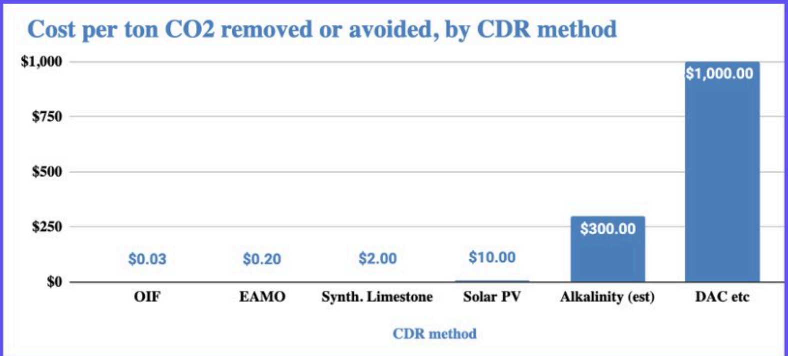
CLIMATE RESTORATION

WORKING PAPER

Cost-Effectiveness of Carbon-Dioxide Removal Methods

Costs determine scalability, and costs vary by a factor of 30,000



Peter Fiekowsky and Carole Douglis
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Introduction

What is Carbon-Dioxide Removal For?

One goal of CO2 removal (CDR) is to provide carbon "offsets" for companies buying them.
The other is to restore the pre-industrial climate by 2050 by removing legacy CO2.

Carbon-dioxide removal (CDR)) tops the climate headlines with increasing frequency, leading to the impression that we are rapidly developing a multitude of mostly industrial options for creating a safe climate.

What many miss is that the vast majority of "carbontech" CDR approaches are designed for the carbon-offset market. By definition, offsets only compensate for continued emissions. They do not touch the 1,000 gigatons of legacy CO2 that is causing most of today's climate havoc.

In fact, CDR today serves two distinct policy purposes. Each has merit, yet achieving the two goals requires quite different approaches and budgets and lead to strikingly different outcomes.

The two goals of CDR are:

1) Developing a CDR industry that underpins the carbon-offset market—thus adhering literally to the 1992 United Nations goal to "stabilize" greenhouse gas levels. Today this means stabilizing at dangerous levels never before experienced by our species. This is of course now called "net-zero emissions;" and

2) Following what appears to be the original intent of the United Nations Framework Convention on Climate Change: to restore GHG levels proven safe for humanity and nature as we know it. Restoring historically safe GHG levels is commonly called “climate restoration.”

Toward net zero

The goal of stabilizing greenhouse gas levels (GHG) was developed in the 1980s when the climate impacts of GHG were still imperceptible and global warming appeared theoretical. If emissions had ceased at that time, the climate would still be safe.

Today, adhering only to the net-zero goal appears problematic for future generations. Reaching net-zero by 2050 would push average atmospheric CO2 levels above 450 parts per million (ppm)—more than 50 percent higher than the pre-industrial levels in which humanity thrived for thousands of years. CO2 at today’s 420 ppm level is already causing havoc. Net zero remains our official goal and its carbon market has birthed a thriving carbontech industry that produces carbon offsets needed by companies that burn fossil fuels.

While the offset market promises good business for emerging CDR tech, and is expected to negate as much as 1% of continued emissions in the next decade…it doesn't reduce the concentrations of GHG in the atmosphere. If it did, it would defy the GHG stabilization goal. Only un-offsetted emissions reductions or carbon removals can actually reduce GHG levels.

Toward a restored climate

The second goal —restoring CO2 levels that have proven safe for humanity over thousands of years— requires more than stabilizing GHG levels. It requires reducing atmospheric CO2 by 40 percent— from today’s level to historically safe levels under 300 ppm. In practical terms, that means pulling a trillion tons of accumulated CO2 from the atmosphere, in addition to negating future emissions.

Different goals, different costs and benefits. Each goal—stabilizing GHGs at today’s level, and restoring a pre-industrial climate—are justifiable and we can achieve both. But it is important to remember that they are different and serve different needs.

We have compared various carbon-dioxide-removal (CDR) methods as to cost and scalability. The results are striking: Direct-air-capture (DAC) and related carbontech methods cost $500 - $1000 per ton of CO2 captured.

In contrast, climate- restoration solutions, based on biomimicry, cost only a few cents per ton of CO2 removed. DAC and iron fertilization of the ocean, for instance, differ by a factor of about 30,000. Even if DAC costs were to drop 90 percent overnight, industrial methods would still cost thousands of times more than CDR methods based on natural processes.

Where are we now?

The more expensive, industrial CDR methods are well suited to the carbon-offset market designed for net-zero emissions. CDR approaches based on natural processes, on the other hand, have been demonstrated to be so inexpensive and effective that they could be deployed on a large enough scale to remove the legacy CO2 and restore a safe climate—with moderate investment.

At this point, funders invest in carbon offsets to meet net zero. Billions of public- and private-sector funds have poured into relatively expensive carbontech for this purpose. Meanwhile, large-scale climate-restoration solutions—while thousands of times more cost effective and ready to go—remain less well known and virtually unfunded.

They will be implemented when the world returns to the original goal of giving future generations a livable planet by *restoring* and then stabilizing GHG levels.

Methods

To compare the methods by cost per ton of CO2 removed, we use data from the developers or Implementers themselves when published; or projections from peer-reviewed studies or institutions such as the National Academies of Science, Engineering, and Medicine (NASEM).

We include current and expected future costs, and separate out capital and operational costs. This allows a comparison of methods that are self-financing (through sales of by-products such as seafood and building materials) with others that would require large sums of public financing to make a measurable impact.We provide best estimates based on current data, neither optimistic or conservative.

Results

It turns out that the cost of CDR varies by a factor of 30,000—from a few cents to

a thousand dollars to remove a ton of CO2 from the atmosphere. *This enormous range makes sense when we consider that low-cost CDR, in particular ocean iron fertilization (OIF), duplicates and optimizes natural processes that have occurred for millions of years, and to which Earth systems are adapted.*

At the other end of the expense spectrum, CDR methods such as direct air capture (DAC), use industrial processes based originally on the technology of removing CO2 from submarines. These processes are designed to produce a pure CO2 product to sell for enhanced oil recovery and other commercial uses, or pumped and sequestered underground.

The startling variation — about 3 cents per ton vs $1,000 — also highlights very different reasons for pursuing CDR. ***Sequestering pure CO2 underground produces carbon offsets for businesses to purchase*** *so they can "offset" their continued use of fossil fuel. While useful to help fossil fuels make a graceful exit from the economy,* ***offsets do not actually reduce the level of CO2 in the atmosphere, as every ton removed is by definition counterbalanced by a new ton of emissions.*** *This keeps them in conformance with the 1992 goal of stabilizing GHG levels.*

Discussion

The carbon market focuses on stabilizing greenhouse gas (GHG) levels by 2050. Doing that will leave levels more than 50 percent higher than humans have ever seen long-term. The survival of human societies, and humanity itself, is frankly uncertain under the conditions of net-zero without restoring pre-industrial levels of CO2, which requires CDR on a much grander scale.

Clearly the 1992 UNFCCC climate goal to stabilize GHG levels is obsolete, with CO2 already 40 percent above historically safe levels and climate systems breaking down at alarming rates. A campaign to update the UN climate goal to "Restore and stabilize GHG levels" has therefore begun.

The premise that humanity has an obligation to future generations to intentionally restore a safe climate is attracting popular support. ***Climate restoration, defined as the goal and actions that restore historically safe CO2 levels below 300 ppm by 2050, appears to be achievable with already demonstrated CDR methods, for less than 1% of what we are (wisely) spending on the energy transition.***

Intermediate solutions such as solar photovoltaics (PV) and synthetic limestone have an important role in reducing future CO2 levels as well. Solar PV avoids *emissions, while synthetic limestone sequesters CO2 in high-quality building materials. Each of these provides carbon-negating services as a side-benefit of what people pay for: energy and building materials.* ***Both solar photovoltaics and synthetic-limestone-based concrete can help achieve net-zero emissions 100 times faster per dollar invested than new tech CDR.***

In years past, climate restoration was often dismissed as "geoengineering" (intentionally interfering with the climate system) and research on it failed to secure government or academic funding. Thus climate restoration approaches were advanced instead by independent scientists and entrepreneurs. With the exception of early work on OIF, It has rarely appeared in peer-reviewed literature. Yet climate-restoration methods have indeed been tested and demonstrated, with safety and efficacy uppermost in mind. They are ready to deploy and to scale.

As more and more of the public clamors to restore a safe climate, the modest capital costs of climate-restoration solutions could be covered by public or philanthropic funds. Otherwise, they are likely to be funded by compassionate grandparents and future grandparents for whom a liveable planet for our children is paramount.

In the meantime, government, industry, and the carbon-offset market can continue to fund expensive CDR projects that, while they have no hope of restoring the climate, are good for business and investors.

