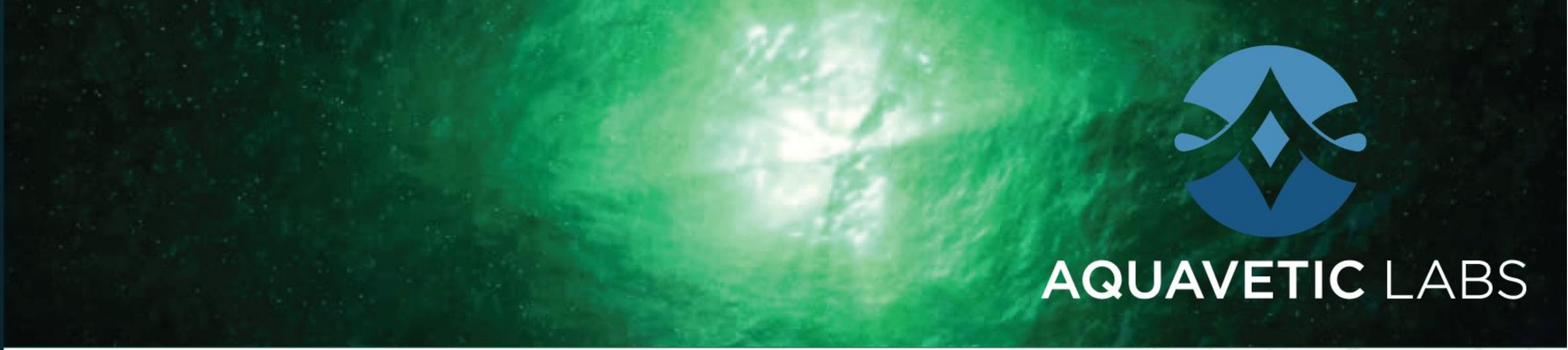


ARTIFICIAL UPWELLING of OCEANIC NUTRIENTS

BYPASSING THE THERMOCLINE SUPPRESSION

Abstract

As our modern industrial world continues to produce overwhelming amounts of greenhouse gas emissions, the resulting temperature increases pose a new set of problems for the world's oceans. Increases in sea surface temperatures (such as El Nino, the Blob and others) affect the depth and intensity of the stratification of the oceanic water column. This reduces the critical function of the upwelling of deeper, nutrient rich water from mixing with the surface water - due to pushing the thermocline lower, out of reach from the mechanical wind-wave action in the pelagic waters, and from the forces of the Ekman transport in coastal waters. This reduction of upwelling directly affects the primary productivity upon which the entire marine ecosystem survives. In addition to significant reductions in the marine food web (which we rely on for food and commerce), this reduction in primary productivity negatively affects multiple critical planetary processes also vital to mankind: carbon sequestration and oxygen production. This paper examines the problem, highlights the two scientifically known approaches to inducing phytoplankton blooms (iron fertilization and artificial upwelling) and suggests the balance between risk and benefit is best choreographed when scientists and engineers collaborate with sufficient funding to empirically determine efficacy. Further, we believe this is a critical pathway in the fight against climate change.

Problem Overview

The Vital Role of Natural Upwelling

Look anywhere in the ocean where deep-water nutrient upwelling occurs and you will find life. As warm, nutrient-depleted surface water is pushed out to sea by currents and offshore winds—most often along coastlines, seamounts, and islands—cool, nutrient-rich deep water rises to take its place, giving phytoplankton the nutrients needed to bloom.

Though it occurs in roughly just one percent of the oceans' surface area, natural upwelling brings nutrients to the euphotic zone (the surface layer of the ocean that receives sunlight) providing the foundation for much of the biological productivity in coastal marine ecosystems.

