NS166 FINAL PROJECT

Estimating olivine particle size effectiveness for carbon capture

NS166: Keeping Earth Habitable
Minerva Schools at KGI

December 2021

Word Count: 2332

Estimating

Introduction

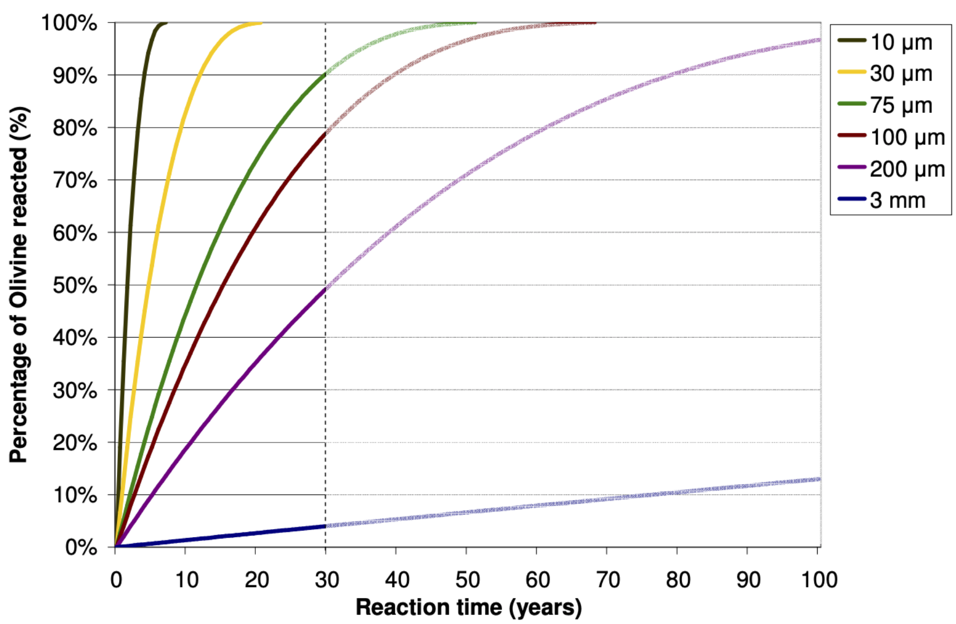
The climate crisis can be framed as an anthropogenic disruption of Earth's carbon cycle. The primary cause is the burning of fossil fuels, which releases carbon from long-term storage in the lithosphere into the atmosphere much faster than it can be reabsorbed. The excess carbon in the atmosphere has warmed the planet by 1.2 degrees to date (Rosen, 2021) and is on track to reach 2-3 degrees by the end of the century (Plummer & Popovich, 2021). Crossing that threshold, millions of people and 20-30% of species would be at risk (Smith et al., 2018).

The solution to this problem can be divided into two necessary components: reducing the flux of carbon into the atmosphere by cutting emissions and increasing the flux out through carbon sequestration. One of the most promising approaches to the latter is enhanced coastal weathering using olivine rocks.

Weathering is a part of the carbon cycle, involving a process of physical and chemical rock decomposition, which draws down carbon from the atmosphere and deposits it in the ocean as solid or dissolved carbonates and bicarbonates (de Cornick et al., 2018). This process operates on a geological timescale of thousands of years and cannot keep up with the current emissions rate, capturing only 0.3% of annual emissions (Beerling, 2020). However, there are several ways to accelerate its sequestration potential, primarily through grinding weathering rocks to increase surface area and taking advantage of the mechanical activation by the ocean (Schuiling & De Boer, 2015).

The rate of weathering using olivine is highly dependent on particle size, as this brings a larger surface area to volume ratio resulting in a much higher rate of dissolution and weathering. However, crushing olivine to smaller particles also comes with exponentially higher energy costs, meaning increased carbon emissions and a higher cost of sequestration. In this paper, we compare three different sizes of olivine particles and their associated carbon drawdown costs to determine if the increased rate of weathering outweighs the related energy costs, thus determining the optimal particle size for enhanced weathering.