CO2 Removal: The Least Effective Methods Get the Most Funding

Method	Cost to remove one ton CO2 (operating cost + capital investment)	Cost ratio: OIF as baseline	Annual cost to public of removing 60 Gt CO2	Investment over last 5 years (est.)
Ocean iron fertilization (OIF)	**$0.03** per ton removed[1] Iron: $0.0006 per ton CO2 removed. +Ships & crew, OIF comes to $.01 - $.03 / ton.	**1 : 1**	**$0** Self-financed from fisheries and donations[2]; $1B / year for full scale implementation	**<$1 million**
Enhanced Atmospheric Methane Oxidation (EAMO, or ISA)	**$0.10** per ton CO2 equivalent (CO2e). Iron chloride: $0.06 / ton CO2e Ships & crew: $0.04 / ton CO2e	**3 : 1**	**$0** Funded by donations, insurance companies. $1B /year at scale	**$1 million**
Synthetic limestone **Blue Planet**	**$0** per ton CO2 = operating cost (revenue more than covers this) + **$50** = capital cost to build capacity to remove one ton per year (est.), depreciated over 20 years = $2.50 / ton	**83 : 1** (20- year plant lifetime)	**$0** CDR is self-financed through sale of rock	**$18 million**
Solar PV projects	**$0** per ton CO2 operating cost **$10** capital / ton of emissions *avoided* over 30 years[3]	**300 : 1**	**$0** CDR self-financed through sale of electricity	**N/A**
Ocean Alkalinity Enhancement, OAE **Enhanced weathering** **Vesta**	No data yet. NRDC and EDF estimate $100/ton for mining, grinding, shipping, distribution. Severe environmental issues: would require the equivalent of annual mining of 30 feet of rock from an area the size of Rhode Island.	**>3,000 : 1**	**$6 trillion or more**	**$200 million**
DAC, etc. **Climeworks** **Occidental** **Heirloom** **Charm**	**$1000** per ton CO2 is today's operating cost at the world's leading DAC facility.[4] This might fall to **$100** / ton by 2050. Plus capital costs of **$2,500 to $18,000** to remove one ton / year [5]	**30,000 : 1** Could fall to 3,000: 1	**$6 trillion to $60 trillion** For comparison: U.S. Federal spending is about $6 trillion.	**$5 billion** See Table 2

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[1] The National Academies' 2022 study (P99) confirms the operational cost of iron distribution as around $.01 to $.02 per ton, assuming Martin's million-to-one ratio of CO2 to iron. Yet it also posits (P97) a higher cost—$25 to $150 / ton which includes the monitoring required for sale of carbon offsets.

[2] Government and NGO funding are not possible until a public commitment to climate restoration is made.

[3] New, large-scale solar capacity costs about $1 million per megawatt (MW). A 1-MW solar farm produces 2,000 MWh of electricity per year. This replaces 2,000 MWh of coal, avoiding 4,000 tons of CO2. Therefore, over its 30-year life, a $1-million solar farm will avoid more than 100,000 tons of CO2 emissions. This works out to $10 per ton of CO2 avoided. Nuclear energy can use this calculation too.

[4] World's largest direct air carbon capture facility will reduce CO2 by .0001% | Electrek

[5] Capital needs are estimated from the 2022 raise of $650 million for the Mammoth plant that will remove 36,000 tons CO2 / year. The 2021 plant was said to cost $10 - 15 million to remove 4,000 tons per year.

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A climate goal that allows for the flourishing of humanity

Humanity has an obligation to future generations to restore a climate in which our species has actually survived long term. And we have an opportunity to do so.

To leave our children a livable world, we need to raise the bar on our climate goals. Rather than just reducing emissions (“net-zero”) and “avoiding the worst effects of climate change,” our aim needs to be restoring the pre-industrial climate which allowed the development of agriculture and civilization. That means bringing CO_2 levels back below 300 ppm.[6] We can do that by removing a trillion tons of legacy CO_2,—reducing CO2 by 130 ppm—before 2050.[7]

Nature has performed roughly this volume of carbon dioxide removal (CDR) at least ten times in the last million years, cooling Earth before ice ages.[8] Volcanic eruptions also cut CO_2 levels significantly, and at a rate approaching what we need. As recently as 1990, scientists figured out how large-scale, natural CDR works— and how we can replicate and accelerate it for pennies per ton of CO_2 removed.[9]

Cost and scalability: Biomimicry solutions cost pennies per ton and could remove 60 Gt a year. Carbontech CDR can’t compete.

Hundreds of startups and corporations are now developing “carbontech” CDR, spurred by government subsidies and the carbon-offset market. Carbontech CDR systems range from direct air capture to bioenergy with carbon capture and storage (BECCS) to ocean alkalinity enhancement, enhanced weathering (EW) on land, biofuel injection, and more. Carbontech has recently become a multi-billion-dollar industry. Most methods cost (or are likely to cost) between $60 and $1000 to remove a ton of CO_2.

Yet we also have simpler methods that amplify natural processes, and can remove a ton of CO_2 for three cents or less. Therefore the cost per ton of CO2 removed varies by a factor of thousands - 30,000 to be more precise. Since cost determines scalability, it makes a difference. Individuals, acting as concerned grandparents, can easily afford to restore the climate by removing 60 Gt of CO2 a year if it costs pennies per ton, or if it pays for itself. Restoration is not possible at $1000, or even $25 / ton.

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[6] See NASA graph, Figure 1, p. 5
[7] See Appendix 2
[8] NASA graph, p.5
[9] See pp. 7 ff

This paper is one of the first to quantify the differences among CDR methods from the perspective of climate restoration—removing 60 Gt CO2 annually. Table 1 summarizes our calculations, in order of least to most costly.

Considering the urgency of climate restoration and the scale of CO2 removal needed to achieve it, we need to start investing in solutions that cost far less and scale far more quickly.

Climate-restoration solutions are low-cost and highly scalable because they replicate Nature's methods through intentional processes categorized as "biomimetics" or "biomimicry." They are capable of removing CO2 for as little as pennies per ton.

In addition, they can produce useful commodities—fish from revived marine fisheries, and building materials—the sale of which could help finance the CO2 removal and even produce a financial return on investment.

Thus, especially if the investment comes from the private sector, the climate -restoration-scale solutions are likely to cost the public nothing. Nothing, vs $1,000 or optimistically $100 / ton of CO2. At $100 / ton, to remove 60 billion tons a year, the total comes to $5 trillion—close to the entire U.S. Federal budget of 2022–for 20 years. At today's cost of $1,000 / ton, restoring the climate would require $50 trillion / year for 20 years. That's half the GDP of the entire world.

DAC-related CDR can serve other commercial purposes, but when our goal is to restore pre-industrial CO2 levels by 2050, it is simply not a viable solution.

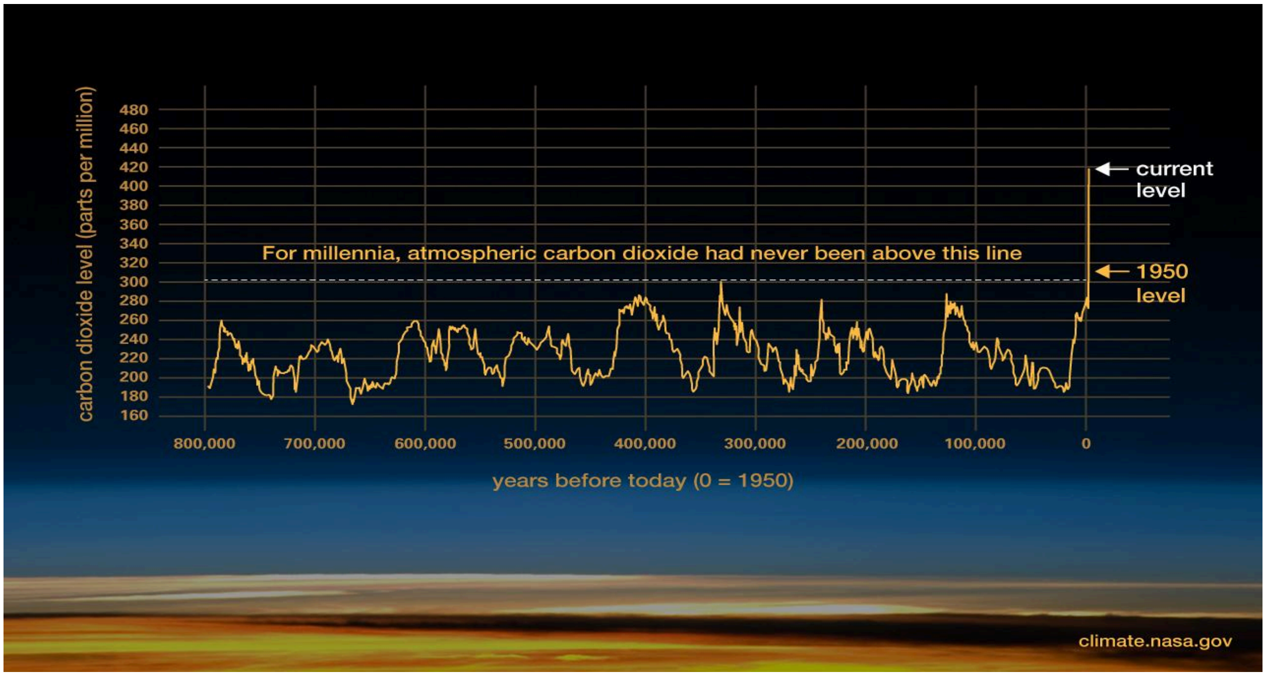

Figure 1. Nature has regularly drawn down massive amounts of CO2 as levels neared 300 ppm. During our species' evolution and development, 300 ppm was never exceeded—until about 100 years ago.

Nature removes massive quantities of GHGs during the ice age cycle—via "ocean iron fertilization"

Nature continuously removes CO2, methane, and other greenhouse gasses (GHG). The major natural processes for removing geologic amounts of CO2 are photosynthesis—in the ocean—and producing limestone on the seafloor. Limestone is almost half CO2 by weight.[10]

In fact, nature has removed up to a trillion tons of CO2 ten times in the last million years, preceding ice ages. The process reduced CO2 levels by about 130 ppm—roughly the reduction we need now to restore the climate by 2050.[11] (See Figure 1.)

The major natural mechanism is photosynthesis in the ocean, boosted through "ocean iron fertilization" (OIF)— minute amounts of iron distributed over the water mainly via dust storms from the land. Just as plants on land need water, marine plants need minerals, particularly iron. Most nutrients for marine photosynthesis are widely distributed, but iron, a requirement for all life, is poorly soluble in water and sinks. Iron-bearing dust storms are the primary source of iron over much of the ocean. They are rarer now than in previous eras, and the huge populations of whales that used to help circulate iron back to the surface are vastly reduced.

