Environment, Resource and Ecology Journal (2022)
Clausius Scientific Press, Canada
DOI: 10.23977/erej.2022.060512
ISSN 2616-3756 Vol. 6 Num. 5

Calculating Feasibility of Ocean Iron Fertilization with Post-Volcanic Eruption Phenomena

Bill Sun

The Webb Schools, 4255 El Molino Boulevard, Chino Hills, United States
cada.develop@gmail.com

Keywords: environmental engineering, bioremediation, volcanic eruption, climate change, iron fertilization

Abstract: This review proposes a novel method to accurately gauge the full ecological impact of manmade iron fertilization upon local environments not through direct experimentation, but by observing similar natural manifestations of fertilization in volcanic eruptions. Two case studies of specific volcanoes - Kilauea in Hawaii and Eyjafjallajökull in Iceland - show that firstly, ocean iron fertilization is capable of self-sustainment after ocean iron fertilization deployments in HNLC (High Nutrient Low Chlorophyll) regions, and secondly, ocean fertilization can be extended beyond the usage of iron dust fertilizer in ideal situations. For example, simple physical disturbances under the shores of one of Hawaii's islands propelled the large-scale development of phytoplankton colonies, in a process called "organic nitrate displacement". Kilauea's volcanic breakouts contributed to greenhouse gas emissions but were proportionally absorbed (7:1 ratio) by local phytoplankton growth. In another case of post-eruption phytoplankton development at Eyjafjallajökull in Iceland, while the volcanic eruptions dispersed a relatively small amount of iron-infused tephra through atmospheric injection and way of local winds, the airborne nutrients heavily stimulated phytoplankton colonies throughout surrounding waters and generated large biomasses of algae that were visible from space. After consecutive months of eruptions by Eyjafjallajökull in 2010, the airborne spread of iron-rich tephra particles lead to visible growths in phytoplankton colonies bordering other nearby countries. Through multiple comparative case studies of post volcanic eruption phenomena, ocean iron fertilization demonstrates its efficiency in initiating phytoplankton growth while revealing unexpected safety concerns in its deployment.

1. Introduction

Since the massive volcanic eruption of 1784 in Iceland that caused an abnormally cold winter around the world, scientists have been speculating about the correlation of eruptions to fluctuations in temperature.[1] It is now commonly known that a variety of natural post-eruption phenomena occur in the proximity of an active volcanic eruption that significantly lower temperatures through physical and biological changes in the environment. One common theory is that atmospheric shielding, the injection of volcanic tephra into a high-leveled environment, causes the greatest change in temperature through physically reflecting solar radiation out of the Earth. However, the stratospheric shielding effect of volcanic tephra lasts only a few years before dissipating into the atmosphere.[2] Besides the provisional effect of atmospheric shields, the cooling effect is heavily offset by the emission of sulfur dioxide gas during an eruption, which can destroy ozone in the stratosphere.[3] With further investigation, it becomes clear that atmospheric shielding by volcanos is more likely to cause temperature rise through chemical interactions than decrease solar radiation. With this, it is more likely that other distinct forms of post-eruption phenomenon - iron fertilization and organic nitrate displacement - help negate their own carbon emissions and contribute to the known global-scale cooling effects of volcanic eruptions.

Ocean iron fertilization is a hypothetical geoengineering technique that aims to artificially induce phytoplankton growth with the introduction of iron oxide as the catalyst.[4] There are reasons why iron oxide is used in place of more-easily obtained fertilizers such as nitrogen or phosphorus. Iron's ecological role as the primary limiting micronutrient in the open ocean heavily impacts the development of all other microorganisms. According to Liebig's Law of the Minimum, the scarcest resource has the greatest impact on its environment.[5] By this idea, iron oxide completely dictates the development of algae blooms and other nutrient-consuming aquatic organisms by the quantity of its supply, but only in areas where iron is scarce. In contrast, while organic nutrients like nitrogen and phosphorus exist in abundance and are also integral to the development of most ecosystems, they may not be as significant as the scarcest resources. Recent studies suggest that a small amount of volcanic ash fallout - consisting of around 2-5% Fe^{+} - can trigger the rapid development of algae blooms in HNLC regions, where nutrients are abundant but lack the visible influence of marine biomarkers.[6] Considering regions surrounding volcanic activity, trace amounts of airborne volcanic ash would contribute to algae bloom growth, creating large cycles of carbon sinks that can greatly alter climate.