Methods



The three sizes chosen for analysis and comparisons are 10µm, 30µm and 75µm. This is because, according to Koornneef & Nieuwlaar (2009), these are the particle sizes that will allow for at least 90% olivine dissolution within 30 years, a realistic timescale for carbon capture and storage considering the climate crisis (see figure 1). 10µm-sized particles dissolve the fastest with 90% dissolution done in 4 years, 30µm-sized particles at ten years, and 75µm-sized particles at 30 years.

While smaller olivine particles are more efficient, they also require more energy-intensive treatment for crushing and grinding. The largest size (75 µm) only requires primary crushing costing 13 kWh/ton, whereas to get to the 30µm size require secondary grinding (83 kWh/ton), while tertiary grinding for 10µm size requires nearly three times the energy requirement (233 kWh/ton), which translates to 20 kg, 120 kg and 385 kg Carbon/ton respectively (Koornneef & Nieuwlaar, 2009). We also factor in the cost of mining (1 kg), transportation (average to about ~96 kg), and olivine spreading (average to about 3 kg) to find the net effective rate after life cycle reduction (Koornneef & Nieuwlaar, 2009). While olivine efficiency estimates range from 0.5 to 1.25 tCO2 captured per olivine tonne, the most commonly cited value is 0.8 (De Boer & Schuiling, 2015; Koornneef & Nieuwlaar, 2009), which we use as a baseline assumption for calculation. From this, we can calculate the effective rate of carbon sequestered per year per tonne of olivine. Detailed calculation is explained further in Appendix A.

In addition, we also calculate the total cost of sequestering carbon with different olivine particle sizes. We reflect the differing costs in energy and take the average industrial electricity price in the United States ($0.06/kWh) (*U.S. Industrial Retail Electricity Price 2020*, n.d.) to calculate the energy cost. We also keep $10.52/tonne constant for other costs, including mining and transportation (De Boer & Schuiling, 2015).

Finally, to put things into perspective, we calculated the hypothetical cost to sequester 1Gt/year (or 1.8% of the world global carbon emission of 55Gt/year) using the effective rate of olivine and the total costs associated with this sequestration, as well as a total percentage of world GDP. We also calculated the percentage of olivine mined out of total olivine reserved and compared that volume to coal mining sectors.

Results

	10 micrometer	20 micrometer	75 micrometer
90% dissolution (years)	4	10	30
Total olivine dissolved per year (ton olivine/year)	0.225	0.090	0.030
CO2 sequestered per ton of olivine (tCO2/ton olivine)	0.8	0.8	0.8
Total rate of CO2 sequestration per year (tCO2/year/ton olivine)	0.18	0.072	0.024
Total carbon cost to remove 1 Gt of Carbon (tCO2/ 1Gt Carbon net)	0.451	0.225	0.12
Total cost of carbon over lifetime (tCO2)	0.3108	0.1837	0.1071
Total cost of carbon per year (tCO2/year)	0.0777050	0.0183673	0.0035714
Net rate of CO2 sequestered (tCO2/year/ton olivine)	**0.1022950**	**0.0536327**	**0.0204286**
Carbon sequestered needed (tCO2)	1,000,000,000	1,000,000,000	1,000,000,000
Total tonnes of olivine needed per year (ton olivine/year)	**9,775,651,822**	**18,645,357,686**	**48,951,048,951**
Energy cost for grinding per tonne of olivine ($/ton olivine)	$15.38	$5.48	$0.86
Additional cost (mining, transport, spreading, etc.) ($/ton olivine)	$10.52	$10.52	$10.52
Total cost to produce 1 ton of olivine over its lifetime ($/ton olivine)	$25.90	$16.00	$11.38
Total cost to produce 1 ton of olivine per year ($/ton olivine/year)	$6.47	$1.60	$0.38
Total cost to sequester 1 Gt CO2 per year ($)	**$63,292,457,724.18**	**$29,828,843,226.79**	**$18,565,501,165.50**

Table 1. Shows results across various metrics, including costs, carbon emissions and mining needs for different olivine particle sizes. Bolded concepts are those relevant to our analysis.

