

# CLIMATE RESTORATION:

SOLUTIONS TO THE GREATEST THREAT  
FACING HUMANITY AND NATURE TODAY

THE FOUNDATION FOR CLIMATE RESTORATION  
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# CLIMATE RESTORATION:

## *SOLUTIONS TO THE GREATEST THREAT FACING HUMANITY AND NATURE TODAY*

### INTRODUCTION TO CLIMATE RESTORATION

#### HUMANITY'S SURVIVAL IS UP TO US

***“If you do not change direction, you may end up where you are heading.”***

**–LAO TZU**

Humans and current ecosystems require a climate similar to the one in which we evolved and flourished.

The global community has achieved substantial climate progress—as evidenced by every new wind farm, solar array, and mile not driven, as well as the brilliantly negotiated 2015 Paris Climate Agreement.

Yet the current international commitment to limit temperature rise to 2° C over pre-industrial conditions would still leave atmospheric CO<sub>2</sub> at well over 450 parts per million (ppm) in 2050 (IPCC, 2018: [Global Warming of 1.5°C](#)). This level of CO<sub>2</sub> is 50 percent higher than human beings have ever survived long-term. We have always, until last century, lived in a world where CO<sub>2</sub> levels were at most 300 ppm.

The last time CO<sub>2</sub> levels reached 450 ppm was close to 3 million years ago, when camels roamed the Arctic. Would eight billion humans survive conditions so radically different from those that enabled the growth of agriculture and civilizations? The answer is likely “No.” We know that 300 ppm and lower has been proven safe for humanity. Nothing higher has passed that test.

Every week the consequences of climate change come into sharper focus. The scientific and public media show us lethal heat waves, fires, floods, drought, crop failures, conflicts over water, climate refugees and security threats, destruction of coral-reef and other ecosystems, massive species extinctions, the spread of new diseases, and other impacts.<sup>1</sup> The climate crisis is already having severe impacts on our income, health, economic prospects, development opportunities, and (planetary) security.

<sup>1</sup>These and other effects are discussed in detail in many other fora; we refer the reader to the reference list and to websites such as Scientific American or National Geographic Society. Elucidating the consequences is critical to proving that climate change is real and important; this paper focuses instead on effective solutions.

The purpose of this paper is to show that we do not in fact need to leave dangerous, unprecedented conditions to our progeny. We have the technology and the financing, now, to reclaim the climate of over a century ago. What we need is the commitment to do so.

We still need to shift from fossil fuels to clean energy. We still need to adapt to rising sea-levels and an overheated planet until the climate is fully restored. Climate Restoration is not a substitute for mitigation (preventing or reducing greenhouse-gas emissions) or adaptation (preventing or reducing damage from global warming)—but a timely and much-needed addition to them. It will allow the world to achieve what climate activists have been working for over the decades: a safe and healthy climate for humanity and the ecosystems we need and enjoy.

## THE POWER OF AN EXPLICIT GOAL

***The emerging field of Climate Restoration sets a new goal: Ensure the survival of humanity by restoring CO<sub>2</sub> to levels proven to be safe for human civilization by the year 2050.***

Similar to the ambitious goals of eradicating smallpox, and flying to the moon and back safely, the goal of Climate Restoration is ambitious, time-bound, specific, and measurable. As with those programs, the goal will guide plans, policy, and technology. Above all, an explicit goal enables a coalition to rally behind it—and make the “unimaginable” a reality.

The smallpox vaccine was developed in 1796. Yet it wasn’t until over 160 years later that the World Health Organisation announced a program with the specific, measurable goal of eradicating smallpox. The goal mobilized the world, and smallpox was eradicated in just 21 years, in 1980.

President John F. Kennedy announced the moonshot program before the necessary technology even existed. Climate Restoration is much farther along: the technology exists today.