Although climate manipulation techniques like ocean iron fertilization are largely unexplored by the scientific community, they are becoming increasingly relevant in modern political talk.[7] Climate change, a central motivation of iron fertilization studies, is a worldwide human-induced phenomenon that increases frequencies of flooding, heat waves and anomalous weather while threatening human livelihood with greater food and water scarcity. The World Health Organization has declared climate change to be a serious issue having the "potential to undermine decades of progress in global health", in correspondence to the communal agreement within the scientific community over the prospective advent of climate change. As a result, climate change is regarded as an imminent threat to quality of life by many countries and often finds itself at the center of political discussions in the US.[8] However, existing regulations to limit the effects of climate change necessitate large economical leaps in transitions between nonrenewable and clean energy. Since global citizens are active in the search for better methods of contributing to environmental sustainability without radical changes to fossil fuel-based industries, ocean iron fertilization may soon be integrated into modern usage by demand.

Despite ocean iron fertilization's rising prominence in the scientific community as an alternative to radical resource conservationism, the feasibility and formal moralities of ocean iron fertilization experimentation remain a barrier to full commercial development. In 2009, an attempt by a German environmental solutions company to conduct iron fertilization research quickly led to a shutdown after environmentalists claimed that the introduction of artificial phytoplankton blooms could damage local reefs.[9] Many other similar experiments by independent companies were also stopped, generally due to concerns over prospective environmental damage. However, the ability of phytoplankton to rapidly multiply after introducing small amounts of iron can be easily harnessed in responsible manners. Most notably, John Martin's posthumous 1980 paper on his large-scale experiments with algae shows that the benefits - high-efficiency carbon sinks - greatly outweigh detrimental effects on local environments.[10] From an alternative perspective, a better method of weighing pros/cons and producing judgements would be to analytically observe more natural occurrences of iron fertilization.

In this paper, I propose a novel method for accurately analyzing the full ecological impact of ocean iron fertilization: to compare and contrast mesoscale volcanic eruption phenomena and capture unique interactions between ecosystems and foreign volcanic tephra. Volcanic eruptions effectively produce - through a diversity of ecological phenomena - biomasses of phytoplankton that quickly reduce the eruption's own gaseous emissions for consumption while, on a global scale, collectively causing significant anomalies in temperature.[11] Besides containing nutrient compositions with levels of iron similar to low concentration iron fertilizer, tephra from volcanic eruptions are disbursed in much greater volumes than humans can supply. Furthermore, volcanic tephra, which can be carried up to great heights of 5 km or more,[12] simulates iron fertilization dispersion through atmospheric wind and initial eruptive force. The algae blooms produced under these conditions will be widespread and can last up to six months in longevity, consuming a significant amount of carbon dioxide to fuel development. In the case of one of Hawaii's major volcanoes, constant volcanic breakouts in one concentrated region created a large biomass of algae in 2018 that lasted for months afterward, revealing that algae blooms are capable of self-sustainability in optimal locations, specifically HNLC regions.[13] A high-VEI eruption, in this case, can be easily charted and interpreted to determine the specific properties of iron fertilization, including its overall efficiency. As such, another goal of this paper is to provide reliable statistical attributes of volcanic eruptions. This paper will attempt to reveal all aspects of natural ocean iron fertilization by closely analyzing two specific volcanic hotspots, including Kilauea in Hawaii and Eyjafjallajökull in Iceland.