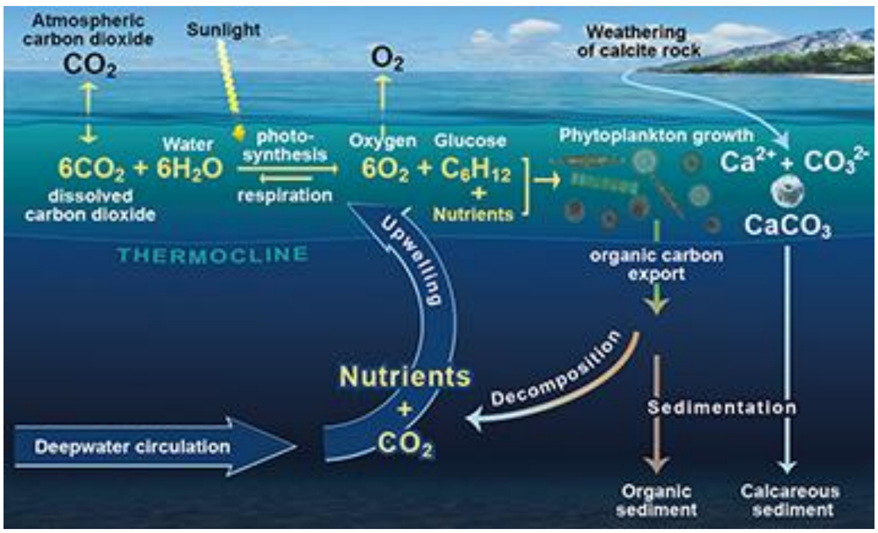
Upwelling is the primary means by which nutrients like phosphorus, nitrates, silica, and iron reach the surface and enable phytoplankton to bloom.[4] And phytoplankton, in addition to playing a vital role in global oxygen production and carbon sequestration, is the foundation on which the marine food web depends.

The Biological Pump

The "biological pump" is a natural process by which the ocean absorbs carbon from the atmosphere and traps it within the seafloor.

Sunlight drives the growth of organisms near the surface that absorb carbon dioxide, either through photosynthesis (by phytoplankton) or the cycling of calcium carbonate into shells (by zooplankton and mollusks). These organisms are eaten and die, creating the marine snow of fecal material and detritus that falls slowly to the bottom of the ocean. The rate of falling carbon is dependent on size of the fecal material, and thus the larger fish such as salmon and tuna can have a big impact on carbon sequestration.

Roughly 60 GtC annually is cycled from the atmosphere to the world ocean.[5] Of the 60 GtC, about 98% is remineralized in the mesopelagic layer, and only 2% reaches the ocean's bottom. The most effective transport of this carbon is when the food web is more than two trophic levels (phytoplankton and zooplankton being levels 1 and 2 respectively). Particulate size in the sedimentary downfall can be increased using nutrient upwelling devices as feeding and breeding grounds for fish species in a complex trophic food web.



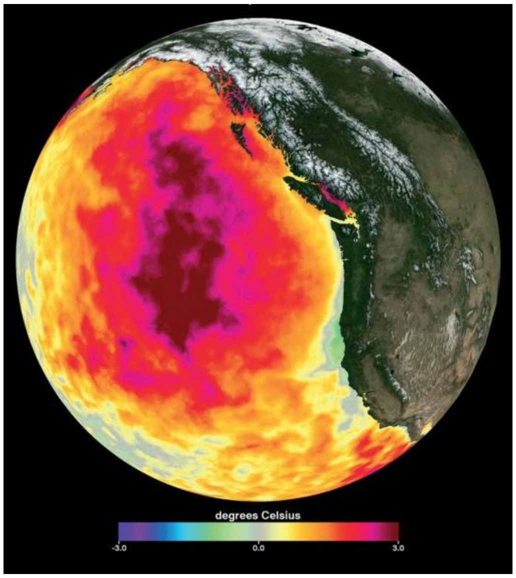
Suppression of Nutrient Upwelling

The effects of anthropogenic climate change are progressively weakening the processes that drive natural upwelling. Natural upwelling is failing (El Nino, the Blob, etc), thanks in large part to rising global temperatures. which have led to widespread changes in sea surface temperatures.