The discovery that iron dust can cause dramatic CO2 drawdown is relatively recent. In the 1980s, the late oceanographer John Martin figured out that an uptick in iron dust and resulting phytoplankton blooms led to the drop in CO2 during ice ages. He combined analysis of ice and sediment cores, with his own experiments and ingenious advances in measuring trace elements in ocean water. He and colleagues determined that today's Antarctic seawater, for instance, today contains only 1/50th the iron it held during the last ice age.

The National Science Foundation hails Martin's "Iron Hypothesis" as one of the greatest discoveries of the 20th century. Beyond discovering the major mechanism for dramatic CO2 fluxes over geologic time, Martin and others realized that we could replicate natural ocean iron fertilization intentionally, through biomimicry. This means distributing the iron-rich dust intentionally, typically from ships, locally and intermittently as from dust storms. In addition to pulling down large amounts of CO2, phytoplankton form the base of the marine food web, feeding fish and other sea life.

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[10] Limestone is $CaCO_3$, with a molecular weight of 100. It comes from CaO + CO_2; CO2 has molecular weight 44

[11] Converting parts-per-million to gigatons: 1 ppm corresponds to 8 Gt. So 130 ppm represents 1040 Gt—roughly a trillion tons. Here's the math: The atmosphere weighs about 5 million Gt. Reputable estimates range from 4.9 to 5.5; we use 5.3 Gt. One ppmv (volume) of the atmosphere weighs a millionth of that, 5.3 Gt. Correcting for the higher mass density of CO2, we multiply by the (molar) density ratio of CO2(44) to air (29), a factor of 1.52. So 5.3 Gt air / ppm X 1.52 (CO2/air) = 8 Gt CO2 / ppm.

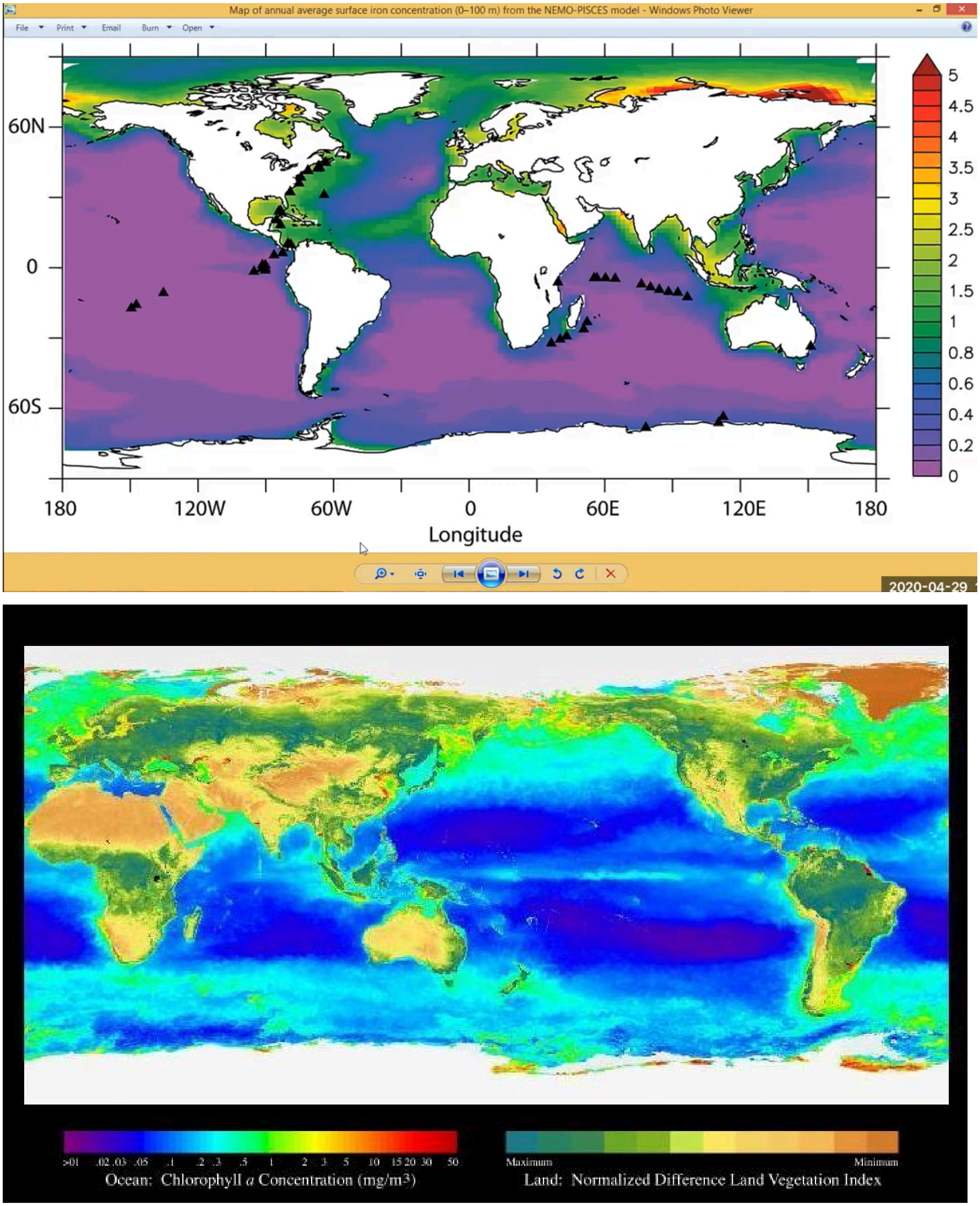

Figure 2. Chlorophyll (a proxy for phytoplankton mass) is relatively low in the three “High Nutrient Low Chlorophyll” (HNLC) regions, about 40 percent of the ocean, where other nutrients are plentiful but iron is scarce. (Public domain) And iron concentration, in ppb (Map of average surface iron concentration, 0-100m (2012) https://doi.org/10.1371/journal.pone.0030931)

We see that nature has repeatedly removed the *quantity* of atmospheric CO2 we need to remove to restore the climate. What about the velocity? Can it happen faster than typical geologic timescales? It turns out that volcanic eruptions frequently shower iron over the ocean, causing photosynthetic blooms and CO2 drawdown remarkably swiftly, corresponding roughly to the speed at which we need to accomplish it.

New analysis (see Appendix 3) shows that about 20 Gt of CO2 disappeared from the atmosphere within a year of the 1991 Mt Pinatubo eruption. This is separate from the well known 0.5C cooling effect from aerosols blasted into the upper atmosphere. The CO2 removal amounted to about 2.3 ppm of CO2. The Keeling Curve shows that at the time that CO2 emissions were rising 1.6 ppm a year—but this was zeroed out for 18 months following the eruption. The trend line stayed 2.3 ppm below where the trends indicate it would otherwise have been—for at least a decade.

Since OIF is based on natural processes powered by the sun rather than complex new technology, and involves easily available and inexpensive inputs, the costs are astonishingly low: roughly $.03 per ton of CO2 removed.

The operating cost for OIF is calculated to be about $.03 per ton of CO2 removed.

Three cents per ton of CO2…when DAC costs $1,000? How can that be? OIF is powered by sunlight and the needed nutrients are in the ocean, except for iron. Intentional OIF just needs to add to the ocean about $0.0006 of iron per ton of CO2 removed. That, plus ship, crew and operational costs, bring it up to $.03 per ton.

The three-cent-per-ton figure may at first glance sound fanciful but it's based on various estimates of the amount of iron needed, and today's cost of the iron.

Higher estimates from other sources include the cost of detailed carbon measurements required when the carbon removal is used to sell carbon offsets. These measurements are called "MRV" for measurement, reporting and verification. They generally increase the cost per ton by a factor of 500 or more.

We calculate the cost of CO2 removal based on several sources, including

- Theory and scientific estimates of the quantity of iron dust needed to pull down one ton of CO2
- The 2021 National Academies of Sciences' Consensus Study: A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration
- The current cost of iron dust, in the form of iron sulfate, on the international market

How much iron dust does it take to withdraw one ton of CO2?

From his pioneering research on iron dust and phytoplankton growth in both ancient and modern seas, John Martin calculated that it takes only one ton of iron to remove a million tons of CO_2 through ocean photosynthesis. In other words, a mere one gram of iron could prompt a phytoplankton bloom that removes a ton of CO2. It takes only 1 milligram per square meter (1 kg per km^2) in iron-starved waters to enable the bloom.

This remarkable ratio underlies Martin's famous 1988 quip: "Give me a half tanker of iron, and I'll give you an ice age," although this remark was a deliberate exaggeration.

Recent estimates of the quantity of iron dust needed to pull down one ton of CO2 range widely—from as low as 1: 20,000 in a few cases to as high as 1: 1.7 million tons. Many come in around one to several hundred thousand. Natural OIF, on which John Martin based his founding research, has been shown to be more effective than intentional OIF so far.

Yet the history of technology development suggests that intentional OIF, as it is practiced and honed, could possibly meet or exceed the effectiveness of natural OIF. This would be consistent with agriculture methodology that now commonly exceeds the food productivity per hectare of natural systems, but originally was considerably less efficient. For that reason we use Martin's million-to-one ratio for calculations.

How much would OIF cost to bring down a ton of CO2?

The National Academies of Science, Engineering, and Medicine's (NASEM) study on ocean CDR is often cited for its analysis of OIF. It is important to note that the NASEM study focus is distinct from climate restoration. Rather, it is a research agenda on ocean CDR as a way to achieve decarbonization (net-zero emissions), especially through carbon offsets. Decarbonization is a pathway to stabilizing CO2 levels, commonly assumed to be by 2050. This leaves CO2 levels more than 50% higher than humans have ever survived long-term. The 2021 NASEM Ocean CDR report characterizes efficient intentional OIF that optimizes natural OIF and might significantly reduce CO2 levels as misbehavior for unspecified reasons. The authors speculate that CO2 level restoration is considered inconsistent with the UNFCCC mission of stabilizing GHG levels and eliminating human interference with the climate system (p. 99).