A high processing rate means the life cycle cost of small-sized olivine becomes significantly higher, up to 3 times the largest size. However, due to a much higher rate of sequestration for smaller sized particles, the 10µm-sized particles end up having the highest net rate of carbon sequestration at 0.102 tCO2/year, whereas 20µm-sized and 75µm-sized particles have a rate of 0.0536 tCO2/year and 0.02 tCO2/year. This means to sequester 1 Gt of Carbon yearly, we would need to mine 9.78 billion tonnes of olivine for 10µm-sized particles, 18.6 billion tonnes for 30µm-sized and 49.0 billion tonnes for 75µm-sized. For comparison, the global mining production for coal is roughly 7 billion

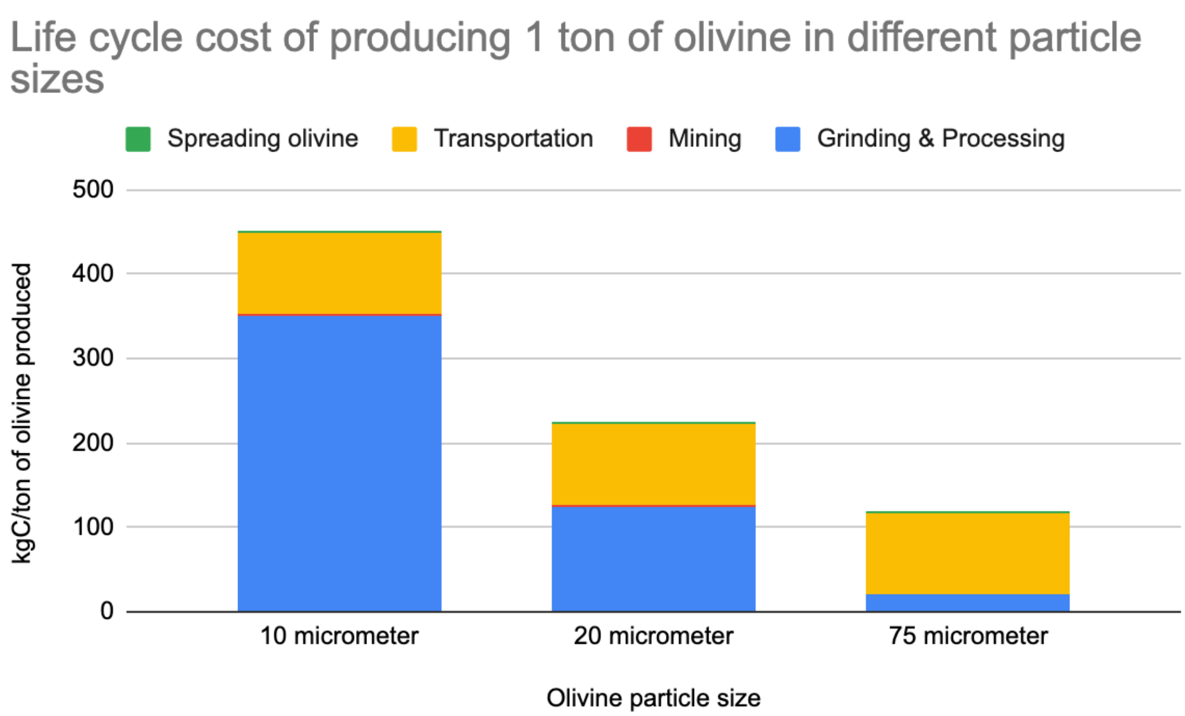


Figure 1. Shows life cycle carbon costs (kgC/ton of olivine) for different olivine particle sizes. Variation in outcomes is due exclusively to to grinding, while mining, transportation and spreading are held constant.

tonnes per year as of 2018 (*Global Hard Coal Production 1993-2018*, n.d.).

However, this higher rate of sequestration comes with additional costs. The electricity costs associated with grinding contribute up to 60% of the total cost of processing olivine in small-sized particles, making the cost to produce 1 ton of olivine $25.90 for 10μm-sized, whereas it's only $16.00 and $11.38 for 30μm-sized and 75μm-sized effectively. Further, this represents the cost of olivine over its lifetime. However, smaller-sized olivine get dissolved faster, meaning the cost per year is higher than larger-sized particles. When dividing the cost by the year they exist, the cost per year for olivine is nearly 20 times cheaper when it's at 75μm-sized.