Rising sea surface temperatures (SSTs) cause increased thermal stratification, which suppresses upwelling. The result is a deepening of the thermocline, the density transition that isolates the lighter, warmer ocean surface layer from the cooler, heavier nutrient rich deeper layers. As a result, the conditions that normally drive upwelling, including ocean currents and offshore winds, are increasingly no longer effective in achieving this vital process.

What happens in coastal areas when upwelling is suppressed is that phytoplankton don't receive adequate nutrients to thrive and accumulate biomass. The entire marine ecosystem suffers, fisheries crash, birds and marine mammals starve. As SSTs and surface CO_2 levels keep rising, so too will the frequency and severity of upwelling suppression. In addition, ocean acidification (OA) will increasingly limit zooplankton and other creatures that incorporate calcium carbonate in their exoskeletons from breeding in sufficient numbers. The marine food web is on track to collapse in many places around the world, setting the stage for a bottom-up trophic cascade of starvation and die-offs.

One such affliction that's received a fair amount of public attention in recent years sits over the Northeast Pacific Gyre, known as the SSTA (sea surface temperature anomaly), or perhaps more commonly known as the Blob.



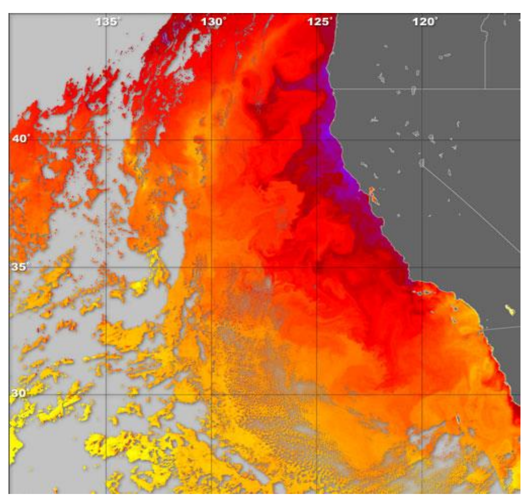
Sea surface temperatures (shown here for 2015) off the North American West Coast have developed an anomalous hot spot dubbed "the Blob"

Historically, upwelling has been seasonal. For a healthy year, upwelling in the California Current is shown in blues and oranges. This phenomenon occurs along the US and Canadian coasts and is responsible for the productivity of the coastal ecosystems.

Similar upwelling occurs in the Southern hemisphere off Peru and drives nutrient upwelling in the Humboldt Current far out into the Pacific, contributing to the rich fishery there.[7] But in El Niño years, when sea surface temperatures increase due to the El Niño Southern Oscillation (ENSO), the fisheries collapse due to lack of upwelling.

The problem is global. In good years, upwelling has driven record harvests of sardines off the coast of Peru. Decreased upwelling in El Niño years, followed by accumulation of warmer surface water, has been known to be associated with crashes in fishery. El Niño once suppressed upwelling only periodically - approximately every 4 or 5 years - but increasing atmospheric and ocean heat threatens to extend negative conditions every year.

The persistent thermal blob is starving open ocean ecosystems, and is likely acting as one of the many causes for declining salmon and diminishing numbers of seabirds from California to Alaska.



In the northern Pacific Ocean, a seasonal hot spot now develops annually on the south edge of the California current. For thousands of years, the California current has been able to turn over this recurring hot spot, sweeping down the coast of North America to bring extensive coastal upwelling that supports rich runs of salmon and other fish. But there is concern that increased sea surface temperatures will inhibit coastal upwelling along the entire west coast.[8] In the past ten years, rising temperatures have caused this hot spot to grow massively in breadth and depth.

A thermocline can extend to such a depth that it decreases the ability of offshore winds and Ekman transport associated with the California Current to displace the hot surface layer via the downward pressure known as Ekman transport.

Climate Change

The relationship between the atmosphere and oceans is closely intertwined, like that of an organism's heart and lungs. Since phytoplankton take in atmospheric CO_2 and produce O_2 via photosynthesis, substantial reductions of nutrient upwelling weaken the natural global processes of carbon sequestration and oxygen production. Sea-level rise, OA, SSTs, harmful algae blooms (HABs), and salinity imbalance are among the ocean syndromes being caused by or exacerbated by the effects of climate change. Conditions are worsening at an accelerating rate.