**Would eight billion humans survive conditions so radically different from those that enabled the growth of agriculture and civilizations? The answer is likely “No.”**

The financing is obtainable, even without major public funding. New technologies may emerge that allow us to achieve the goal faster and more easily, but we don’t need to wait. We can’t afford to wait.

**“President John F. Kennedy announced the moonshot program before the technology even existed. Climate Restoration is much farther along: The technology is ready now. The financing is obtainable even without major public funding.”**

## The Foundation for Climate Restoration developed this paper to:

- Define Climate Restoration;
- Restore hope that young people and their children can have a bright future;
- Show that Climate Restoration is already possible, and introduce methods that can work, starting now;
- Suggest how policy, individuals and organizations can help ensure the survival of humanity; and
- Inspire leaders and readers to join the Global Coalition for Climate Restoration.

## WHAT IS CLIMATE RESTORATION?

The goal of Climate Restoration is to restore atmospheric CO<sub>2</sub> by 2050 to the safe, healthy levels last seen over a century ago. Those levels are defined by the concentration of greenhouse gases in the atmosphere expressed in parts per million.

Restoring the climate means reducing atmospheric carbon dioxide from today's levels of nearly 415 ppm ([Scripps Oceanographic Institute, 2019](#)) to below 300 ppm by 2050. We exceeded 300 ppm a hundred years ago ([Monroe, 2015](#)).

To lower CO<sub>2</sub> by 115 ppm by 2050 requires sequestering one trillion tons of carbon dioxide (see Appendix 3). The task—capturing a trillion tons of CO<sub>2</sub> and storing it forever—sounds gargantuan. It is. Yet, while not yet widely known, both the technology and financing methods to restore the climate already exist.

## PROOF THAT WE CAN RESTORE THE CLIMATE IS WRITTEN IN STONE

### WE HAVE THE TECHNOLOGY TO PERMANENTLY SEQUESTER ALL EXCESS CO<sub>2</sub> BY 2050

In 2017, a Swiss start-up company launched the world's first commercial plant to pull CO<sub>2</sub> out of the air. The company, [Climeworks](#), has developed scalable, low-energy, CO<sub>2</sub>-filtering machines that can operate anywhere ([Rathi, 2017](#)).

In Iceland, the CarbFix project has for years been capturing CO<sub>2</sub> from a geothermal plant and pumping it deep into formations of porous basalt ([Matter et al., 2011](#)). The CO<sub>2</sub> binds with minerals in the basalt, particularly calcium, and becomes carbonate rock (like limestone) in a few months.

The projects came together: Today Climeworks/ CarbFix2 sucks CO<sub>2</sub> out of the air, concentrates

it, then pumps it deep into basalt formations where it mineralizes—literally turning from gas to stone.

CarbFix2 shows that we have the technology, right now, to draw all the excess CO<sub>2</sub> out of the atmosphere and sequester it safely and permanently. Every continent bears significant basalt deposits that could store far more than the trillion tons of CO<sub>2</sub> required.

If the world were to mobilize around the goal of Climate Restoration, enough carbon-removal machines could theoretically be built to safely sequester all trillion tons of excess CO<sub>2</sub> by 2050.

No major breakthroughs are needed. In fact, the methods are decades old (Panko, 2017). Climeworks and CarbFix2 simply refined the process with smart engineering, and financing to commercialize it. Individuals, organizations, and Iceland now buy CO<sub>2</sub> sequestration to offset their carbon footprints.

Climeworks is not alone: Companies have been developing carbon removal and storage through mineralization in Oman, Australia, Canada, the United States, South Africa, and parts of Europe (e.g., Mineral Carbon International), (Fountain, 2018) (Gertner, 2019).

It currently costs about \$600 to capture and store a ton of CO<sub>2</sub>. Climeworks expects that to drop to \$100/ton by 2025 (Climeworks, 2019) (Peters, 2019). At \$100/ton, deep-underground sequestration of all excess CO<sub>2</sub> by 2050 would

cost about \$100 trillion—\$3 trillion a year for 30+ years. By comparison, the global economy is about \$80 trillion/year (World Economic Forum, 2018), and global military spending totals \$1.9 trillion/year (SIPRI, 2019).