Thus, even accounting for the faster rate to sequester carbon in smaller-sized olivine, the effective cost to sequester 1 Gt CO_2/year is over $18 billion for 75μm-sized

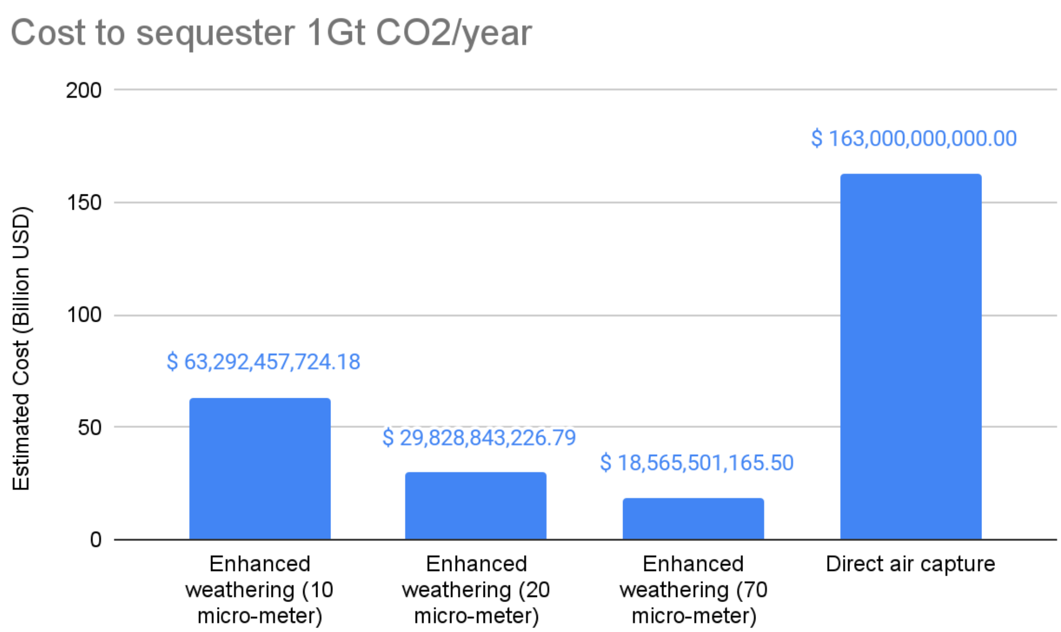


Figure 2. Shows costs of sequestering 1GtC/year for different olivine particle sizes, with a comparison to direct air capture, a competing sequestration technology

particles, $29 billion for 30μm-sized and $63 billion for 10μm-sized. As a baseline comparison, we also add the estimated cost to sequester the same amount of carbon using direct air capture, a common carbon capture, and storage alternative. Even in the worst-case scenario (10μm-sized), enhanced weathering is 2.5 times cheaper, and in the best-case scenario (75μm-sized), it is 8.8 times more inexpensive than the typical alternative.

Discussion

From the analysis above, it is clear that using larger-sized olivine particles would be more beneficial financially. However, this analysis is incomplete and elementary because we also need to consider other impacts on effectiveness from different parts of the weathering process and aspects of the environment that enhanced weathering might influence.

Firstly, the carbon sequestration rate is highly dependent on the environment where olivine is dispersed. Coastal or open ocean environments are preferred as they increase the speed of sequestration through mechanical activation (Schuiling & De Boer, 2015). Particle size has a significant impact when spreading directly on the open ocean because of the different rates at which particles sink. According to Köhler et al. (2012), only 1μm particles remain in the mixed surface layer of the ocean (the zone with necessary temperatures for sequestration) long enough to fully dissolve (3 years). By comparison, 10μm particles would remain for only ten days, enough for only 2.5% dissolution, and larger particles have worse results (Hauck et al., 2014). Thus open ocean spreading is not an option for larger particle sizes.

