Ocean Acidification: The Invisible, Imminent Threat To Human Health

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Abstract

The ocean provides life with many resources necessary for survival, but rising levels of atmospheric carbon dioxide are hampering its life support capacity. One of the lesser known ways the ocean is impacted is through ocean acidification, hereafter termed OA. Despite being long thought to only affect the health of marine life, OA impacts human health as well, albeit indirectly. In this paper, I'll review the available literature regarding OA, arguing that it can dramatically impair human longevity and quality of life through a variety of pathways. Additionally, I'll discuss some of the most promising strategies to help governments mitigate OA and its effects, noting that an area's socioeconomic background profoundly influences the scope of action. If not addressed, OA has the potential to permanently hinder the health of all humans.

1 Introduction

It's critical to understand the delicate connection between the health of the ocean and humans, one that has been ignored for far too long in the face of other environmental threats. The ocean provides us with the resources needed for survival, including water, food, medicines, natural spaces, global warming alleviation through carbon dioxide (CO_2) absorption, and climate regulation [Gas17]. The altering of these benefits, especially through OA, can offset the fragile balance between humans and the ocean, adversely affecting human well-being. This paper aims to expand the existing research regarding OA by exploring its harmful effects on vital aspects of human health and well-being such as nutrition and longevity.

The ocean plays its part in the carbon cycle by naturally absorbing 25% of atmospheric CO_2 [Cal03]. However, as humans continue to rely on fossil fuels for power, atmospheric CO_2 levels rise at an unprecedented rate, greatly surpassing "natural" proportions. This steep incline has increased the amount of ocean-absorbed CO_2, which lowers the pH of seawater, greatly acidifying it.

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Such OA has already been shown to negatively impact various marine organisms and the intricate ecosystems dependent upon them.

The scope of the available research regarding OA tends to go no further than its effects on marine organisms because "...acidification manifests in layers of complexity involving indirect effects and interactions" [Fal20]. It's true that a rich understanding of an issue comes first from a strong comprehension of its direct impacts. However, research must go beyond the impairments to marine life and should explore the ramifications of OA on humankind that clearly exist.

As the negative health costs of rising anthropogenic CO_2 levels begin to manifest around the world, the connection between ocean and human health has begun to receive some attention, but there is still room for more. Many strategies have been shown to effectively combat OA, but challenges such as socioeconomic conditions have prevented their full implementation.

This paper presents an overview of the connection between OA and human health by exploring the scientific concepts behind OA, its impacts on marine and human life, and strategies that have the capacity to control these effects (and why they should be implemented). The paper is structured in this manner because it's imperative to first identify OA's origins and then understand the chain of events through which we are affected, for only then can the human impairments be truly understood and properly mitigated. Overall, I intend to demonstrate just how life-threatening impaired oceans can be to humanity, and that it's possible to lessen the major stressors to a certain extent, despite the obstacles.

2 Ocean Acidification

Before discussing the most salient of OA's impacts, it's vital to first comprehend the science behind it. An aqueous solution's pH is a measure of its hydrogen ion concentration ($[H^+]$), which influences biological processes. [Don09] explains that oceanic pH is regulated by multiple reversible chemical reactions occurring in seawater. Atmospheric CO_2 is absorbed by the ocean, where it reacts with water, forming carbonic acid (H_2CO_3), which then dissociates into bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}) ions. Normally, the availability of aforementioned reactions' reactants is sufficient for the reactions to reach a state of chemical equilibrium, stabilizing oceanic pH. However, an influx in aqueous CO_2 increases seawater $[H^+]$, which lowers its pH (pH = $-\log_{10}[H^+]$), acidifying it. These surplus ions can react with CO_3^{-2} to form even more HCO_3^-, depleting $[CO_3^{-2}]$.

$$CO_2\ (g) \leftrightarrows CO_2\ (aq) + H_2O \rightleftarrows H_2CO_3 \rightleftarrows H^+ + HCO_3^- \leftrightarrows 2H^+ + CO_3^{-2}$$

Figure 1: The chemical reactions behind OA [Don09].

Minor decreases in pH can be very dangerous, and they're already happening now. The ocean's average surface pH has decreased by 0.1 units since the Industrial Revolution, and it's expected to drop another 0.4 units by the end of the 21st century [Cal03]. While these changes may appear insignificant, each pH increment alters the quantity by a factor of 10, so the expected drop is equivalent to about a 150% increase in [H^+], and a 50% decrease in [CO_3^{-2}] [Orr05]. The scale and speed at which these pH changes are occurring creates the potential for disastrous consequences.