Human population will reach eight billion by 2024. The world ocean has always been an important source of food for humans. Fish stocks worldwide are declining. It's absurd to think we can feed a growing human population while continuing to over-exploit and deplete the world's fish stocks. It's expected that ocean food supply will continue its shift from wild-caught fish to farm raised fish. Done right, aquaculture and permaculture may reduce overfishing in the marine environment. But conventional fin-fish farming can consume several pounds of wild-caught forage fish for every pound of market fish produced.

We believe there is a hybrid option, part aquaculture and part marine fisheries, which has greater potential value than either by itself—an option that restores the health of the marine environment in localized areas, enhances the food web, protects against short sighted overfishing, and creates the conditions for the marine biome to grow.

Humans are really good at exploiting, extracting and harvesting. Can we also get really good at growing wild fish through ecosystem development and enhancement? Probably, but we must approach it holistically, if possible, to create a sustainable system.

Problem Summary

If we were to describe the world ocean as a patient, we could rightly say this patient has multiple compounding ailments and syndromes – and, after two centuries of the Industrial Age, the oceans are not in good health.

As SSTs continue to rise, thermocline suppression of upwelling (and its critical nutrients) continues to increase in severity, and ocean acidification continues to limit zooplankton and other exoskeletal creatures from breeding in sufficient numbers, the marine food web will collapse in many places around the world. Unless these trends are countered, they will result in a bottom-up trophic cascade of starvation and mass die offs. This will affect multiple systems on a global scale, reducing global oxygen production, reducing the ocean's uptake of atmospheric CO2, and accelerating climate change via multiple devastating feedback loops.

Serious efforts to reverse this trajectory will require focused effort, financial resources, and time—which is running short. Now is the time to build a new model for designing, developing and testing interventional technologies that can counterbalance the effects of the suppression of deepwater nutrients. We can develop solutions to some of the conditions that will sustain a thriving food web in targeted areas.

Known Solutions: Introduction

The pelagic ocean surface is nutrient-limited, and the only way to achieve a higher biomass density is to supply more iron, nitrate, phosphate, and silica in the right proportions, typically found in the sub-thermocline water depths. In theory, this could be achieved by adding those nutrients or from upwelling.

There are two primary approaches to increasing overall biological productivity in a targeted area via stimulation of phytoplankton growth:

1. Nutrient Upwelling
2. Nutrient Fertilization

While there have been proponents of artificial upwelling and for nutrient fertilization (OIF) to increase carbon sequestration, there have also been detractors. Given the importance of the surface ecosystem in establishing the quantity of carbon exported to the bathysphere, and the ways in which nutrient upwelling influences ecosystem productivity, more research and development of nutrient upwelling and nutrient fertilization is needed.[6]

The differences between the two methods go well beyond the technology involved. While ocean nutrient fertilization is about adding iron fertilizer to a target area on an intermittent basis, the goal of engineered upwelling is establishing a continuous and autonomous process of bringing deep water rich with nutrients—which includes iron, nitrates, phosphorus, and silica—to the surface layer in a way that mimics natural upwelling. Essentially, it is the same water, whether it is brought to the surface from natural wind and wave action or from a man made device.

Nutrient Upwelling

Concept

The approach is simple: an upwelling device is comprised of a spar buoy with a hollow center tube, an energy source (solar, wind or wave kinetics), and a pump that moves water from 100+ meters deep to the surface. The earliest invention of an upwelling device used a check valve in the 100M pipe and vertical wave action to slowly move a column of deep water to the surface.

In the same way that a medical device can help a human by regulating and supporting existing body processes, an engineered upwelling device can serve as a medical device for the ocean, restoring a naturally occurring and critical process that we know can remediate systemic breakdowns caused by the effects of anthropogenic climate change.