The case for 10μm particles does not improve in coastal spreading, as they are light enough to be carried by the wind into the open ocean, where they are too heavy to stay in the mixed layer zone (Köhler et al., 2012). On the other hand, 75μm particles are more likely to stay on the coast longer to weather carbon. It is, therefore, likely that the effective sequestration rate for 10μm particles would be lower than estimated compared to that of 75μm particles in coastal weathering. Nonetheless, we could not find accurate calculations or empirical evidence for the loss in weathering rate in different areas.

Supporting larger particle sizes further, the environmental life cycle assessment for enhanced weathering using olivine found that crushing and grinding olivine accounts for roughly 30% of the negative impact of enhanced weathering on marine aquatic ecotoxicity and over 20% of the negative impact on terrestrial ecotoxicity (Koornneef & Nieuwlaar, 2009). This effect is because electricity production during crushing and grinding emits hydrogen fluoride, mainly from coal combustion in electrical utilities, accounting for up to 80% of fluoride concentration in the atmosphere (National Research Council, 2006). Bioaccumulation of fluoride leads to inhibition of enzymatic activity, thus disrupting many critical biological processes, including glycolysis and protein synthesis in algae and many other aquatic organisms (Camargo, 2003). Therefore, reducing the energy consumption associated with crushing and grinding when using larger particles will have a net positive impact on ecosystems due to the reduction in hydrogen fluoride released. However, since this is directly correlated to coal combustion, the same effect can be achieved if we switch to more sustainable energy sources.

Increased mining is another serious concern, as it has implications for ecosystems and human health. According to our calculations, weathering using 75μm particles would require around five times more olivine extraction to match the sequestration rates of 10μm particles on the timescale of the climate crisis. This would undoubtedly result in much more significant environmental disturbance, especially in terms of land-cover removal and health effects from particle suspension. Moreover, the higher demands of extraction may be unachievable, or at least significantly harder to scale, as olivine production would have to grow from 8Mt/year today to 48Gt/year (Flipkens et al., 2021). Other effects like chemical contamination are less of a concern. A 2019 study of an olivine mine in Iceland found slightly elevated concentrations of Mg and Ni in freshwater near the site. However, Mg is a macronutrient, which is not considered a contaminant, and the Ni levels were negligible (Søndegaard, 2019).

Different particle sizes also pose different levels of health risk. Though larger particles imply increased extraction, the most severe health risks come from particles <10μm (Koornneef & Nieuwlaar, 2009). Any particle less than 75μm in diameter can potentially impact human health. However, smaller particles are more dangerous because they can enter the thorax (at <10μm) and the lungs (<4μm) (Taylor et al., 2016). Any of the scenarios we modeled may adversely affect health, but as particle size decreases so does respirability.

In summary, there is a high degree of uncertainty of the effects different particle sizes will have on the environment. Our analysis of the carbon and financial costs of mining, grinding, transportation, and spreading favors larger particles (75μm) but does not account for how effective different sizes will be during implementation and negative environmental and health externalities. Larger particles benefit from higher dissolution rates in coastal environments and lowered marine and terrestrial ecotoxicity impacts from HFs. They also pose less risk to human health, as they are less respirable than smaller particles. On the other hand, smaller particles weather at a much faster rate and would demand five times less mining, meaning this approach is potentially more scalable and would have less of an impact on terrestrial environments. These costs and benefits must be weighed against each other, though this is difficult because of the high degree of uncertainty about how these scenarios would play out in practice. We believe research into how different particle sizes react after spreading and into the impacts of mining as critical next steps. For the moment, we tentatively favor larger particles due to the lower cost and potentially higher economy of scale. Especially since enhanced weathering is sequestering nowhere near the rate of 1 Gt/year, reducing costs for carbon sequestration would be more imperative than other concerns.

Though in this paper, we have highlighted several costs to enhanced coastal weathering (and many more could be mentioned, like disturbances to marine benthic communities (de Boer & Schuilling, 2015) and effects on aquatic trophic chains (Köhler, 2012)) these costs must be placed in perspective. Very few other carbon capture technologies appear to have the potential of enhanced weathering. Direct air capture and storage remains 2.5 as expensive as the most costly weathering scenario in our estimations (10μm) and 8.8 times more expensive than the cheapest (75μm) scenario. Furthermore, scaling these technologies proves to be a lot more complicated compared to enhanced weathering, where all of the tools are readily available, and the process is easily replicable in many parts of the world.