3 The Major Impacts of Ocean Acidification on Marine Life

OA directly impacts the marine organisms and ecosystems we rely on to sustain our own health and livelihoods. Impairments to marine life also affect human life, so it's crucial to understand the entire process through which OA can hamper human health and well-being. Here, I'll discuss the more general effects OA has on marine life as they relate to more specific impacts on human health.

3.1 Calcification

One of the most direct effects of an increase in [H^+] is a decrease in [CO_3^{-2}]. CO_3^{-2} is of particular significance to countless marine organisms in the form of calcium carbonate ($CaCO_3$), which is produced from the reaction of a calcium ion with a carbonate ion. $CaCO_3$ is the primary component of the shells and skeletons that provide support to many invertebrates, and its formation is dependent on [CO_3^{-2}], as they can dissociate at lower concentrations if not already protected by organic coatings.

As shown in Figure 2, a decrease in [CO_3^{-2}] also decreases calcification rate (the production rate of $CaCO_3$), meaning it takes more time to produce a certain amount of the mineral. [Orr05] claims that these conditions can manifest at anthropogenic CO_2 levels that are only double the preindustrial ones, which will likely occur within the next 5 decades. Calcifying organisms, or organisms that form $CaCO_3$ shells, may be unable to maintain shells in undersaturated water [Fee88]. These organisms greatly support marine food chains, so any threat to them has the capacity to impair entire systems, and by extension, to humans as well.

3.2 Survival

OA doesn't only endanger the survival of calcifying organisms. Through direct impacts in physiology at the key stages of development, the chemical changes associated with OA can affect the survival, growth, and reproduction of numerous species. While some species' survival seems to be unaffected by increased CO_2, low and unsuccessful hatching rates in other species indicate a potential risk to fish stocks. The entire developmental process of many marine organisms

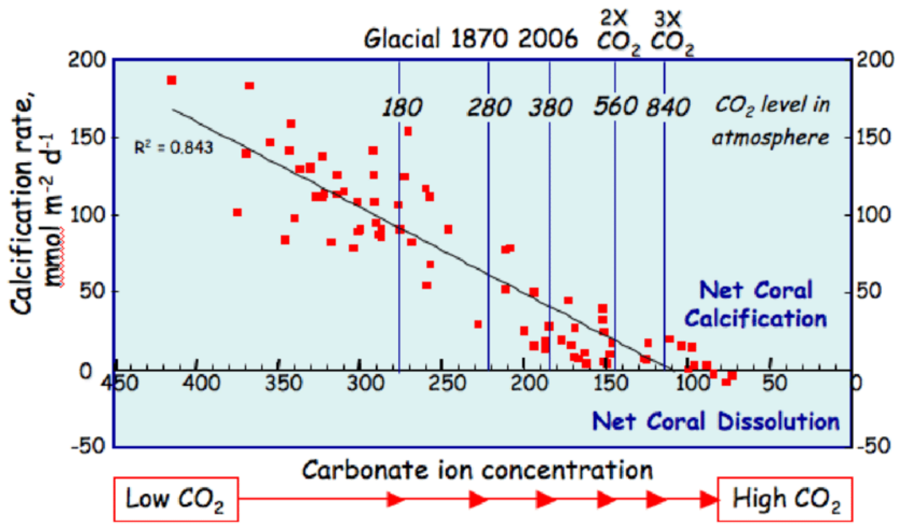

Figure 2: The relationship between CO_2 levels, $[CO_3^{-2}]$ and calcification rate [Sim12]

are also negatively impacted [Kro13]. Ultimately, reduced survival of marine species limits the quantity available to humans.

4 The Predicted Impacts of Ocean Acidification on Human Health and Well-Being

OA has the capacity to cause immense effects to all aspects of human health and well-being. Four main adverse impacts examined here are: 1) malnutrition and poisoning; 2) respiratory issues; 3) mental health concerns; and 4) loss of medical resources [Fal20].

4.1 Malnutrition and Poisoning via Altered Food and Quantity

4.1.1 Decreased Seafood Quantity

One of the most crucial resources the ocean offers is food through marine organisms. Humans have long relied on them as a source of protein - it's been shown that the most vulnerable communities are exceedingly reliant on the oceans for food. As demonstrated earlier, the chemical changes associated with OA can alter the survival and availability of marine species commonly consumed by humans. While this may not be devastating to those who don't heavily rely on seafood, vulnerable coastal communities may face far greater impacts as aquatic resources are their main source of nutrition and livelihoods.

