroves and seagrass beds that support their own reliant species (Kleypas & Yates, 2009). Calcifying corals provide structural complexity to their reef ecosystem, supporting tens of thousands of marine species (De'ath et al., 2009). If coral erosion rates were to pass those of calcification on reefs, the process of reducing skeletal density would be counterproductive as net accretion becomes negative and reefs begin to shrink. Reefs would be unable to support the vast number of species they currently can, with negative implications for the biodiversity and health of not only the reef, but also other connected communities and habitats.

Effects of Coral Bleaching

Corals have an endosymbiotic relationship with tiny organisms called dinoflagellates, a type of algae able to live inside them, that "provide more than 95% of the metabolic requirements of the coral host" by trapping solar energy and nutrients (Hoegh-Guldberg et al., 2007, p. 1739). In return, corals provide the dinoflagellates with a place to live—until the temperature of the water gets too high, rising above the maximum summer temperature of the region by 1 to 2 degrees Celsius for an extended period (Bonin et al., 2009). At this point, the dinoflagellates, giving corals their colorful pigment, are expelled from the heat-stressed coral, meaning the coral loses both its color and its primary energy source (Bonin et al., 2009). While corals can still survive on their own and possibly recover, they are susceptible to a reduction in "growth, fitness, and physiological condition" (Bonin et al., 2009, p. 216), as well as decreased calcification and resilience to disturbances such as disease, another bleaching event, or overexploitation (Kleypas & Bates, 2009).

Bleaching events are also detrimental to the health and abundance of reliant species, as bleaching effects the quality of coral as both a food source and place of shelter (Bonin et al., 2009). To worsen the matter, coral mortality quickly eradicates the presence of fishes specifically suited for reef living, largely reducing the amount of biodiversity present (Bonin et al., 2009). The loss of biodiversity in marine environments as critical as coral reefs can result in the degradation of ecological resilience to disturbances, however minor (Kleypas & Bates, 2009), and greater potential shifts in ecosystem structure (Doney et al., 2020). When compounded with decreased calcification, the groundwork for large-scale changes in the structure, complexity, and biodiversity of reefs is established.

Combined Impacts of Reduced Calcification and Bleaching

It is clear that ocean acidification and warming have stand-alone adverse effects on coral reefs. What happens when these two forces combine? Coral bleaching and reduced calcification both inhibit the growth and overall health of corals, while a high carbon dioxide environment accompanying these events assists the spread of a coral competitor—algal communities (Doney et al., 2020). In an environment rich with carbon dioxide, certain types of algal communities are not only able to increase their biomass and diversity, establishing a basis for creating a stronger, more abundant community, but also simultaneously deter the settlement of young corals on existing reefs (Doney et al., 2020). Algae continue to grow, while slowing the growth for the already slower-growing corals, creating an even wider gap between the two. Algal overgrowth and corresponding changes in coral abundance limit the structural complexity and biodiversity of reefs, causing reef-dwelling populations to be displaced or forcing them to rely on the macroalgal communities replacing corals.

Macroalgal and turf algal communities can quickly gain the momentum needed to dominate coral reefs, once coral growth has been slowed enough (Hoegh-Guldberg et al., 2007). As previously explained, both decreased calcification and coral bleaching take a severe toll on the growth rate of corals. Add competition with macroalgae that can thrive in high carbon dioxide environments to the mix, and the success of coral is very much threatened, putting the resilience of the reef at risk.

Mass bleaching events effectively lower the “immune system” of corals, per se, which among a variety of effects previously discussed, can further reduce calcification of reef-building corals, causing a snowball effect on the decreased growth rate of corals (Hoegh-Guldberg et al., 2007). Coral reefs become less ecologically resilient the more often and longer they undergo disturbances and must compete with the faster growing macroalgae (Hoegh-Guldberg et al., 2007). This means that once disturbed or inhibited, a “regime shift” to a different ecosystem state is possible, wherein a “tipping point” has been reached (Kleypas & Bates, 2009). Coral communities may quickly become an algae-dominated community, with little to no resilience to return to their previously coral-dominated reef state (Hoegh-Guldberg et al., 2007).

This tipping of scales would effectively lay the foundation of a new community, as the biodiversity of the ecosystem would be lost, as well as the habitat itself. Corals are central to the function and food webs of reef ecosystems, as well as the foundation of their existence, and reef loss is not an isolated event (De’ath et al., 2009). Habitat loss places stress on displaced organisms to compete in a new, similar habitat, and on the structure of refugee habitats, creating a ripple effect. Therefore, coral-reliant organisms are forced to adapt and/or relocate while successfully competing with others, or do not survive. Such disruptions to populations relying on reefs have a cascading effect on the structure and function of related invertebrate and fish communities (Doney et al., 2020).

Conclusion

While the ocean has historically been a partial solution to atmospheric cooling, carbon dioxide has a range of effects on marine life, which are "exacerbated when combined with temperature extremes, potential problems of oxygen deficiency that arise from global warming, eutrophication, or potential carbon dioxide disposal strategies" (Pörtner, 2008, p. 204). Thus, the effects of carbon dioxide being absorbed by the ocean are complex and intensified by related anthropogenic environmental issues.

By the end of the century, pH is expected to drop from 8.1 to 7.8—increasing ocean acidity by about 150% (Kerr, 2010). Compared to the 30% increase over two centuries, an increase five times the size in less than half the time will have major implications for marine life (Kerr, 2010). On top of acidification, if atmospheric carbon dioxide and global temperatures continue to increase, mass coral bleaching, coral disease, and mortality of corals are all expected to increase in severity and frequency (Hoegh-Guldberg et al., 2007). The dangers of ocean acidification and warming are intensifying and will continue to do so. Yet, the United Nations Framework Convention on Climate Change (UNFCCC) has not specifically addressed the issue of ocean acidification. While it is agreed the best way to reduce the severity of ocean acidification and warming is to reduce carbon dioxide emissions, more action is needed than is currently being taken. The intensity of future projections for seawater pH and global temperatures are the byproducts of human activities, but as environmental consequences worsen, these problems can no longer be considered "byproducts." It is important to understand that reduced calcification and coral bleaching are only two issues caused by ocean acidification and warming, respectively, and likewise acidification and warming are only two of the broader issues facing the ocean, and thus human populations, today. All marine ecosystems, not only coral reefs, are feeling the impacts of a variety of human-caused problems, such as overfishing, deoxygenation, unsustainable tourism practices, pollution from agricultural practices, trash and plastic pollution, oil spills, and more. The carbon dioxide problem affecting the health of marine ecosystems is part of a much wider, far-reaching problem facing not only the ocean and marine life, but the majority of Earth’s populations and ecosystems in totality.

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