The NASEM study proposes a research budget of $33M to $42M a year (p. 100-01) over 5 to 10 years for OIF—field study implementation, water sampling at various depths, modeling, monitoring by ships, autonomous water vehicles, satellites…the works.

Financing for science and for implementation must be, however, distinct. They serve different purposes and for integrity must be managed separately, thus we separate them, clarity and efficiency. We assume that government agencies will continue to fund research focused on achieving net-zero emissions, while a range of concerned groups, conceivably including government agencies, would pay for climate restoration implementations.

As to implementation, the NASEM study (p. 99) confirms a cost of "$1M - $2M for hundreds tons of iron and a small ship." Based on John Martin's calculations, the hundreds of tons of iron would remove hundreds of millions of tons of CO2 for $1M to $2M. With this ratio, it would therefore cost about $0.01 - $0.02 per ton of CO2 removed. (We increased the estimate from "one or two cents" to three cents, so it sounds slightly less crazy.)

OIF implementations usually use iron sulfate (ferrous sulfate) powder, which is inexpensive and typically sold as a fertilizer as well as a treatment for anemia (low iron levels in the body). Often produced as an industrial by-product, ferrous sulfate fluctuates in price but hovers around $200 /ton on the international market. Iron sulfate is ⅓ iron by weight, putting the cost of the iron at $600 per ton, or $0.0006 per ton of CO2 removed (dividing by a million). Thus, even if ten times more iron turns out to be needed, the iron would still only cost $.006 per ton. That would bring implementation costs from $0.03 to $0.036 per ton of CO2.

Restored fisheries figure into the equation too

By definition, OIF stimulates photosynthesis in phytoplankton, and phytoplankton forms the base of the marine food web. While much of this plankton community will sink, taking its biocarbon with it, much of it will also feed fish and other sea creatures (which also eventually sink or get eaten). In other words, well planned and timed OIF is likely to dramatically boost fish stocks— phytoplankton feeds fish, after all— which could provide a potential economic boon to communities that depend on fishing.

Dust from a volcanic eruption in Alaska in 2008 led to a phytoplankton bloom offshore, which preceded a record sockeye salmon run in 2010.That year, salmon numbered 34 million—up from 1.7 million the year before. Canadian pink salmon similarly increased by a factor of 44 from 2008 to 2009.

The 2012 OIF distribution off the Pacific coast of Canada was located and timed to feed Pacific salmon, which had been dwindling for decades. Alaska fishery records recorded the highest totals in history after the 2012 project. Some scientists point out that we cannot prove that these record catches following OIF were caused by the OIF. Yet no specific alternative explanations account for the numbers.

Parties interested in restoring fisheries, including public-private partnerships, might be well placed to partially fund OIF, paying for it out of increased revenue from revitalized fish catches. Therefore this CO2 removal process is likely to be self-funding after initial philanthropic investment.

A caveat: If OIF were funded through carbon offsets as assumed by the NASEM report (P97) instead of philanthropy and fish sales, its operating cost would likely be $25-$50 per ton. The added expense stems mainly from complex offset certification requirements—Measurement, Reporting and Verification (MRV).

Is OIF safe?

Understandably, adding anything to the ocean makes people nervous. While researchers have proposed testing in very large ocean areas, implementations would only be done in small areas called mesoscale eddies, smaller than the regions occasionally fertilized by volcanic eruptions.

Nature has been conducting localized intermittent iron fertilization frequently for millions of years, so marine ecosystems are already well adapted to it. Despite the fact that no detrimental side effects have been reported from natural or intentional OIF, such side effects have been a popular topic for speculation. A consortium of leading oceanographers and marine biologists now planning operational research confirms that OIF is by all accounts a safe process. In 13 field demonstrations performed since 1990, no detrimental side effects have been observed.

Any intentional OIF implementation must be accompanied by appropriate monitoring, with procedural corrections implemented when necessary. In case of unforeseen negative effects, phytoplankton blooms dissipate and the ocean patch reverts to pre-OIF status in a matter of months.

In sum, operational details can be refined, and implementation needs to be closely monitored, as with any intervention. But intentional OIF is not a new technology--it's a carefully replicated natural process. (See also Appendix 4)

Is OIF legal?

"There are currently no legally binding international treaties dealing specifically with ocean fertilization," according to legal experts at the Sabin Center for Climate Change Law at Columbia University.[12] So while opponents routinely claim otherwise, OIF is legal on the high seas, the only place it can work. Individual nations have authority over their territorial waters and to our knowledge none has banned OIF off their shores.

How might OIF be implemented now?

With OIF's effectiveness, safety and legality and low costs demonstrated, what is needed to jump-start the safe scale-up of this primary climate restoration method?

With operational costs starting below ten million dollars per year, with full scale estimated to be less than a billion dollars per year, and with the US government already investing billions per year in unscalable CDR methods,[13] It appears that climate restoration for the benefit of our children and future generations is simply not yet a priority for government, science, or academia.

At least three for-profit corporations designed to implement OIF have failed since 2005. Some scientific and environmental communities have objected to using the ocean as a source of profits, especially using carbon offsets that slow down the energy transition. It seems that a

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[12] The report is useful should you care to delve into attempts by opponents to halt OIF. Such efforts are also covered here.

[13] The US just invested more than $1 billion to kick-start the carbon-removal market | MIT Technology Review

non-profit which is accountable to the key stakeholders, youth, parents and grandparents is needed. This organization (or organizations) would align the interests of future generations, fisheries, environmental organizations and especially scientists. Raising the several to several hundred million dollars per year from concerned families appears to be viable.

If OIF is delayed 10 years, what is the alternative?

The scientific community frequently says that OIF implementations should be delayed until more is known (what needs to be known before starting scaleup is not clear). Excluding OIF leaves two climate alternatives: To not restore the climate, or to restore CO2 with the next lowest cost approach, synthetic limestone. Following UNFCCC guidance to stabilize but not restore the climate assures destruction of hundreds of cultures and ecosystems, but leaves leadership blameless as they follow their guidance. Restoring CO2 levels using synthetic limestone instead of OIF would cost almost 100 times more, and likely take 20 years longer, leaving extinct most cultures and species now in danger.

Removing methane— also critical for climate restoration

While we don't hear as much about methane removal, removing a ton of atmospheric methane produces 120 times the cooling impact of capturing a ton of CO_2. Oxidizing methane can also protect us (and the rest of life on Earth) against a potential existential threat: a swift methane burst from melting permafrost that could produce an extinction-level temperature spike.

Here again, Nature provides the model: natural processes oxidize 95% of the roughly 600 million tons of methane emitted by natural and anthropogenic sources each year, leading to the gradual increase in CO2 levels.[14] Recently, scientists have learned to accelerate this process. Enhanced atmospheric methane oxidation could double the natural rate and appears to be relatively inexpensive to implement. Articles on it are in progress andl awaiting publication.

Methane removal could quickly rewind the clock on climate change by eight years of today's warming. We calculate that less than $1 billion per year invested in methane oxidation could remove enough methane to reduce warming by 10%.

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[14] When 100% of methane emitted is oxidized each year, the methane level is constant. Methane levels today are increasing 0.4% per year, which multiplied by the 12 year methane lifetime indicates that emissions are 5% more than removals.

by 2030.[15] Modeling **shows that implementing OIF and methane-removal together could, by 2050, reduce warming to where it was in 1990**—before the monster storms, droughts, floods, and wildfires now plaguing the planet (Fiume 2023). (See Appendix 1)

Methane removal is measured in terms of "CO2 equivalent" (CO2e). One ton of methane removed is currently considered in common contexts to have equivalent climate impact to 25 tons of CO2 removed (European Commission).

Solar and other zero-emission solutions are also low-cost investments in climate restoration

Solar and wind farms efficiently reduce future CO2 levels, lowering them 100 times more per dollar than direct air capture, (although 300 times less per dollar than OIF). Thus, anyone looking to meaningfully reduce CO2 levels for our children can feel safe and conservative investing in solar PV.[16] Wind farms are similarly effective, but harder for individuals to contribute to.

Solar and wind power does not *remove* the CO2 already in the atmosphere, but does efficiently *avoid* current and future emissions. Every $10 invested to build a solar or wind farm avoids the release of one ton of CO2 over 30 years, the lifetime of a typical farm. As a rule of thumb, each solar panel saves a barrel of oil (or equivalent in coal or natural gas) per year.

Nuclear power can be compared with this number too. However it costs 3 to 10 times more than solar per kWh and thus per ton of fossil fuel CO2 avoided. It commonly requires 5 to 10 years to build, compared to 1 to 2 years for solar. Nuclear, as a 24/7 "base load" source, is competing in most markets against storage, such as batteries, whose costs are rapidly decreasing.

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[15] Wittmer and Zetzsch 2017 showed that 78 atoms of Cl can be produced per molecule of FeCl3 during an hour of daylight. Multiplying that rate by 6.4 hours of sunlight per day and 10 days expected lifetime of the aerosol gives a total 5000 Cl atoms per iron atom. Most of those chlorine molecules will oxidize methane. Some will oxidize other molecules such as ozone and hydroxyl radicals whose concentration is a few percent of methane's (a few parts per trillion). FeCl3 has a molecular weight ten times that of methane. Thus one ton of FeCl3 could oxidize 5000/10 or 500 tons of methane under suitable conditions. At $750 / ton the $FeCl_3$ removes methane for $1.50 per ton, or $.06 per ton of $CO_{2\text{equivalent.}}$
Reducing methane levels by 50% may require oxidizing half of total methane emissions of 600 Mt / year with ISA. This would require about 600,000 tons of FeCl3 per year. At $750/ton, this is $450 million per year for $FeCl_3$, plus an estimated $150 million per year to operate the required ships, barges and dispersion equipment, totaling $600M per year, well below $1 billion.