4.1.2 Decreased Nutritional Quality of Seafood

Nutrition is a key component of human health and well-being. A large portion of the world's population depends on nutrient-rich marine foods, so any impact on the nutrition of these resources will have a globally widespread negative effect on human health. The chemical changes associated with OA can potentially decrease the nutrient concentrations in seafood. Additionally, changes in sensory quality of consumed seafood may be observed, negatively affecting consumer demand and economic viability.

While seafood's nutritional value is most commonly attributed to its high protein supply, it harbors many other important nutrients as well. Proteins help to support and maintain the body, carbohydrates and lipids are potent energy sources, and other nutrients serve as barriers against chronic conditions, facilitate the processes necessary to life, and more. OA can deteriorate seafood's nutritional quality by depleting its lipid and protein levels, as has already been seen in cultured whelk species [Tat17]. Like proteins, lipids are important to human health, particularly a type known as polyunsaturated fatty acids. These supply the human body with fat-soluble vitamins, combat inflammation and abnormal heart rate, maintain proper blood circulation, and reduce the risk of heart disease [Sim91].

4.1.3 Chemical Contaminants (Pollutants)

Seafood pollution can make it unsafe for human consumption. Pollutants can be added to environmental systems by human activities, primarily through municipal runoff [Gaw14]. Organisms can consume and transfer pollutants along the food chain, which ultimately accumulate in human tissue and alter physiology [Paz18]. Such substances include heavy metals, pharmaceuticals, and active ingredients in personal care products [McD11]. High levels of such chemicals can harm human food safety. For example, mercury-containing compounds hinder the central nervous, cardiovascular, and immune systems. They can even impair fetal development, causing attention deficit and developmental delays [Ala17]. Increased copper intake can damage the liver and cause gastrointestinal symptoms [San10].

OA has been shown to further the spread of such pollutants, ultimately intensifying their "effects across biological levels of organisms from genes to ecosystems" [Ala17]. Acidified seawater can also lead to epithelial damage, making the penetration of harmful chemicals much easier to further weaken organisms. By lowering fish growth rates, OA can increase mercury concentrations as well. As pollutants become concentrated in organisms at higher trophic levels, humans are at increased risk of consuming contaminated organisms and being exposed to the effects they bring.

4.2 Respiratory Issues via Impaired Air Quality

OA can also exacerbate respiratory problems caused by harmful algal blooms, such as the dinoflagellate *Karenia brevis*, which release brevetoxins as they break up in the surf. A phenomenon known as a “Florida red tide” then occurs - the released brevetoxins mix into sea water aerosols, spreading across the air [Fle11]. First-hand witnesses complain of throat irritation, itchy eyes, and burning of the upper respiratory tract in response to inhalation of such aerosols [Wat08]. This leads to upper airway irritation, exacerbation of asthma symptoms, and decreased pulmonary function [Fle11]. By altering dinoflagellate occurrence and composition, OA can heighten their growth. As atmospheric aerosol concentration increases, the aforementioned impacts' duration and potency can too, proving to be a further cause for concern.

4.3 Mental Health Impacts via Modification of Natural Spaces

A large aspect of human health and well-being that remains ignored is mental health. Oceans benefit mental health by providing livelihoods, recreational activities, and social connections. Marine environments support the in-demand and economically independent seafood, tourism, construction, transportation, and shipbuilding industries, among others [OA]. Job security directly impacts mental health; those with less stable / no jobs are more likely to experience mental health issues and become distressed, as they may here [ME11]. Individual engagement with natural environments is heavily boosted by the nature-based exercise and recreation opportunities the ocean provides. These include coastal walking, fishing, and swimming, and facilitate positive emotions, improve attention span, and alleviate anxiety [Wei20]. Additionally, it's recognized that interacting with nature encourages “social interactions that lead to greater social cohesion... and a positive sense of community” [Kim04].

As previously discussed, OA is set to alter the supply of seafood circulating through the fishing industry, which can deprive many livelihoods. As fish stocks devalue, mass unemployment in fishing communities could cause financial pressures and societal stress [Fal20]. And, by depleting marine habitats and increasing exposure to undesirable phenomena such as migration of poisonous species, OA can reduce the amount of “blue spaces” available. This can lower the standards to which humans perceive marine nature-based experiences, eradicating connections to nature and each other. They may even avoid visiting coastal areas and adopt an indoor lifestyle, further limiting social interactions.