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**The project shows that we could use today's technology and finance to remove and permanently sequester all the excess CO<sub>2</sub> in our atmosphere by 2050.**

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## **WHY ISN'T THE WORLD CLAMORING FOR CARBON REMOVAL AND STORAGE?**

The lack of publicity on this Climate Restoration solution can seem baffling. That the technology works and can scale up rapidly is not in doubt. And many people would agree, if asked, that a healthy climate is worth expansive government funding.

Climate Restorationists (a label we hope catches on) suggest that the climate community and policymakers are not rushing to take on CO<sub>2</sub>-removal projects because the world has not yet set an explicit goal of Climate Restoration.

Not only are governments not budgeting for Climate Restoration, but most climate advocacy groups are not yet asking for it. Even people who stand to make vast sums with their technology have not been promoting large-scale Climate Restoration. Climeworks has set a modest goal

of sequestering 1 percent of emissions per year (Gertner, 2019). This amount comes to only one thousandth of the 50 GT of CO<sub>2</sub> per year that would need to be stored to meet the Climate Restoration goal.

The good news is that, until such time as sufficient government support is budgeted, there are market-based Climate Restoration solutions that can pay for themselves.

Climate Restoration is emerging as an idea whose time has come. The First Annual Global Climate Restoration Forum, leading into the 74th UN General Assembly, signals a turning point for global leaders to explicitly commit to restoring a climate favorable to humanity's survival and forge a coalition making that happen.

# Sufficient basalt deposits exist on every continent: if the world mobilized to restore the climate, we could build enough carbon-removal machines to safely lock away all the excess CO<sub>2</sub> by 2050.

## WHAT'S A CLIMATE RESTORATION SOLUTION?

### DEFINING A “CLIMATE RESTORATION SOLUTION”

In the meantime, the alternative—or complement—to public funding is to remove and store carbon commercially. Currently, two markets exist that are large enough to make sequestering sufficient CO<sub>2</sub> commercially viable: rock and fisheries. As Climate Restoration progresses, more markets will surely evolve to buy our excess carbon.

### CRITERIA FOR EXISTING CLIMATE RESTORATION SOLUTIONS: PERMANENCE, SCALABILITY, AND FINANCEABILITY

Dozens of methods for removing carbon dioxide from the atmosphere have been proposed and developed, but most are not primary Climate Restoration solutions. A Climate Restoration solution must meet three basic criteria: It must be permanent, scalable, and financeable.

**PERMANENT** means that CO<sub>2</sub> stays securely out of circulation for at least a century. Mineralization, for example, is permanent.

The following methods are not permanent: fizzy drinks made with captured CO<sub>2</sub>; carbon-neutral fuels, which can replace fossil fuels but do not sequester CO<sub>2</sub>; “enhanced oil recovery” (EOR), which uses carbon-capture for the purpose of extracting more fossil fuels.

**SCALABLE** means that a Climate Restoration solution could be scaled up within a decade to remove and store at least 25 GT of CO<sub>2</sub> per year. With this requirement, even if only two solutions reached full scale, 50 GT of CO<sub>2</sub> could still be withdrawn from the air each year. Mineralization and

ocean restoration, for instance, are scalable. Methods that are not scalable include approaches that compete for significant land acreage needed for food or forest production (Burns, 2017).

**FINANCEABLE** means that funding is already available or can be mobilized.

We consider methods “financeable” when they produce something that can satisfy a large existing market, such as that for construction materials (Kuhar, 2014) or seafood (Shahbandeh, 2018). Both of those markets, given policy support, would allow either the public or private sector to finance carbon storage through purchasing materials needed anyway. Farm products grown on soil improved with carbon-storing methods (e.g. char) would also qualify.