[16] New, large-scale solar capacity costs about $1 million per megawatt (MW). A 1-MW solar farm produces 2,000 MWh of electricity per year. This replaces 2,000 MWh of coal, avoiding 4,000 tons of CO2. Therefore, over its 30-year life, a $1-million solar farm will avoid more than 100,000 tons of CO2 emissions.

While clean energy is not CDR, it reduces future CO2 levels ten times more efficiently than carbon-offset funded CDR. It thus should be considered to be a competitive option.[17]

Synthetic limestone: Paving and building with CO2

Limestone is nature's second silver bullet for removing hundreds of thousands of gigatons of CO_2. Nature has sequestered, over the last billion years, 99 percent of all of Earth's carbon in limestone and similar rocks, mostly on the seafloor. Limestone accumulates from the sunken skeletons and shells of dead plants and animals. Emulating the way an oyster creates its calcium-carbonate (limestone) shell, several companies have begun to produce synthetic limestone. We consider this a Plan B for climate restoration, with OIF being Plan A.

Like limestone from the seabed, the manufactured version is nearly half CO_2 by weight. Synthetic limestone is already being produced and sold as a high-quality substitute for quarried rock. (Blue Planet Systems. 2023). The San Francisco International Airport is building new runway and terminal facilities with concrete made with synthetic-limestone aggregate. Since synthetic limestone is profitable to sell, its cost per ton of CO_2 removed is zero after the capital investment is made.

Producing synthetic limestone requires roughly 1000 times more capital investment than OIF. **But operating costs are covered by the sale of building materials— so again, no need for public funding.** If OIF were to fail to scale for some unexpected reason, synthetic limestone provides a viable, although more capital intensive, alternative.

The leader in synthetic limestone, Blue Planet aggregate sequesters roughly half a ton of CO2 per cubic meter of concrete, even after being mixed with standard cement. A number of other companies (Grandoni 2023) are developing and offering low-carbon or negative-carbon concrete, although they still sequester an order of magnitude less CO2 per cubic meter as Blue Planet.

Seaweed: another scalable CDR

Not listed on the chart is the fourth CDR technique which is capable of removing more than 10 Gt CO2 per year, production of kelp and sargassum seaweed in the deep ocean.[18] Like OIF and synthetic limestone, it produces valuable products which makes it a self-financing pathway. Its capital costs per ton of annual capacity are expected to be several times higher than synthetic limestone. However its operational cost to the public is still zero because it can be a profitable business, selling high value food, fuel, and chemicals with roughly half of the harvested crop. The rest sinks into the deep ocean where the carbon will stay for centuries or millennia.

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[17] The 2023 Levelized Cost of Energy Analysis by Lazard suggests that utility-scale solar costs less than \$1,000 per kilowatt (KW), while the comparable cost per KW for nuclear power is between \$6,500 and \$12,250. At present estimates, the Vogtle nuclear plant will cost about \$10,030 per KW.

[18] Seaweed is described in "Climate Restoration: The Only Future That Will Sustain the Human Race", 2022 Fiekowsky and Douglis, chapter 4.

This pathway is powered by free sunlight as is OIF and doesn't compete for space on land, making it easily scalable. However it requires significant structures and effort for harvesting and turning the seaweed into products, slowing down the scaling process, making it a "Plan C" for carbon removal at the scale needed to restore an historically safe climate. On the chart of cost effectiveness it would be between synthetic limestone and solar.

DAC-related CDR: Good business in the carbon-offset market

Most public and commercial CDR funding currently flows to DAC-related, highly mechanized carbontech at the top of the cost range, for political and commercial reasons. These technologies enjoy major corporate support and lobbying, media buzz, and a business model that earns profits from the burgeoning carbon-offset market (Grandoni 2023). They assume that DAC costs will fall from today's quotes for $1000 / ton to perhaps $40 / ton, which will produce a trillion dollar market. However the trillion dollar funding source is yet to be discovered.

DAC-related CDR methods derive from century-old methods that remove CO_2 from submarines, with new approaches emerging regularly. They have a role to play in restoring the climate. CDR startups engage the public in climate discussions and inspire climate policy. They offer climate-action jobs. They may provide pure CO_2 for industry without burning natural gas. As long as we continue to use fossil fuels, they provide verifiable carbon offsets for individuals and companies wishing to lower their carbon footprint while still employing fossil fuels (IEA 2023).

Is climate restoration possible using DAC-related CDR?

The simple answer is: No, because it's not financially viable. While cost estimates vary widely, (Keating 2023). Climeworks, the world's leading DAC company, charges about $1,000 to remove a ton of CO_2. To remove 60 gigatons of CO_2 a year at today's rate would cost $60 trillion a year. That's about half of the GDP of the entire world. At half that —$500 per ton CO2—using DAC to restore the climate would cost more than the GDP of the United States.

Practitioners optimistically project the cost of DAC to fall by a factor of ten, to $100 / ton or less by 2050. But **even at $100 / ton, the price tag of removing 60 gigatons through DAC and other carbontech comes to $5 trillion per year.** That's getting close to the entire U.S. Federal budget. In any case, by 2050, we need to be finishing the job of climate restoration, not starting it.

After billions in investment already, DAC technologies now capture only about 10,000 tons of CO2 a year. The International Energy Agency estimates that perhaps they could scale to 980 million tons by 2050. That's roughly 1% of the climate restoration capacity required to restore the safe CO2 levels. It's also less than 2% of what's needed just to reach net-zero.

DAC costs thousands of times more than OIF or methane oxidation. Entrepreneurs expect its CDR price tag to decline over the next ten years. But the costs of climate-restoration solutions based on natural processes are likely to decline even more rapidly. This is because DAC technology is already 20 years more mature. The extraordinary cost efficiency ratio is likely to remain or increase.

Ocean alkalinity enhancement (OAE) and land-based enhanced weathering (EW)

Another technique garnering attention today is ocean alkalinity enhancement, which consists of adding finely ground alkaline substances, including basalt, olivine, or lime, into seawater to counteract ocean acidity and draw down CO2. Still in the testing phase, ocean alkalinity enhancement is classified as “marine CDR” (or “mCDR”) like iron fertilization, and it is often confused with OIF. “Enhanced weathering” generally refers to applying such rock dust on land, sometimes as soil enhancement.

Because OAE and EW are still in early days, we lack data on safety, effectiveness, speed or cost. Theoretical cost estimates range from $70 to $160 per ton of CO2 removed at the needed scale, while some hope that net costs may become as low as $3 per ton.

Based on the geological process of weathering, OAE sounds gentle. However, at the scale required for climate restoration, it could cause enormous environmental disruption. Due to the basic chemistry involved, it **takes between one and three tons of alkaline rock to remove *one* ton of CO2.**[19] This is roughly a million times more material than OIF.[20] In other words, more than a million times more rock would need to be processed, requiring almost a million times the cost and environmental damage.

Let’s take the average and say 2 tons of rock to 1 ton of CO2 removed. Then removing 60 Gt CO2 per year using OAE would require mining, grinding, and shipping roughly 120 billion tons of rock per year. That’s twice the quantity of all substances mined today, from rocks to coal, to metals. It’s ten times the amount of coal mined worldwide.

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[19] Consider limestone: one molecule of CaO combines with one molecule of CO2- so the CO2 capture ratio is roughly one to one (actually, 1.3 tons of CaO to 1 ton of CO2). WIth other alkaline rocks, up to three tons is needed to chemically absorb one ton of CO2.

[20] According to the widely accepted iron hypothesis, about one ton of iron may be able to remove about a million tons of CO2 (Martin, 1990) while a ton of alkaline rock can remove less than one ton of CO2. (See note above)

Mining on this scale would require removing 30 feet of rock over 10,000 sq km[21] (larger than the area of Rhode Island) every year for 30 years. When the source of the alkaline rock is inland, such as near Salt Lake, Utah--transportation alone takes a tremendous amount of energy.

Several variations on OAE that use electricity to reduce the amount of rock required have been proposed. These methods, mainly theoretical at this point, are also commonly projected to cost about $100 per ton of CO2.

Another variation would use mine tailings— the waste stream from mineral extraction and processing. Mine tailings are often alkaline and could be dumped off nearby seashores to reduce ocean acidity locally. This might help restore shellfish production, which is now collapsing in many areas due to ocean acidification. If such activities are allowed by the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter,, they might be profitable and perhaps benefit local communities.

But they would have essentially no impact on the climate: The scale of such action is a fraction of a percent of what is needed for climate restoration.

The business model for OAE, as for most CDR projects, is based on selling offsets in the carbon market. If carbon prices are high enough, OAE companies could sell offsets to companies that are still emitting CO2. OAE then, like other offsetting technologies, would allow buyers to continue to postpone their move to clean energy. While offsets can prolong the use of fossil fuels, nevertheless they support UN climate goals, which include expanding carbon markets.

In sum, OAE could have co-benefits such as restoring local shellfish beds. But there is no existing financial model in which it actually reduces atmospheric CO2 levels, so it is not a climate-restoration solution.

This may be the first time that the potential environmental disruption of large-scale OAE has been quantified; most OAE research focuses on chemistry. Our hope is that these calculations contribute to policy making and help inspire investment into fruitful climate-restoration solutions such as OIF.

Why do we not list common “nature-based” CDR methods as climate-restoration solutions?

Reforestation, afforestation, biochar, soil regeneration, regenerative agriculture, and other eco-restoration techniques greatly benefit the environment, ecosystems and human health. They should be pursued in their own right. They draw down a substantial amount of CO2 a year, and depending on policies and the practices of people throughout the world, have the potential to

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[21] 100 Gt of rock is about 50 km^3, assuming a density similar to limestone. If 10m (33 feet) depth is quarried each year, that requires digging up 5000 km^2 annually, an area larger than the state of Rhode Island. This could raise environmental and aesthetic concerns.

withdraw even more. However, wildfires, drought, and other disturbances can wipe out some types of projects in a season or even an hour. Therefore their CO2 storage is unreliable and would not be considered permanent.