Enhanced weathering also compares well to the most popular nature-based solution, planting trees. The safest places to store carbon are in the lithosphere and ocean sediment, which stores carbon permanently on a human scale (100,000-1,000,000 years) (Renforth & Henderson, 2017). Comparatively, storage in organic matter is temporary and ends with the matter's death. This exposes organic carbon reservoirs to threats like massive wildfires, which have become more common as the planet warms (Goss, et al., 2020). Additionally, implementing sequestration through reforestation at the same rate as enhanced weathering would demand a much higher percentage of land. Even if we use all the current available land around the world for planting new forests and reviving new ones, we can only trap an extra 206 GtC over a century, or 2.06 GtC/year (Bastin et al., 2019). In contrast, given the land required for olivine is roughly 2% of total land in the world and are continuously available after 4 - 30 years to continually capture carbon dioxide.

Lastly, we need to consider the cost of enhanced weathering versus those of a more severe climate crisis. Though many questions remain about enhanced weathering, it is one of the most promising known solutions in terms of scale and cost. In addition to theoretical research, the field needs more scalable operations to empirically test the calculations and contribute to carbon sequestration.

Appendix

Appendix A: Detailed calculations

The calculation is found in this sheet.

Appendix B: Work distribution

Ha: Methods + Result + Discussion, data analysis, revision, figures

Mateus: Intro + Discussion, revision, figure captions

HC & LO Index

#measuringmonitoring: We have provided enough justification and detail for every assumptions made for the calculation we made for the cost of olivine for different particle sizes. We have also explained the implications of the results, as well as things that were not included in the calculations (secondary impacts on health, environment, ecosystem, etc.) that need to be taken into consideration.

#scales: We have explained how the temporal scale plays a role in carbon sequestration (fitting from natural timescale to human timescale) and how they influence the effective rate of carbon sequestration based on particle size. We have also compared spatial scale in terms of mining olivine with coal mining to give a better understanding of the solution.

#effectivesolutions: We consider multiple angles as to why this is an effective solution, given the limitations and benefits that it brings in clear details. We also provide reason as to why this solution in particular is a lot better than any other alternatives.

#cyclingandflow: we characterized the problem in terms of the carbon cycle, and used this framing to compare enhanced weathering to other sequestration solutions, like reforestation.

#estimation: We have applied many estimation and approximation techniques. Figures of interests are used frequently, and all assumptions are clearly stated. The final estimate is plausible because it is in line with other estimation for cost of sequestration for olivine.

#dataviz: We have created clearly labeled and captioned data visualization including table for calculations, and two graphs for visualization of important data.

#rightproblem: we have clearly and effectively characterized the problem, including its initial state, goal state, scale and obstacles.

#utility: We have clearly stated the benefits and limitations of olivine, and come to the conclusion given all these considerations which one brings the most utility. We have explained our reasoning clearly as to why we make this decision (since utility of preventing climate effects are a lot higher than associated cost of weathering).

References

Bastin, J.-F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C. M., & Crowther, T. W. (2019). The global tree restoration potential. *Science*, *365*(6448), 76–79. https://doi.org/10.1126/science.aax0848

Beerling, D. (2020, July 9). *Guest post: How 'enhanced weathering' could slow climate change and boost crop yields*. Carbon Brief. Retrieved December 16, 2021, from https://www.carbonbrief.org/guest-post-how-enhanced-weathering-could-slow-climate-change-and-boost-crop-yields

Camargo, J. (2003). Fluoride Toxicity to Aquatic Organisms: A Review. *Chemosphere*, *50*, 251–264. https://doi.org/10.1016/S0045-6535(02)00498-8

de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., Dong, W., Ford, J., Fuss, S., Hourcade, J. C., Ley, D., Mechler, R., Newman, P., Revokatova, A., Schultz, S., Steg, L., & Sugiyama, T. (2018). Strengthening and Implementing the Global Response. In Global warming of 1.5°C: Summary for policy makers (pp. 313-443). IPCC - The Intergovernmental Panel on Climate Change .