2. Case Study: Kilauea, Hawaii

Kilauea is the southernmost volcano in Hawaii's chain of islands, known for being the most active out of five other volcanoes. Kilauea's breakouts from 1985 to 2018 have perplexing, contradictory effects on local climate and global anomalies. The volcano has maintained a steady VEI 3 volcanic eruptive chain for 35 years, emitting 100-200 tons of superheated SO_2 per day into the atmosphere.[14] Sulfur dioxide is a poisonous greenhouse gas that also disrupts the cooling effects of the ozone layer.[14] Kilauea also emits CO_2 on a large scale, which similarly contributes to global warming. As such, gaseous emissions from Kilauea and other volcanoes are generally assumed to elevate temperatures through a constant greenhouse gas supply.

Despite a volcanic eruption's ability to contribute to global warming through sulfur emissions and toxic stratospheric injections, it has an equal ability to offset organically-consumable gas products. 10 million kilograms of CO_2 reach the sea by means of phytoplankton consumption, nearly 12 percent of Kilauea's net carbon emissions on an active eruptive day.[15] Within six months of the most recent eruption of the Kilauea volcano in Hawaii, in December 2021, NASA's satellite identified a visible cluster of green biomass surrounding the volcano. However, the algae have consistently thrived around the island for over 30 years according to Smithsonian's weekly reports of volcanic activity. Kilauea reveals that resulting carbon emissions from an eruption can be easily offset by phytoplankton gaseous product consumption of the same magnitude. The volcano's daily eruptions create a habitable environment for phytoplankton and other chlorophyll-containing organisms to thrive in, by constant deliverance of carbon dioxide and iron-infused dust.

Besides iron fertilization, Kilauea's ecological cycle of providing for phytoplankton blooms has another significant mechanism called "organic nitrogen displacement".[16] When seawater comes into contact with hot lava, it becomes buoyant and quickly rises towards the surface, uprooting organic carbon and nitrate particles from the seafloor created by dead organisms. The organic nutrients soon rise to the surface and fertilize phytoplankton development. In Kilauea's case, its underwater flow of lava has spawned a significant volume of phytoplankton blooms, comparable to its effect on growth by aerial dispersion of tephra. This particular interaction between heated bottom-level seawater and nitrogen effectively produces an ideal environment in which algae can consistently feed on iron, carbon, and nitrate nutrients. Although low VEI volcanoes like Kilauea cannot easily change climates with its initial eruptions, they are still capable of causing vast phytoplankton growth within their surroundings and thereby altering CO_2 levels.

Despite the volcanic breakouts successfully spawning multiple carbon sink systems, the health hazards posed by airborne volcanic tephra is a legitimate concern to humans and wildlife. Unlike manmade ocean iron fertilization, there are a variety of natural metals inside airborne tephra particles such as aluminum, iron, and sulfur. The side effects of tephra contamination include acute poisoning, death of aquatic animals, and disruption to ecosystems through plant life decline. To humans, certain metals within volcanic tephra can cause respiratory issues such as sore throats and coughs through inhalation.[17] In severe cases, human DNA can also be damaged.[17] The pH of rainwater can also be altered through acidification by volcanic tephra. While these are examples of side effects of ocean iron fertilization that can be generally avoided through adjustment of fertilizer composition and dispersion methods, they are representations of what can happen if ocean iron fertilization is inappropriately used.

Ultimately, Kilauea is a prime example of ocean iron fertilization successfully cooperating with other forms of algae development catalysts. Algae blooms utilize their unique location where nutrients are easily derived from airborne tephra particles, as well as underwater organic particle dispersion to spontaneously grow. In the case of manmade ocean iron fertilization, a self-sustaining HNLC region is most optimal for post-fertilization phytoplankton growth.