Just like a surgically implanted bypass can compensate for a blocked artery in the heart, an upwelling device can be used to bypass the thermocline and move deep water filled with nutrients to the warm, nutrient-depleted surface layer. By drawing up deep water, we can stimulate phytoplankton and zooplankton growth, which are in turn eaten by feeder fish, then larger fish, ultimately leading to sedimentation of larger fecal matter and a more effective method of oceanic carbon sequestration.

In effect, an upwelling device could create a free-range mariculture outpost by sparking a proximal phytoplankton bloom, which in turn would attract and feed populations of marine life within its effective radius. These devices would also help create local habitat for a segment of the marine life it attracts, as well as attenuate SSTs proximally, produce oxygen and increase sequestration of carbon via the biological pump.

History, References, Results

Upwelling reduction due to thermocline suppression was first noted when a patent was filed for engineered upwelling in 1974 after scientists saw how rises in sea surface temperature led to increased thermal stratification and impaired natural upwelling.

Dr. B. von Herzen of The Climate Foundation, in work featured in a Discovery Channel documentary on restoring ocean productivity, attempted to drive upwelling in the Pacific off Hawaii using a tubular system with a valve powered by wave action.[10] Some upwelling was obtained and plankton productivity was stimulated, in turn attracting fish. However, the system soon failed and no effect on carbon sedimentation was documented.

With funding from the Hertz Foundation, the Climate Foundation has pursued additional work under the title "Marine Permaculture Array." As an outgrowth, a proposed wave-powered pump is combined with a submerged lattice for supporting kelp.

In 2017, China informed the London Convention that it had conducted engineered upwelling experiments. One sea trial has been conducted in the East China Sea and two in Qiandao Lake, through Zhejiang University. In 2010, the researchers developed a pumping system and tested it using wave energy, allowing it to operate on its own for long periods.[11, 12]

What Is Needed

Aquavetic Labs is designing an artificial upwelling device and developing the case for the R&D expenditure. Given the multitude of benefits, we believe the economics will pencil out. Considering the herculean task humanity has before it: to cut emissions, develop new technologies, change behavior, change policies and ultimately come together to fight climate change, this technology has the potential to play a significant role. Unlike many other forms of carbon sequestration, nutrient upwelling mimics the natural process using natural ingredients and ultimately has multiple positive externalities.

The estimated social and economic costs of the effects of climate change can readily justify the financial investments into ocean remediation, including the development of upwelling devices, particularly given their potential for increasing the ocean's natural carbon sequestration process. But upwelling devices can be designed in such a way as to stimulate economic activity in coastal communities, by establishing areas of sustainable biologic support thru increasing primary productivity, which will be to the benefit of local fisheries.

Nutrient Fertilization

Concept

The iron fertilization approach is simply to add fine grain iron to the ocean in controlled dispersals under specific conditions as a nutrient fertilizer to induce phytoplankton growth. It is our belief that iron fertilization is, by itself, not a good tool to combat climate change. Without an ecosystem development approach, just creating more phytoplankton in the pelagic ocean, could produce hypoxia and increased OA (ocean acidification).

Iron has been demonstrated to be an essential micronutrient required by marine phytoplankton for photosynthesis, and insufficient iron has been suggested as a growth-limiting factor in numerous offshore ocean regions.[13]

History, References, Results

The Iron Fertilization Hypothesis was suggested by J.H. Martin as a way to enhance primary productivity (PP) in ocean waters where iron may be the limiting nutrient.[13] Martin's hypothesis was that the primary source of iron in the ocean is wind-blown dust originating from the continents, and additions of this element could enhance phytoplankton growth in oceanic regions where iron is the limiting nutrient.