Methods that are not financeable include those without existing, sufficiently-sized markets, like reforestation (which requires significant public subsidies) or Direct Air Capture (DAC) (often funded by offset credits).

Governments do in fact have the ability to cover the entire cost of Climate Restoration (given that the global economy is estimated to be \$80 trillion/year (World Economic Forum, 2018), and global military spending is \$1.9 trillion/year (SIPRI, 2019)). It would likely take 3–5 percent of global world product per year, for 20–30 years.

For the purposes of this paper, we will consider public funds to be unavailable, as governments have not yet publicly mobilized to restore the climate or committed funding to do so.

**“The alternative—or complement—to public funding is to remove and store carbon commercially. Today two markets exist that are large enough to make sequestering sufficient CO<sub>2</sub> commercially viable: rock and fisheries.”**

## **SAFETY AND DANGER**

Safety must be defined before discussion of solutions. Safety is required for any solution that ensures the survival of humanity. If it is not safe, it is not a solution. For example, taking no action beyond achieving net-zero emissions is unsafe for humanity and cannot be an option. (This safety requirement for humanity is an important new constraint on climate approaches. The traditional view of safety focusing on nature, is historically maximized by the elimination of humanity, which may be happening.)

Safety considerations of climate solutions are a priority and this paper will address safety aspects of each major solution. For any Climate Restoration project, intensive testing, monitoring, course correction, and continuous improvement—the fundamentals of careful project management—are required.

## **CLIMATE RESTORATION AND THE PRECAUTIONARY PRINCIPLE**

The “first, do no harm” test, or “precautionary principle,” was proposed around 2000 (Kriebel et al, 2001) to keep risky materials from being introduced into the environment (Hanson, 2018), and has guided funding for climate and environmental research and intervention since then. At the time, the environment was considered to be safe and relatively stable. Applying the precautionary principle strictly can lead to inaction indefinitely, which is fine when the status quo is safe.

However, that is not the situation today. The status quo today is leading us down a path toward the probable extinction of our species and thousands of others, called the “ongoing sixth mass extinction” (Ceballos et al, 2017).

Therefore restorationists propose to supercede the precautionary principle with a new safety principle that balances the risks of action versus the consequences of inaction.

The new safety principle would take into account the number of people who might be at risk or might die if the action is taken along with suitable feedback and precautions and compare to the number who would certainly be at risk and would certainly die if such action is not taken. A similar comparison of the number of species likely to go extinct in each case will be valuable.

To date we have seen few such discussions in scientific or public media. This more balanced test is critical as we mobilize to restore the climate safely.

## BOX 1. IT'S COUNTERINTUITIVE: MAKING COMPLEX ACTIVITY SAFE

Flying seven miles above ground, at 500 miles per hour, through air 40° below zero and too thin to breathe, with tons of highly flammable fuel stored underneath your feet...sounds completely unsafe. Why would anyone voluntarily travel by airplane?

We fly not just to travel quickly, but in part because flights are now safer than driving or walking. In an average year, of those who die in planes, more succumb to their own medical issues than to crashes (Crewdson, 1996).

Even during “bad years” for plane accidents, the difference in risk remains dramatic. What makes air travel safe is the long-term commitment to make it so, with teams of analysts and engineers dedicated to flight safety (Syed, 2015).

Likewise, ensuring safety for humanity during Climate Restoration activities will require testing, monitoring, continuous improvement, and, invariably, course correction.

## OVERVIEW OF CLIMATE RESTORATION SOLUTIONS

Climate Restoration solutions must be permanent, scalable, and financeable. The solutions that meet these criteria were developed through “biomimicry” and “geomimicry,” copying natural processes that significantly reduce CO<sub>2</sub> levels.

The solutions mimic how nature has recovered from previous mass extinction events associated with increases in CO<sub>2</sub> levels, and are designed to accelerate the timeline. In nature, atmospheric CO<sub>2</sub> drops as it is sequestered into limestone and into underwater biocarbon stores (Dutkiewicz, 2019).