3. Case Study: Eyjafjallajökkull Ice Cap, Iceland

Eyjafjallajökull had a final major eruption (VEI 4) in March 2010, emitting 0.27 km^3 of tephra into the atmosphere after constant seismic disturbance. The eruption column reached a significant height, going up to 10 km in the atmosphere and dispersing over a long region. According to one source, the grain size of tephra particles from the volcanic column ranged from .25-250 um, which is relatively small compared to conventionally-measured tephra sizes.[18] Despite Eyjafjallajökull registering a mere 4 on the VEI scale, tephra presence was widespread based on the total dispersion of micronutrients throughout the region.[19] During the last day of major seismic activity - March 20th - in the proximity of Eyjafjallajökull, the volcano ejected a glass-rich plume that got quickly picked up by strong surface winds, spreading over a large proximity. The noticeable abundance of dry soot and tephra contributed to the wind-fueled cloud of dust.

Although the volcanic eruption deposited gray-colored tephra over a wide region of 570,000 sq km,[19] algae development was relatively minimal in comparison to other eruptions in Table 1. Fe+ cycling was improved in local regions and a reported 10%-20% increase in phytoplankton from a series of locations around the volcano was observed, contrasting with John Martin's posthumous experimentation that produced thirtyfold biomass of algae under a controlled environment. Since acute metal poisoning and other natural detrimental phenomena cannot have taken place at Eyjafjallajökull,[20] these possibilities are left out of the broader picture.

However, satellite images of Eyjafjallajökull clearly reveal oceanside patches of green a month after its final day of volcanic activity.[21] Separate images show surrounding regions of water, closest to Ireland, filled with green swathes of chlorophyll, which may have been spawned with the help of Eyjafjallajökull's eruption. Since algae blooms tend to mature over a time period of six months, the slow growth of phytoplankton may be explained by the presence of two limiting nutrients. In Eyjafjallajökull's case, although tephra particles abundantly fertilized local waters, the rapid growth of phytoplankton colonies in the initial stages causes equally rapid nitrate consumption. Samplings done around Eyjafjallajökull's area of eruption reveal an unprecedented decrease in nitrate rates in certain HNLC water regions.[20]

This case study reveals that even though volcanic eruptions have the capabilities of supporting iron fertilization on a massive scale, biological change will not occur in case of a lack of a certain essential nutrient, like organic nitrate. Algae blooms are known for quickly dematerializing after disproportionate and unsustainable growth. Some species of phytoplankton are more resistant to nutrient deprivation with adjusted levels of nutrient consumption, in exchange for a slower growth rate. Eyjafjallajökull's eruption showed that in the case of cost-effective deployment of manmade ocean iron fertilization, location matters heavily in all aspects. Misjudged nutrient deployments cause little change, while targeted deployments have the potential for thirtyfold-and-beyond algae materialization.[22]

4. Conclusion

Since the time of ancient civilization, volcanos have been known as harbingers of destruction for their fiery eruptive traits and imposing plumes of dust. However, despite their cultural depiction, volcanoes equally foster new development in bio marine ecosystems by covering oceans with iron dust (aerial tephra sediment) and supplying phytoplankton, a base food chain component, with the necessary nutrients for growth. Both volcanic eruptions examined within this study exhibited high efficiency in causing global temperature drops with natural processes of ocean iron fertilization occurring. We know that ocean iron fertilization compensated for a large percentage of regional carbon dioxide sink in certain cases of eruptions. The original hypothesis - ocean fertilization being effective in altering global CO_2 levels - is furthered by positive correlations to VEI and post-eruption tephra volume and a logically-consistent negative correlation to sea proximity. Interestingly, the Kilauea volcanic eruption case study reveals that the growth of algae blooms is sustainable for long periods of time, suggesting that man-made iron fertilization efforts are long-term solutions to increasing carbon emission levels, if deployed in ideal conditions. The volcano's cyclical pattern of emitting gaseous vapors and being proportionally absorbed by organisms also shows that large phytoplankton blooms are capable of mediating the atmospheric effects of volcanic eruptions.