Ocean iron fertilization (OIF) has been identified as a candidate driver of the ocean biological pump and at least 6 natural and 13 engineered OIF experiments have been performed to study its effectiveness.[14] Dissolved iron has been introduced into the surface mixed layer (upper 60 m) as an acidified sulfate with small amounts of a tracer compound such as sulfur hexafluoride (SF_6) to distinguish the injected iron from that naturally occurring in the ocean. Experiments were carried out in regions exhibiting high levels of primary nutrients (nitrogen and phosphorus) but low chlorophyll, suggesting that low iron levels may be the controlling micronutrient. A review of all 13 of these experiments and a synthesis of results can be found in Yoon et al 2018.[14]

Although OIF has generated considerable interest over the last 20 years, none of the 13 engineered experiments cited has found conclusive evidence of an enhanced transport of carbon from the surface mixed layers to deeper water as a result of iron fertilization. What they did demonstrate, however, was the effectiveness of iron fertilization as a means of creating a phytoplankton bloom.[6]

Such large experiments in open water are difficult and more studies are indicated, including consideration of possible side effects and unintended consequences that may negate the benefits of OIF. Some possible problems that have been mentioned are deceased oxygen concentrations (hypoxia/anoxia), toxic algal blooms, production of other greenhouse gases (N_2O, CH_4, halogenated volatile organic compounds), changes in the phytoplankton communities present and legal issues arising from the International Convention on the Prevention of Marine Pollution (ocean "dumping").

Some of the potential problems with OIF may result from the episodic injection of a single limiting micronutrient, whereas natural supplies of iron (mixed with additional naturally occurring nutrients) from airborne dust, river transport and coastal upwelling are relatively steady, long term mechanisms that can support stable ecosystems. Geo-engineering solutions that have the best chances for success are likely those that mimic natural processes.

What Is Needed

Additional research and testing is needed to expand beyond the addition of a single nutrient to a more targeted blend of nutrients based on silica, phosphorus and nitrate conditions where iron is limited. Additionally, more robust studies with sufficient experimentation time and better measurement capabilities and instrumentation are requisite.

The international parties to the London Dumping Convention will need to clarify their position and craft a legitimizing protocol with regulatory oversight, for interventional, coordinated, and measured iron (and/or other nutrient) fertilization that is repeated for a long enough duration to measure potential results.

Additionally, engineers need to create low-cost dispersal methodologies that can facilitate globally coordinated, measured and monitored nutrient fertilization in parallel with diagnostic studies. The accelerating rate and severity of the effects of climate change dictates that many of these tasks need to be done in parallel.

Nutrient Fertilization and Nutrient Upwelling Summary

There are benefits and drawbacks to both approaches. Fertilization is lower cost and can produce a larger spatial area of effect. Nutrient upwelling creates a stable ecosystem and provides a mechanism for us to monitor, manage and remediate any unintended consequences.

A combination of approaches could provide the best potential outcome – pending further study, location selection, engineering, regulatory adherence, etc. Also, one or the other may prove more effective in certain locations.

Although nutrient fertilization is less expensive, with a larger spatial area of affect, it does not by itself have any quality effect on total ecosystem or multi-level trophic development. Artificial upwelling is more expensive and has a smaller area of effect, but has the potential to induce a more comprehensive and longer term effect on ecosystem development, control and maintenance.

We believe both nutrient fertilization and engineered upwelling devices ***could be*** valid, complementary approaches and should be studied and tested for ecosystem development, biology support, oxygen production, ocean health restoration, and atmospheric carbon drawdown to mitigate climate change.

Potential Side Effects of Inducing Phytoplankton Blooms

Any direct intervention into nature's processes carries a risk of unintended side effects. Some possible effects are toxic or harmful algae blooms (HABs), hypoxic episodes, acidic water, and chemical composition unfriendly to certain phytoplankton communities. We anticipate that we will need to modify our process to mitigate or adapt to whatever undesirable side effects we encounter. Along with deploying devices to upwell nutrient rich water, we will institute careful monitoring of the results so that we can stop the upwelling at any time and analyze the causes should we encounter such results. In some cases, we may implement other interventions to counter any such side effects and improve the effectivity of our upwelling devices.

There are some known and not desirable side effects to blooms. There may also be other negative side effects. As part of a complete program, an entity engaged in upwelling or iron fertilization, must also have active measures to monitor, mitigate, and reduce or avoid any of the unintended problems resulting from phytoplankton blooms.
The 4 we know about are:

- Toxic harmful algae blooms (HABs)
- Hypoxia due to death and decay of phytoplankton
- Potential of upwelling of more acidic water if location or depth is inappropriate
- Location and chemistry conditions that prevent blooms during OIF Is this a risk or just a failure?