4.4 Decreased Opportunity to Develop Medical Resources via Loss of Biodiversity

Of course, with all of the discussed ailments comes the question of treating them, the answer to which can be found in the very oceans that are acidifying. Marine ecosystems are home to a great deal of biodiversity, which can benefit all of Earth's organisms in the form of medicine if properly tapped into. This is evidenced by [Cen10], which estimated that there are about 250,000 known marine species. However, as the ocean covers 70% of the planet, it remains largely unexplored [San20], explaining why only 10 out of the 34,000 molecules of medicinal interest are marine-derived [Zho20]. This being said, within the unexplored territory of the ocean lies countless opportunities to curtail many modern health crises. These include coral reefs, which provide biologically beneficial compounds called new marine natural products [Lea12], and microbial species, home to much biodiversity.

However, with OA comes the increasingly likely possibility that the biodiversity that allows for such medicinal resources will be significantly reduced. After all, coral reefs are seriously threatened by the decrease in [CO_3^{-2}], microbes adapt to their environment's chemical composition [WS11], and the scope of harm that can come to other valuable organisms is immense. In this scenario we are dangerously close to, we will lose the chance to explore and better understand ocean systems and the highly beneficial resources that can (potentially) treat severe ailments.

5 Combatting Ocean Acidification's Impacts

With all of the talk about OA's disastrous impacts comes the question of how to manage the deleterious impacts, the responsibility of which is often delegated to governments. The OA crisis will only worsen over time, so it's critical that we work to alleviate the stressors on marine environments and our own health. Here, I'll discuss strategies that show great potential to effectively respond to OA, along with obstacles and incentives to implementation.

5.1 Obstacles to Implementation

There are many ways for governments to help mitigate OA's effects, but full implementation of such programs is yet to be realized due to some obstacles. [Kel13] identifies one prevalent in the US as "no more stringent laws". Here, states don't include federal limits for environmental regulations into their constitution, allowing them to alter the statutes to their liking. Many lawmakers then reduce the federal limits, demotivating any agency from taking environmental action. OA is also an extremely complex issue, so not all strategies to combat it may be as feasible or efficient. For example, suppressing OA's effects doesn't entirely get rid of the issue - it only gives us more time to decrease CO_2 emissions, which has been notoriously hard to do since so much of the Earth runs on fossil fuels.

5.2 Incentives to Implementation

There are numerous ways governments can combat OA's impacts, but they often hesitate due to the aforementioned obstacles. Eventually, OA will become any environmental agency's main focus, but there are incentives to immediate action, primarily those that benefit the economy and human psychology.

5.2.1 Economic Incentives

The industries that OA affects have great economic value to all. According to the NOAA, 14% of the coastal U.S. counties are responsible for 45% of the annual GDP. The seafood industry is constantly in high demand due to seafood's high nutritional value, "rapid population growth and income improvement... and growing health consciousness", among other factors [Sup18]. Such high demand only boosts the industry's influence and growth in the economy. Coastal communities are especially benefited, as they heavily depend on the ocean for economical support. It's evident that the seafood industry is of economic importance, so its likely degradation from OA can push leaders towards acting to protect the industries.

5.2.2 Behavioral Incentives

Behavioral incentives are very powerful, as personal satisfaction is very important to the individual and the business and thus is a large driver of action. For example, the European Union started issuing trade sanctions known as "yellow cards" and "red cards" to reduce unsustainable fishing practices. When Thailand received a yellow card in 2015, they reformed their fisheries to avoid the threat of trade sanctions, showing how communities often work towards achieving good standing. Incentives can also apply to individual businesses, as customers favor companies with sustainable goals [Acc19]. By working to protect the environment, government agencies can live up to their self-established standards, improving their credibility. Governments can also be motivated to make certain decisions based on how they think their constituents will respond, especially now since the worsening environmental conditions are drawing much public attention and calls for change. Overall, incentives are powerful tools in driving actions, and if aligned with sustainable goals, can be a source for good to manage OA.

5.3 Potential Policies

5.3.1 Preventing Further Acidification

OA is a complex issue impacted by a variety of factors that, when combined with other stressors, can further exacerbate effects. These stressors include impaired water quality from runoff; therefore, it's important to manage and monitor pollution levels to ensure aquatic environments remain healthy [Fal20]. Section 5.1 discussed the failure of US states to improve upon federal water quality levels through "no more stringent laws". Thus, as [Kel13] claims, a logical step in the right direction would be for local governments to increase the stringency of their water quality and technology standards. Under harsher criteria, more waters will be identified as "impaired", eliminating point sources of pollution as risks to further OA. Non-point sources can be addressed through additional alterations of water quality criteria. Existing water pollution limits are often ignored, rendering the original action useless. Thus, governments can criminalize pollution, which significantly reduces the amount of negative feedback received, allowing legislators to shift their focus to another aspect of combatting OA.