In addition, when CDR methods are implemented primarily for income through the carbon-offset market, CO2 levels will not drop. When, say, a forest is planted for offsets, every ton of CO2 it removes for a few decades is negated by a ton of CO2 emitted that stays in the atmosphere for centuries. That's the offset revenue model: you only get paid to "offset" emissions as long as there are discretionary emissions to offset.

Why do DAC and other high-priced tech get most of today's CDR funding if they can't restore the climate?

Here's one explanation: DAC and related methods are politically safe investments for the many people who want to demonstrate doing something impressive for the climate—while avoiding the reputational risk of being accused of "geoengineering" or "letting oil companies off the hook."

Carbontech is seldom labeled geoengineering, since, ironically, it cannot actually reduce CO2 levels in any existing financial model. This is because the cost is prohibitive. Thus the amount of CO2 it can remove is miniscule. For DAC to remove current emissions alone (36 gigatons a year) would cost $30 trillion, five times more than the U.S. Federal budget. And as mentioned, it thus far captures only about 10,000 tons of CO2 a year—less than a millionth of our emissions—despite billions in investment.

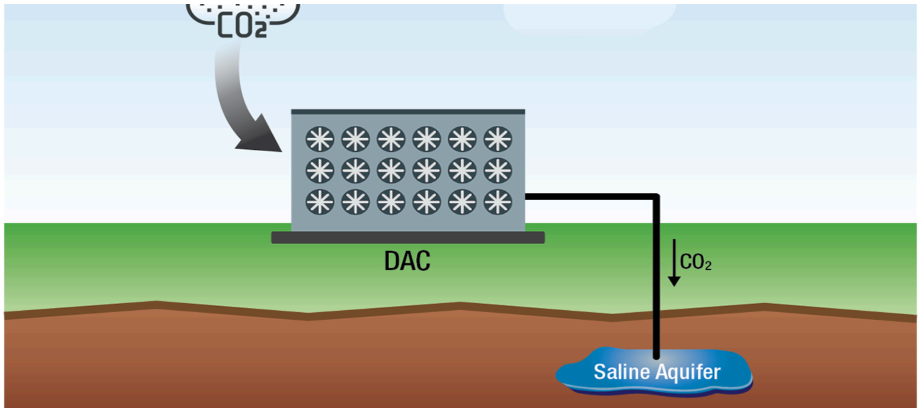

Figure 3. A DOE representation of DAC with underground storage. High-tech chemical and mechanical processes are receiving billions in public funding.

Another reason DAC receives strong funding: the purified CO2 from DAC is widely used in profitable oil and chemical production which then justify tax subsidies for it. For years, most of it has gone right back into producing more fossil fuels through "enhanced oil recovery." Because the CO2 gets pumped down to push more oil out of oil fields, petroleum corporations and their lobbyists generate powerful support and high subsidies for DAC.

A third reason for the attention and funding flooding to carbontech CDR: While it can't restore the climate, it can make money for investors. The carbontech CDR business model relies on carefully designed subsidies and carbon offsets (Hiar 2021).   The catch is that every ton of CO2 captured is, by definition, negated by at least a ton of CO2 emitted—so CO2 levels remain the same.

OIF and Methane oxidation have a thousands-to-one advantage in cost and scalability. So why aren't they widely funded?

This has been a perplexing question for years. One likely answer is that the climate goal set by the United Nations back in the early 1990s and adopted by the world is to "stabilize greenhouse-gas levels." When the stabilization goal was established, CO2 levels were around 350 parts per million (ppm) and climate change was nearly imperceptible: stabilizing seemed to be a safe target.

However, with CO2 levels now above 420 ppm and climbing fast, we urgently need to update our climate goal. If we reach only net-zero in 2050 (that is, where CO2 removals balance out additions) CO2 levels will be 50 percent higher than humans have survived long term. **To ensure a viable future, our climate goal should be "to restore and stabilize" GHG levels.**

Conclusion: We already have the tools we need to restore our climate

Climate restoration for the flourishing of humanity has barely made an appearance on the public agenda. After all, future generations mostly do not vote, pay taxes, demonstrate, or lobby.

Instead of supporting the most effective climate-restoration solutions— ocean iron fertilization and methane removal— business and political interests are investing billions in expensive, new, and far less effective CDR technologies. What many do not realize is that these methods actually support today's fossil fuel economy, as they provide carbon offsets to energy and chemicals industries, and to anyone else who continues to emit CO2 instead of investing in and transitioning to clean energy.

Providing offsets does, however, contribute to the widely accepted goal of "stabilizing greenhouse gas emissions" and preventing human interference in the climate system as set by the United Nations in the early 1990s—now commonly referred to as net-zero emissions. But by now, CO2 levels are so high that stabilization only is a recipe for global calamity. Achieving net-zero emissions alone, without restoring safe CO2 levels, would by 2050 leave us with atmospheric CO2 levels higher than those of today, which are already causing climate-related disasters around the world.

Archaic official goals aside, as humans we have a moral obligation to leave our descendants a liveable world, which includes a climate that humans have actually survived over the long term. That translates to CO2 levels under 300 ppm—not 460 ppm, which is where net-zero alone would bring CO2 by 2050.

Today's inconvenient truth is that nearly all public and private funding for CDR today goes to technology that cannot restore safe levels of CO2: the least effective and the most expensive. After billions of investment, DAC draws down a grand total of 10,000 tons of CO2 a year. Even with technical improvements, and a 90 percent cost reduction, restoring the climate with DAC would cost close to the entire U.S. Federal budget each year, for 20 years.

If we care about future generations, we will urgently fund the few CDR methods that can scale quickly and cheaply enough to bring back a safe climate for humanity and nature. These climate-restoration solutions replicate and accelerate processes proven by Nature over millions of years. OIF at scale could pull CO_2 back to safe levels by 2050, giving future generations a future to look forward to rather than dread. Enhanced Atmospheric Methane Oxidation could restore pre-industrial methane levels within a decade, cooling the planet and simultaneously protecting humanity and nature from a possible devastating methane burst.

While major funding continues to flow to technology that cannot touch the trillion tons of legacy CO2, concerned individuals such as grandparents and future grandparents—driven by the desire to leave their descendants a healthy, delightful world—are stepping up. They are helping to make climate restoration an idea whose time has come and provide seed funding. In addition, a growing number of far-sighted political leaders are passing or considering resolutions calling for climate-restoration so that future generations may thrive.[22]

We encourage their efforts.

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[22] For instance, in July 2023, the California State Senate unanimously passed a climate-change resolution. Other states as well as national legislators considering sponsoring similar proposals.

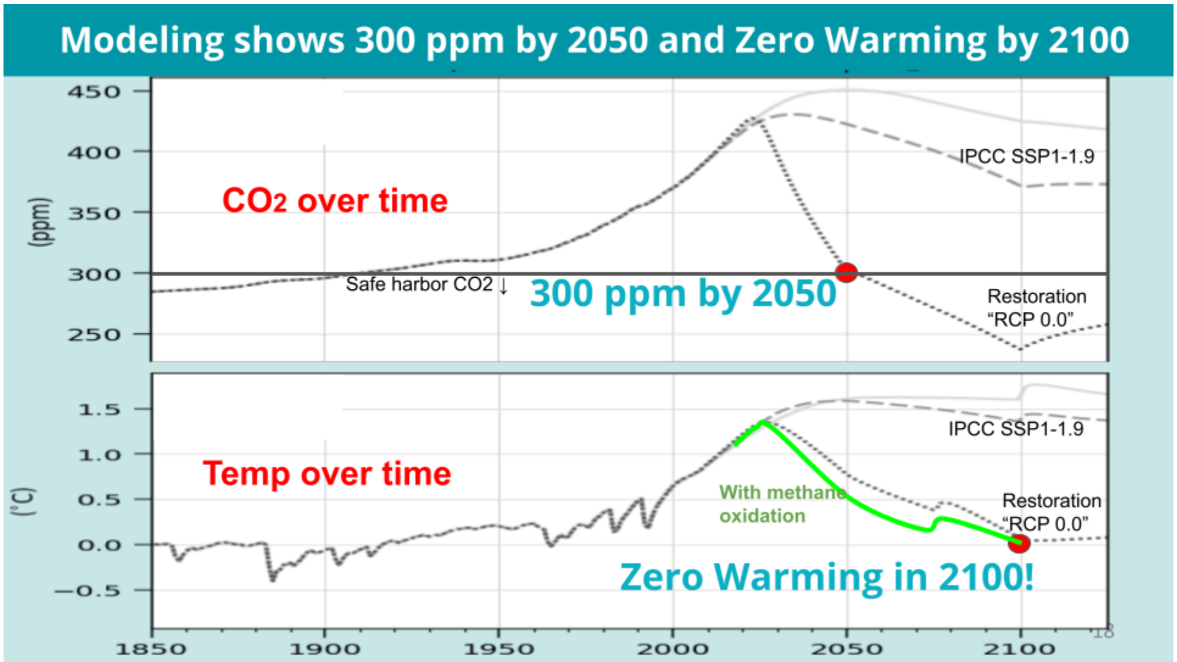
Appendix 1

Climate modeling shows that OIF and EAMO could restore CO2 to 300 ppm by 2050 and pre-industrial temperatures by 2100

Recently published climate modeling (Fiume 2023) shows that OIF alone could reduce CO2 levels to 300 ppm by 2050 by removing 60 Gt of CO2 a year for 20 years (2030-50).[23] While not quite "pre-industrial," 300 ppm is a level that we know humans have survived. At 300 ppm, temperatures would drop significantly. Warming (over pre-industrial temperatures) would reduce to about 0.8°C by 2050 —roughly the level in 2005. (See Figure XY)

Continuing to remove CO2 through 2100—at half the initial rate—would restore pre-industrial CO2 levels AND temperatures by the end of the century.