The political implication of this conclusion is significant: the support for utilitarian methods of manually reducing carbon emissions is growing in an era of human sustainability and protection for the environment. If supported, man-made ocean iron fertilization processes can be used to reduce global temperatures by the equal absorption of greenhouse gasses, presenting a tangible solution to a seemingly impossible-to-solve problem. The material needed for ocean iron fertilization - powder Fe^{+} - can be easily mass-manufactured by individual companies to provide for governmental purposes.[6] Iron fertilization efforts by individuals can also be capitalized and divided into shares to promote purchase and support of environmental efforts by the private sector, thus constituting an economically sustainable business cycle. Publicly-funded firms such as Planktos and Climos have previously been able to garner sufficient funds for their projects, although their efforts were eventually rejected by international environmental committees on accounts of ocean pollution. However, as shown in our study of post-eruption phytoplankton growth, ocean iron fertilization has the vast potential to absorb greenhouse gasses and power the phytoplankton carbon sink that holds the future to solving climate change.

Further research will be needed to compile a statistical database on attributes of volcanic eruptions to find definitive correlations between the intensity of an eruption and anomalies in temperature. Although it is beyond the scope of this study to provide a detailed implementation of iron fertilization, it can be assumed that geoengineering concepts such as ocean iron fertilization will not be utilized until more rigorous research can determine the true ecological impact of these environmental transformations.

Acknowledgements

I would like to thank my mentor for offering perceptive insights regarding the deeper ends of my research. I would also like to express my gratitude to my parents for thoroughly supporting my studies.

References

[1] Zambri, B.; Robock, A.; Mills, M. J.; Schmidt, A. Modeling the 1783–1784 Laki Eruption in Iceland: 2. Climate Impacts. Journal of Geophysical Research: Atmospheres 2019. https://doi.org/10.1029/2018jd029554.

[2] Robock, A. The Volcanic Contribution to Climate Change of the Past 100 Years https: // www. sciencedirect.com/ science/article/abs/pii/B9780444883513500349?via%3Dihub (accessed 2022 -08 -03).

[3] Eric Klobas, J.; Wilmouth, D. M.; Weisenstein, D. K.; Anderson, J. G.; Salawitch, R. J. Ozone Depletion Following Future Volcanic Eruptions. Geophysical Research Letters 2017, 44 (14), 7490–7499. https: // doi. org/ 10. 1002/ 2017gl073972.

[4] Martin, J. H. Glacial-Interglacial CO2change: The Iron Hypothesis. Paleoceanography 1990, 5 (1), 1–13. https: // doi. org/10.1029/pa005i001p00001.

[5] van der Ploeg, R. R.; Böhm, W.; Kirkham, M. B. On the Origin of the Theory of Mineral Nutrition of Plants and the Law of the Minimum. Soil Science Society of America Journal 1999, 63 (5), 1055–1062. https: // doi. org/ 10. 2136/ sssaj1999. 6351055x.

[6] Emerson, D. Biogenic Iron Dust: A Novel Approach to Ocean Iron Fertilization as a Means of Large Scale Removal of Carbon Dioxide From the Atmosphere https://www.frontiersin.org/articles/10.3389/fmars.2019.00022/full (accessed 2022 -08 -03).

[7] Fuentes-George, K. Consensus, Certainty, and Catastrophe: Discourse, Governance, and Ocean Iron Fertilization. Global Environmental Politics 2017, 17 (2), 125–143. https://doi.org/10.1162/glep_a_00404.

[8] Antilla, L. Self-Censorship and Science: A Geographical Review of Media Coverage of Climate Tipping Points. Public Understanding of Science 2008, 19 (2), 240–256. https://doi.org/10.1177/0963662508094099.

[9] Thiele, S.; Fuchs, B. M.; Ramaiah, N.; Amann, R. Microbial Community Response during the Iron Fertilization Experiment LOHAFEX. Applied and Environmental Microbiology 2012, 78 (24), 8803–8812. https: // doi. org/ 10. 1128/ aem. 01814-12.

[10] Martin, J. H.; Fitzwater, S. E.; Gordon, R. M. Iron Deficiency Limits Phytoplankton Growth in Antarctic Waters. Global Biogeochemical Cycles 1990, 4 (1), 5–12. https://doi.org/10.1029/gb004i001p00005.