5.3.2 Adapting to the Changes Caused by Ocean Acidification

Reversing OA will take time and implementing major changes, so additional focus on responding to the issue's impacts is necessary. To bring more attention to OA, states can begin incorporating its impacts into environmental reviews, especially since its sources overlap with those of other issues [Kel13]. Merely talking about OA can greatly help to take action, making this simple strategy quite effective.

With any change will inevitably come the need to adapt our activities, and OA is no different. One way to do this is by consuming more species that remain unaffected/prosper from OA, or transitioning to entirely new nutrient sources [Dou18]. However, these may not provide the same nutritional standard, and to compensate for altered sensory qualities, artificial add-ins can increase, further harming health [CL18]. Ocean-reliant businesses can adapt to accommodate acidifying waters. For example, in order to access an unaffected supply of larvae, a Willapa Bay-based oyster grower began operating out of a Hawaii-based hatchery [Wel12].

5.3.3 Important Contextual Factors to Consider When Discussing Action

Not all of the strategies to properly mitigate OA and its impacts are viable in some regions, especially those home to socioeconomic inequality. Environmental legislation is expensive to maintain, mainly in areas where environmental issues are not prioritized due to poverty or war, and often, developing nations are not capable of such financing. As OA progresses, destroying coastal economies and making certain goods rarer, regions dependent on such resources will be further harmed. It's crucial to keep this in mind because socioeconomic context is already a large stressor on human health (health issues tend to worsen in poorer areas), so the addition of another stressor will aggravate the disproportion. Thus, action should be altered to better suit certain regions, or regions that are better-off should support developing ones after they enforce policies themselves. Overall, there are many measures that can lessen the damage caused by OA, but they must first be globally recognized.

6 Conclusion

Ocean acidification, often termed "the other CO_2 problem", is a major concern to oceanic health which occurs from rising amounts of anthropogenic atmospheric CO_2 levels that increase seawater hydrogen ion concentration, acidifying seawater. This phenomenon can become not only a major crisis for the environment, but for public health as well through affecting seafood supply and quality, air quality, "blue" natural spaces, and loss of medicinal resources. As OA progresses, its impacts on human health and well-being will be further exacerbated and experienced, so it's imperative to act to mitigate it now. Countless methods to combat OA have been identified, but obstacles still prevent leaders around the globe from taking decisive action, despite the many incentives. One primary obstacle is the widespread lack of research and education regarding the issue. The vast majority of OA research has focused on its impacts on marine organisms, but, as this paper has aimed to demonstrate, the issue is far more complex.

Future research should focus on the link between oceanic and human health and strategies that align with a region's socioeconomic context to optimize the impact against OA. However, specific research regarding its negative ramifications on human health should progress beyond the nutritional impairments to seafood so that the risks posed to the other aspects of human health are encompassed as well. The chemical changes resulting from OA are indeed decreasing seafood's quantity and nutritional quality, along with jeopardizing human systems through contamination. Nonetheless, the incorporation of brevetoxins into oceanic air is becoming more frequent and severe, disrupting respiratory activity. Deteriorating "blue" spaces are diminishing job security and adversely impacting mental health by enhancing negative emotions. Finally, decreased marine biodiversity is leading to the loss of opportunity to employ marine medicinal resources in combating ailments. While the risks to seafood are very prominent, additional focus must be placed on the impairments to the other aspects of human health, as they are just as occurrent and dangerous.

It's also crucial for the world to recognize just how connected marine health in general is to our own. After all, the oceans provide us with necessities and maintain other environmental, social and economic systems. When the ocean is harmed, these services, and humans, are too, a relationship that has gone unnoticed for far too long. Thus, it's imperative that we protect the ocean now. To at least partially reverse OA, we can minimize its root causes through regulating land use, enforcing harsher water quality standards, and penalizing failure to comply with such criteria. To modify ocean-dependent behaviors in the wake of the changes associated with OA, individuals can consume less-impacted marine species, and businesses can raise species in healthier aquatic conditions and/or culture them. By effectively working together to combat OA, we may yet be in a position to reverse this trend which could have devastating effects on life as we know it. Stabilizing oceanic pH is critical to maintaining life in complex marine ecosystems, both for its inhabitants and humankind.

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