Mitigating HABs

Harmful algae blooms come in two flavors: normal algae that can succumb to a bacterial or viral infection or infestation or algae that is just by its nature, toxic. In both cases, the harm is to both marine life and to humans - just in varying degrees. In the event that an upwelling system produced a harmful algae bloom, shutting the upwelling off for a period of time could let it die out. Alternatively, killing the bloom via an apparatus utilizing germicidal fluorescent UV light with a wavelength of 2537 angstroms. If this measure is taken, the resulting decay of phytoplankton might cause some hypoxia.

Resolving Hypoxia

In the event we kill off a harmful algae bloom and it results in some hypoxic waters, we can re-oxygenate the water using compressed air pumped through tubing into what is called air stones. These air stones are porous and as compressed air is pushed into them, they produce micro bubbles which stay in the water column, if done right, for longer periods of time than larger bubbles. Additionally, mixing of the water column can also relieve hypoxia conditions. The two methods might be used in concert.

Location and Chemistry Content

For both upwelling and for fertilization approaches to inducing phytoplankton blooms, there are location specific and ocean chemistry considerations which can improve effectivity. We do not pretend to know, at this stage, all of the parameters to effectivity. What we do know is that depth, chemistry content and proximity to more complex trophic levels can play a positive role in this effort.

Ocean Acidification

In some places, higher carbon dioxide levels exist below the top 200 meters of the ocean. In the occurrence that upwelling brings up more acidic waters, calcium carbonate can be introduced as a countermeasure to mitigate the effects of acidity. While this is not a great solution, it is one that can improve conditions vs doing nothing. And speaking directly to scientists: doing nothing is no longer an option.

While we do not pretend to have all the answers, we understand that among the scientific community and among some portion of the general population, human intervention seems risky. However, we believe we need to be able to experiment and learn from interventional approaches to mitigating the negative effect we have had on our planet. There are no silver bullets - no easy solutions - only tradeoffs. Nothing is free.

Long Term Objectives

Marine Ecosystem Development

Nutrients such as nitrates, iron, and phosphates are key components to marine ecosystems. However, there are big differences between coastal marine ecosystems and pelagic ecosystems. These are mainly in the type and volume of marine life. By comparison, the pelagic ocean is much less abundant in marine life than coastal ecosystems—primarily due to coastal upwelling.

Currently, the pelagic ocean surface is nutrient-limited, and the only way to achieve a higher biomass density is to supply more nitrate, phosphate, silica and iron in the right proportions. The right ratio is typically found in sub-thermocline water and it is by upwelling that those nutrients are brought up to the photic zone.

Engineered upwelling devices can affect the territorial range and establishment of trophic conditions for marine life. Upwelling can provide nutrients, food web enhancement and growth, thermal attenuation, and mixing of the water column for salinity and oxygen level balance - all in a fixed location for long term benefit. Additionally, an array of engineered upwelling devices can provide a platform for additional interventional reaction and response, enabling access for research, collaborations and other initiatives or conversely, upwelling technology can add a feature to existing platforms such as oil rigs or offshore wind farms.

Carbon Sequestration

Phytoplankton by itself is not the best method for long term carbon sequestration. As part of a healthy ecosystem, phytoplankton blooms are fed upon by zooplankton who are fed upon by feeder fish who are then fed upon by larger fish. In this way, carbon passes through the food chain to be transported quickly to the bottom of the ocean and sequestered long term as fish waste. This is an ideal form of carbon sequestration. Absent that food chain and the larger fish fecal pellets, the zooplankton fecal matter moves slowly through the water column and mostly gets remineralized, making the ocean more acidic. Thus, the appearance of phytoplankton and zooplankton alone won’t achieve the total desired effect - but growing more fish will.