[11] Phytoplankton as Key Mediators of the Biological Carbon Pump: Their Responses to a Changing Climate. Sustainability 2018, 10 (3), 869. https://doi.org/10.3390/su10030869.

[12] Sharpton, V. L.; Ward, P. D. Global Catastrophes in Earth History; an Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality; Geological Society of America, 1990.

[13] How Kilauea's lava fed a massive algae bloom https://www.sciencenews.org/article/kilauea-lava-eruptions-fed-massive-ocean-phytoplankton-bloom.

[14] Siegel, B. Z.; Siegel, S. M.; Nachbar-Hapai, M.; Russell, C. Geotoxicology: Are Thermal Mercury and Sulfur Emissions Hazardous to Health? Natural and Man-Made Hazards 1988, 589–597. https://doi.org/10.1007/978-94-009-1433-9_39.

[15] Wilson, S. T.; Hawco, N. J.; Armbrust, E. V.; Barone, B.; Björkman, K. M.; Boysen, A. K.; Burgos, M.; Burrell, T. J.; Casey, J. R.; DeLong, E. F.; Dugenne, M.; Dutkiewicz, S.; Dyhrman, S. T.; Ferrón, S.; Follows, M. J.; Foreman, R. K.; Funkey, C. P.; Harke, M. J.; Henke, B. A.; Hill, C. N. Kīlauea Lava Fuels Phytoplankton Bloom in the North Pacific Ocean. Science 2019, 365 (6457), 1040–1044. https://doi.org/10.1126/science.aax4767.

[16] Browning, T. J.; Bouman, H. A.; Henderson, G. M.; Mather, T. A.; Pyle, D. M.; Schlosser, C.; Woodward, E. M. S.; Moore, C. M. Strong Responses of Southern Ocean Phytoplankton Communities to Volcanic Ash. Geophysical Research Letters 2014, 41 (8), 2851–2857. https://doi.org/10.1002/2014gl059364.

[17] Siegel, B. Z.; Siegel, S. M.; Nachbar-Hapai, M.; Russell, C. Geotoxicology: Are Thermal Mercury and Sulfur Emissions Hazardous to Health? Natural and Man-Made Hazards 1988, 589–597. https://doi.org/10.1007/978-94-009-1433-9_39.

[18] Su, X.; Kushima, A.; Halliday, C.; Zhou, J.; Li, J.; Hatton, T. A. Electrochemically-Mediated Selective Capture of Heavy Metal Chromium and Arsenic Oxyanions from Water. Nature Communications 2018, 9 (1). https: // doi. org/ 10. 1038/ s41467-018-07159-0.

[19] Pyle, D. M. The Thickness, Volume and Grainsize of Tephra Fall Deposits. Bulletin of Volcanology 1989, 51 (1), 1–15. https://doi.org/10.1007/bf01086757.

[20] Achterberg, E. P.; Moore, C. M.; Henson, S. A.; Steigenberger, S.; Stohl, A.; Eckhardt, S.; Avendano, L. C.; Cassidy,

M.; Hembury, D.; Klar, J. K.; Lucas, M. I.; Macey, A. I.; Marsay, C. M.; Ryan-Keogh, T. J. Natural Iron Fertilization by the Eyjafjallajökull Volcanic Eruption. Geophysical Research Letters 2013, 40 (5), 921–926. https: // doi. org/ 10. 1002/ grl. 50221.
[21] Mason, B. Magnificent Marine Algae Blooms Seen From Space https://www.wired.com/2010/08/phytoplankton-blooms-gallery/ (accessed 2022 -08 -09).
[22] Duggen, S.; Olgun, N.; Croot, P.; Hoffmann, L.; Dietze, H.; Delmelle, P.; Teschner, C. The Role of Airborne Volcanic Ash for the Surface Ocean Biogeochemical Iron-Cycle: A Review. Biogeosciences 2010, 7 (3), 827–844. https://doi.org/10.5194/bg-7-827-2010.