The MAGICC modeling also shows that adding EAMO methane oxidation from 2025 could reduce temperatures even faster, to 0.5° C warming in 2050. That would resemble the amount of warming in the early 1990's.



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[23] We say 60 Gt / year for 20 years instead of 50 to take into account removing continuing emissions.

Figure 4. New modeling with MAGICC shows that “RCP 0”-- restoring CO2 levels to 300 ppm by 2050—would reduce warming to about 0.8°C above pre-industrial by 2050 and to pre-industrial levels by 2100. These results depend on both CO2 removal and methane removal at scale.

Appendix 2

Net-zero won't save humanity. Climate restoration will.

The highest CO2 level humans have actually survived long term is 300 ppm. The level today is above 420 ppm. Achieving net-zero emissions by 2050 would result in CO2 above 460 ppm—more than 50 percent higher than the highest that humans have ever survived long-term.

Extrapolating from the last million years of geological data, eminent climatologist James Hansen projects that global warming "in the pipeline" will bring us to about 10°C above pre-industrial averages (Hansen 2023). That's eight times hotter than today's 1.2°C. (This would be after a few centuries, as glaciers melt and ocean temperatures stabilize.)

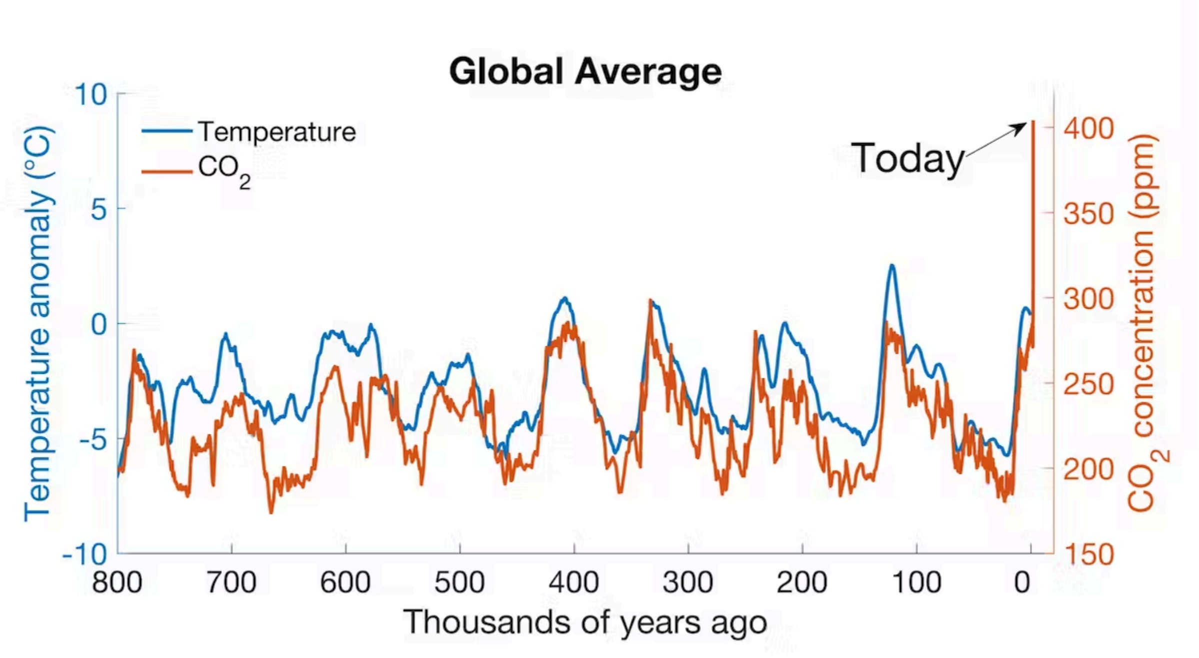


Figure 5. The highest CO2 level that humans have survived long-term is 300 ppm. *Data from Parrenin et al. 2013; Snyder et al. 2016; Bereiter et al. 2015). Ben Henley and Nerilie Abram*

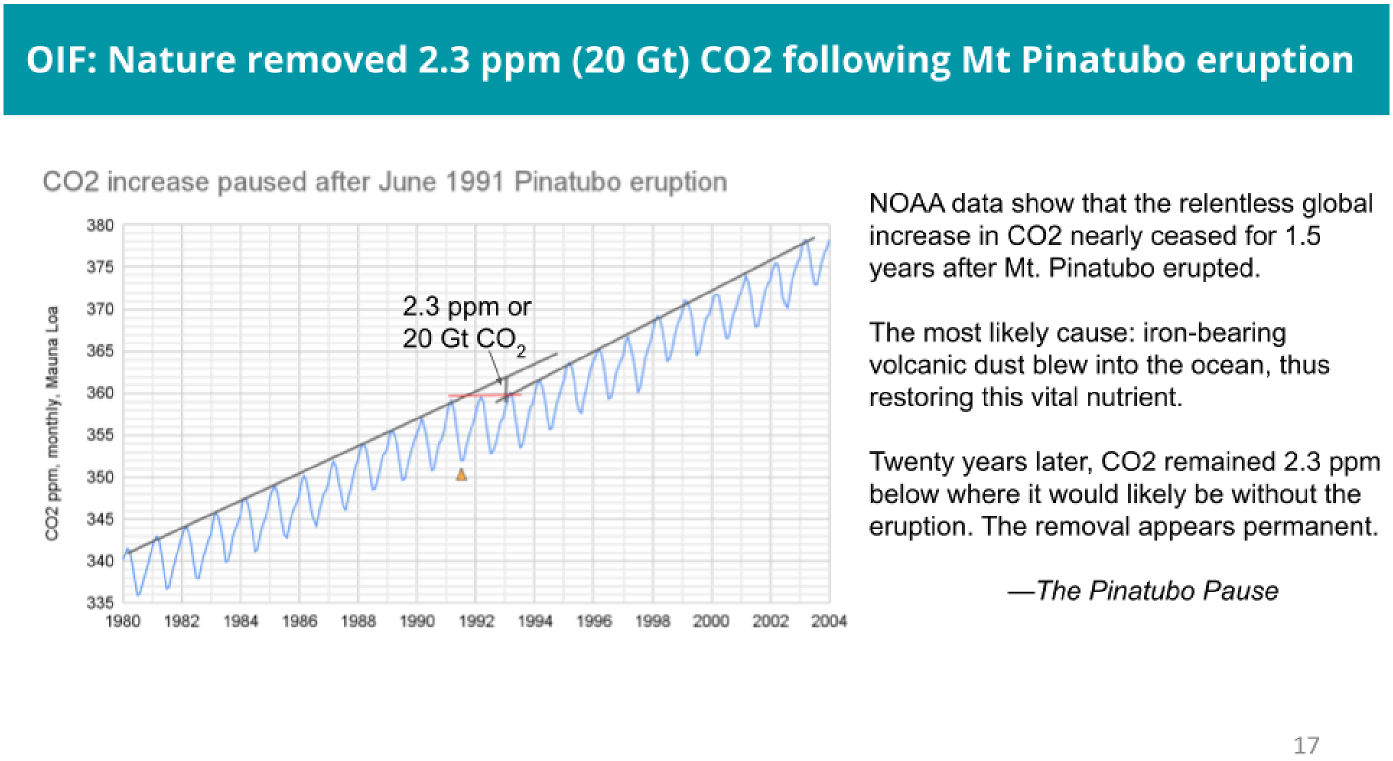
"In the pipeline" means that 10°C above pre-industrial after a few centuries, even if we completely halt emissions tomorrow, with CO2 just over 420 ppm. Wildfires, storms, floods, and droughts that are already disastrous would become fatal. Even after our own extinction, such a temperature surge would be harsh on nature.

For those committed to sustaining humanity as we know it, restoring CO2 to levels we've survived long-term (below 300 ppm) is the only acceptable path.

Appendix 3

Mt. Pinatubo eruption preceded permanent removal of 20 Gt of CO2 over a year

The speed with which nature can remove atmospheric CO2 can be seen in the widely available Keeling curve data from 1992. Significant atmospheric C02 removal—20 gigatons— followed the 1991 Mt. Pinatubo eruption within a year, and the effect has been long-term, altering the CO2 trend for at least two decades. This is separate from the well known 0.5°C cooling effect from aerosols blasted into the upper atmosphere.



OIF: Nature removed 2.3 ppm (20 Gt) CO2 following Mt Pinatubo eruption

CO2 increase paused after June 1991 Pinatubo eruption

NOAA data show that the relentless global increase in CO2 nearly ceased for 1.5 years after Mt. Pinatubo erupted.

The most likely cause: iron-bearing volcanic dust blew into the ocean, thus restoring this vital nutrient.

Twenty years later, CO2 remained 2.3 ppm below where it would likely be without the eruption. The removal appears permanent.

—*The Pinatubo Pause*

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Figure 6. Keeling curve CO2 data from 1980 to 2004 showing steady increase in CO2 levels, approximately 1.5 ppm per year before and after the eruption.

Data on the ice age cycle (Figure1) show that natural OIF can remove 1000 Gt CO2; data from the 1991 Pinatubo eruption indicates that the process can also occur very quickly using only 0.1% of the ocean area, with no reported detrimental effects.

This natural analog suggests that OIF can be safely and rapidly scaled up to restore a historically safe climate by 2050. The cost of OIF is minimal, thousands of times less than for DAC: it could restore historically safe CO2 levels for less than $1 billion per year.[24]

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[24] Efficiency improvements over time are likely to drive the cost even lower.