With increased stratification at the ocean’s surface - because warm water, nutrient poor layers on top do not mix with cooler water below the thermocline - higher sea surface temperatures (SST) can inhibit the amount of carbon the oceans can absorb from the atmosphere.

Global carbon credit markets need to build out an evaluation framework for ocean-based carbon sequestration that measures effectivity across all methods - from phytoplankton blooms (upwelled or fertilized) to the specifics of trophic food chain carbon transfer to kelp, eel grass and other photosynthetic species.

Summary

The Opportunity in Nutrient Upwelling Devices

Facilitating upwelling on a meaningful scale is a worthy goal in itself, climate change notwithstanding. But upwelling also happens to be a well-understood and effective mechanism by which many other ocean systems can begin to repair themselves - from carbon sequestration to temperature attenuation – and to foster ocean oases where life can develop and thrive. Deployed in numbers, these devices can have an outsized and cost-effective impact on both fisheries productivity and other important ocean systems - including a drawdown of atmospheric carbon.

Increased Marine Life Through Ecosystem Development

What would happen if marine life worldwide were increasing in number, not decreasing? Human populations would have more abundant food sources and all marine life would have greater genetic diversity – to name just a few benefits.

Expanded Biodiversity Hotspots

There are small numbers of internationally recognized marine biodiversity hotspots that need better conservation protection. However, just reducing fishing pressure in these locations is not a complete solution. Conservation does not reduce ocean acidification, temperature increase, or declining upwelling and productivity; much less the consequential food web disruption.

For example, if we were to place engineered upwelling technologies radially around a location such as Palau, this could augment the footprint of its biodiversity, increasing the habitat and productivity of its marine ecosystem and protecting corals. We anticipate this result would be achieved only after years of controlled studies to ensure mitigation of side effects could be managed effectively.

Increased Carbon Sequestration

Engineered upwelling technologies could significantly increase atmospheric carbon sequestration if deployed in numbers worldwide. To combat climate change, we will need to draw down atmospheric carbon now, along with reducing emissions and employing other methods of carbon dioxide removal or sequestration.

Compared to land-based carbon sequestration, engineered upwelling technologies create more marine life, more sustainable fisheries, and more positive effects worldwide. There is far more potential for carbon sequestration in our oceans than on land: not least because they represent a large percentage of our planet’s surface. We believe this form of carbon sequestration will be accepted on major carbon credit markets, post verification and validation.

Platforms for Additional R&D of Ocean Health Technologies

Nutrient upwelling devices could offer stable, multi-use platforms in the pelagic ocean. This could create a cost-effective opportunity for other research groups or technology companies to use the platforms for additional purposes. For example, suppose a university lab is working on a sponge-like material that can sequester marine carbon, but they need a larger deployment for a pilot study and can’t afford to build their own buoys. Our upwelling devices could serve their needs, and those of many other emerging experiments and research projects.

There are many problems related to ocean health that engineers and scientists can apply themselves to, and these buoys can provide a platform for many of them.

Free Range Mariculture

Upwelling buoys in the Pacific could also serve as a location for aquaculture farms. Given the phytoplankton and zooplankton blooms caused by upwelling nutrient rich deep water, the rest of the food chain will follow.

Fishing "sustainably" in a rapidly changing climate is simply riding the escalator down. There are more things affecting fish populations than overfishing. The new way forward is ecosystem development. We must create more than what we harvest such that fish populations increase year over year, which in turn will enable larger and sustainable fisheries.

These devices could prove vital in creating life in the ocean and be sources of considerable fisheries productivity while also drawing down atmospheric carbon. Clusters of upwelling devices could even help support schools of salmon migrating into the open Pacific, fish that would otherwise struggle to find food given the SSTA.

Aquavetic Labs

Aquavetic Labs is an engineering think tank and ocean health technology incubator located in Seattle. We are developing engineering concepts for upwelling focusing on maximizing effects, minimizing costs, and creating a sustainable and scalable business model.

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intended to be a justification for the development of engineered upwelling devices. It is not a scientific paper or a study. If you have questions, contact Anton at anton@aquaveticlabs.com.

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