De Boer, P., & Schuiling, O. (2015, January 1). *Mitigation of CO 2 emissions by stimulated natural rock weathering Fast weathering of olivine in high-energy shallow seas*.

Flipkens, G., Blust, R., & Town, R. M. (2021). Deriving Nickel (Ni(II)) and Chromium (Cr(III)) Based Environmentally Safe Olivine Guidelines for Coastal Enhanced Silicate Weathering. *Environmental Science & Technology*, *55*(18), 12362–12371. https://doi.org/10.1021/acs.est.1c02974

Global hard coal production 1993-2018. (n.d.). Statista. Retrieved December 16, 2021, from https://www.statista.com/statistics/267578/production-of-hard-coal-worldwide-since-1993/

Goss, M., Swain, D. L., Abatzoglou, J. T., Sarhadi, A., Kolden, C. A., Williams, A. P., & Diffenbaugh, N. S. (2020). Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters*, *15*(9), 094016. https://doi.org/10.1088/1748-9326/ab83a7

Hauck, J., Köhler, P., Abrams, J. F., Völker, C., & Wold-Gladrow, D. A. (2014). Climate Engineering Conference, 2014. In *Impact of open ocean dissolution of olivine on atmospheric CO2, surface ocean pH and the biological carbon pump*. Berlin; Alfred Wegener Insitut. Retrieved December 16, 2021, from https://epic.awi.de/id/eprint/37181/1/hauck_-_impact_of_open_ocean_dissolution_of_olivine.pdf.

Köhler, P., Abrams, J. F., Völker, C., Hauck, J., & Wolf-Gladrow, D. A. (2013). Geoengineering impact of open ocean dissolution of olivine on atmospheric CO_2, surface ocean pH and marine biology. *Environmental Research Letters*, *8*(1), 014009. https://doi.org/10.1088/1748-9326/8/1/014009

Koornneef, J., & Nieuwlaar, E. (2009). *Environmental life cycle assessment of CO2 sequestration through enhanced weathering of olivine.* https://www.semanticscholar.org/paper/Environmental-life-cycle-assessment-of-CO2-through-Koornneef-Nieuwlaar/786abdb8bbcf163386dd3ff916da3e9d95ed415b

National Research Council. (2006). *Fluoride in Drinking Water: A Scientific Review of EPA's Standards*. The National Academies Press. https://doi.org/10.17226/11571

Plumer, B., & Popovich, N. (2021, October 25). *Yes, there has been progress on climate. no, it's not nearly enough.* The New York Times. Retrieved December 16, 2021, from https://www.nytimes.com/interactive/2021/10/25/climate/world-climate-pledges-cop26.html

Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Reviews of Geophysics*, *55*(3), 636-674.

Rosen, J. (2021, April 19). *The Science of Climate Change explained: Facts, evidence and proof*. The New York Times. Retrieved December 16, 2021, from https://www.nytimes.com/article/climate-change-global-warming-faq.html

Smith, P., Price, J., Molotoks, A., Warren, R., & Malhi, Y. (2018). Impacts on terrestrial biodiversity of moving from a 2 C to a 1.5 C target. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376(2119), 20160456.

Schuiling, R., & De Boer, P. (2011). Rolling stones; Fast weathering of olivine in shallow seas for cost-effective CO2 capture and mitigation of global warming and ocean acidification. *Earth System Dynamics Discussion*, *2*. https://doi.org/10.5194/esdd-2-551-2011

Søndergaard, J. (2019). Environmental monitoring at the former Seqi olivine mine in Southwest Greenland. and no.: Scientific Report from DCE–Danish Centre for Environment and Energy, (319).

Taylor, L. L., Quirk, J., Thorley, R. M. S., Kharecha, P. A., Hansen, J., Ridgwell, A., Lomas, M. R., Banwart, S. A., & Beerling, D. J. (2016). Enhanced weathering strategies for stabilizing climate and averting ocean acidification. Nature Climate Change, 6(4), 402–406. https://doi.org/10.1038/nclimate2882

U.S. industrial retail electricity price 2020. (n.d.). Statista. Retrieved December 15, 2021, from https://www.statista.com/statistics/190680/us-industrial-consumer-price-estimates-for-retail-electricity-since-1970/