The most likely hypothesis today that can explain the magnitude and permanence of the carbon removal is that the iron in the volcanic ash precipitated a natural OIF event. Alternate scenarios proposed result in much less CO2 removal and only for 1-2 years, which is inconsistent with the data. These scenarios involve increased land photosynthesis and increased CO2 dissolved in surface water cooled by half a degree from reduced solar radiation following the eruption.

In the OIF scenario, restoring iron in the water enabled phytoplankton growth at a high rate that was still 35% lower than some of the highest rates observed in the Humboldt Current System by Danieri et al (2000). Haeckel et al. (2001) indicates that ⅓ of a million km^2 received the ash, roughly 0.1% of total ocean area. The high iron levels would also have enabled nitrogen-fixing cyanobacteria to provide the needed nitrogen.

There were no satellites at that time capable of recording the assumed bloom. Including the action of cyanobacteria allows current OIF theory to allow a permanent removal of this magnitude. Without considering the nitrogen fixing bacteria, theory indicates that the global maximum removal is 3.7 Gt CO2 / year (NASEM 2021).

We expect that intentional application of the right dust, at the right places, right times, and right concentrations could be similarly or more effective than the natural OIF. Further, duplicating the effect in multiple regions could, with good confidence, increase the total removal rate as needed, by a factor of five. This would remove the 60 Gt CO2 / year required to achieve an historically safe CO2 level below 300 ppm by 2050 while involving less than 1% of the ocean's surface each year.

Appendix 4

A closer look at OIF: Common concerns

What about side effects?

In 13 OIF field tests and several natural OIF occurrences, no evidence of harmful side effects have been reported. After all, dust storms and volcanoes have distributed iron dust over the ocean for millions of years. Like natural, wind-driven ocean fertilization, intentional OIF is localized and intermittent. Treating 1% of the ocean is expected to be sufficient. “Whole basin” OIF has been scientifically discussed but is not needed, would be unnatural and could risk serious ecosystem changes.

As to beneficial side effects: Annual reports of fisheries ministries following the 2012 test show that the salmon catch quadrupled in parts of Alaska and Canada in the years following OIF.

Aren’t algal blooms bad?

Feared harmful algae blooms (HABs) and de-oxygenation have occurred only in coastal waters and lakes, mostly in response to sizable nutrient runoff from farms. In contrast, OIF is performed in the open ocean, in areas where nutrient volumes are much lower and iron in particular is largely absent. The iron additions are minute: after OIF, the water contains 1/10,000 the quantity of the mineral typically contained in coastal waters.

Some studies say that very little of the carbon reaches the bottom of the ocean.

Although only 10% of the carbon removed reaches the seafloor, this was also true with ice ages; the carbon mostly remains stored in the ocean depths. During ice ages the amount of carbon stored in the ocean increases only about 2%. The same would be true when the climate is restored.

If it’s so powerful, inexpensive and based on nature, why is OIF controversial?

OIF became controversial after a field trial about a decade ago mainly because its ability to reduce CO2 levels was considered a distraction from the UN goal of reducing fossil fuel emissions.

For further discussion, see the Ex-OIS website, particularly: https://oceaniron.org/potential-solutions/#QandA. Ex-OIS is a consortium of dozens of leading oceanographers and marine biologists researching OIF.

Appendix 5

Estimated cost of removing CO₂, by CDR method

To restore a safe, healthy climate by 2050, we need to pull 60 gigatons of CO2 a year out of the atmosphere, for 20 years. That includes removing 1,000 Gt of CO2 total, plus new CO2 emitted on the way to net zero. And we need to do it in a way that is safe, permanent, easily scalable—and doesn't bankrupt the world.

So how much do various methods cost, per ton of CO2 removed (or avoided)?

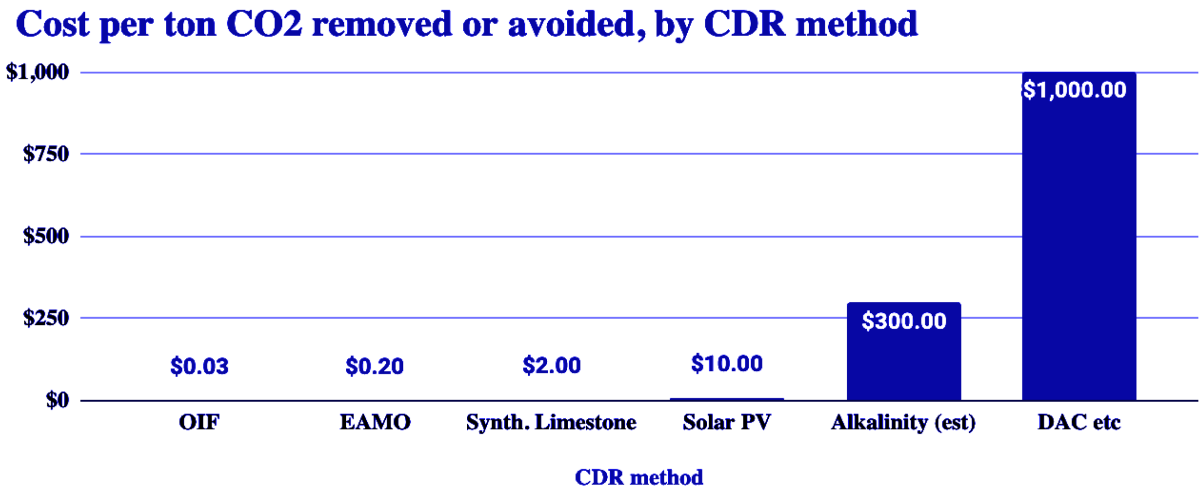

Figure 7. Cost per ton of CO2 removed or avoided, by method

How many gigatons of CO2 removal would $1 billion buy?[25]

Considered another way—what we may get for $1 billion spent on CDR—we find a mirror image.

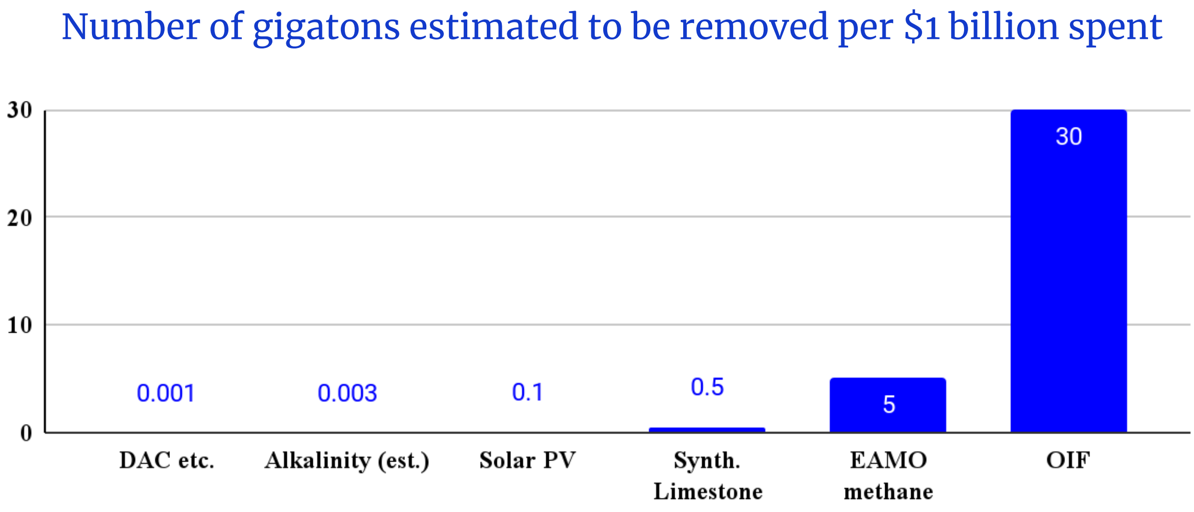

Figure 8. Cost per ton of CO2 removed or avoided, converted to Tons per $1 billion.

An investment of $1 billion per year into OIF could potentially remove 30 gigatons and put our planet on a 20-year path to pre-industrial CO2 levels. Today's investments of approximately $1.2 billion a year in DAC, for offsets, will not decrease the amount of CO2 in the atmosphere. Worse, funding for DAC could continue to displace funding for OIF, likely our most powerful ally for climate restoration.

Where has the investment gone?

All CDR methods are likely to become more cost-efficient with more experience and investment. Excluding Solar PV, which is not technically CDR, DAC is farthest along the technology maturation curve, with about 500 times more investment and development than OIF to date.

As Table X shows, investment in the most expensive, least effective CDR pathways dwarfs that of the others by many orders of magnitude.

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[25] In 2022 costs. Technically this is CO2-equivalent (CO2e) since we consider methane removal as well.

Estimated investments to develop some of the CDR methods, to date

CDR Method	Investment over last 5 years (est.)	Details
Ocean Iron fertilization	1 M	ExOIS funding since 2022
Enhanced Atmospheric Methane Oxidation	1 M	Philanthropy, since 2019
Synthetic limestone	20 M	Blue Planet Systems
Ocean alkalinity	200 M	Vesta 170 Planetary Technologies 8
Direct air capture	5,000 M (5 million+)	The Bipartisan Infrastructure Law allocated $3.5 billion to DAC hubs, starting with $1.2 billion for the first two in August 2023; [26]

Table 2. Approximate investment to date in CDR approaches, by type. Perversely, the most effective methods have gotten the least investment. This pattern is consistent with the UNFCCC goal to eliminate human interference in the climate system. OIF, if used to restore historically safe CO2 levels, would defy that goal and reduce CO2 ppm by 40%. DAC, however, even if given the entire US government budget would not reduce CO2 at all.

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[26] Climeworks has raised $762 million so far. Also in 2023, Occidental Petroleum invested 1.1 billion in its purchase of Carbon Engineering. Svante raised $479 million. Global Thermostat, Carbon Collect, and many others have collectively garnered hundreds of millions of dollars.