Solutions that meet all three criteria include mineralizing CO<sub>2</sub> into synthetic limestone, and promoting photosynthesis through two ocean-restoration methods. These solutions have large existing markets to finance their expansion, although they require initial investment. Any one of them could reasonably scale to remove all trillion tons of excess CO<sub>2</sub>, profitably.

Other CO<sub>2</sub> removal approaches that meet only one or two restoration criteria are still valuable as complementary methods, and many have important side benefits. This section will focus on solutions that meet all three criteria.

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**Climate Restoration solutions mimic and accelerate nature's recovery from previous mass extinction events.**

## SOLUTIONS AVAILABLE NOW

### HOW CO<sub>2</sub> REMOVAL-AND-STORAGE METHODS COMPARE ON THE THREE CLIMATE RESTORATION CRITERIA

CO <sub>2</sub> SEQUESTRATION METHOD	SCALABILITY (>25 GT CO <sub>2</sub> /YR)	FINANCEABILITY (FUNDING AVAILABLE NOW)	PERMANENCE (100 YRS +)	OTHER BENEFITS
<b>SYNTHETIC LIMESTONE</b> (Blue Planet, 2019)	Yes, can scale to >25 GT CO <sub>2</sub> /yr.	Yes, can be paid for by the construction industry buying product they would buy anyway.	Yes, CO <sub>2</sub> is sequestered for >100 yrs.	Resulting limestone is well suited to construction needs. Reduces the need for quarries.
<b>OCEAN IRON FERTILIZATION</b> (Martin, 1988) <sup>3</sup>	Yes, can scale to >25 GT CO <sub>2</sub> /yr.	Yes, can be paid for through sales of commercial fishing licenses and taxes as fisheries rebound.	Yes, CO <sub>2</sub> is sequestered for >100 yrs.	Can revitalize marine ecosystems, providing food and livelihoods for struggling coastal communities.
<b>MARINE PERMACULTURE/ RESTORING PRIMARY PRODUCTIVITY OF OCEANS</b> (The Drawdown Agenda, 2018) <sup>4</sup>	Yes, can scale to >25 GT CO <sub>2</sub> /yr.	Yes, can be paid for through sales of kelp and commercial fishing licenses.	Yes, CO <sub>2</sub> is sequestered for >100 yrs.	Provides important food source for marine life, improving ecosystem health.
<b>DIRECT AIR CAPTURE (DAC) WITH CO<sub>2</sub> PUMPED UNDERGROUND</b> (Doukas, 2017) <sup>5</sup>	Yes, can scale to >25 GT CO <sub>2</sub> /yr.	No, would require government or donor funding, currently unbudgeted (Temple, 2019). <sup>6</sup>	Yes, CO <sub>2</sub> is sequestered for >100 yrs	N/A
<b>OCEAN ALKALINIZATION</b> (Ilyina et al, 2013)	Yes, can scale to >25 GT CO <sub>2</sub> /yr.	No, would require government or donor funding, currently unbudgeted (Wang, 2012). <sup>7</sup>	Yes, CO <sub>2</sub> is sequestered for >100 yrs.	Reduces ocean acidity.
<b>BIOENERGY WITH CARBON CAPTURE AND STORAGE</b> (BECCS) (IPCC, 2018) <sup>8</sup>	No, can scale to 0-8 GT CO <sub>2</sub> /yr.	No, cost of biofuel exceeds the market price for renewables, and growing biofuel competes with acreage for food crops and forests.	Yes, CO <sub>2</sub> is sequestered for >100 yrs.	Provides clean energy.
<b>AGRICULTURE, FORESTRY, AND IMPROVED LAND USE</b> (AFOLU); (IPCC, 2018). <sup>9</sup>	No, can scale to 1-11 GT CO <sub>2</sub> /yr.	No, could be financed through coordinated public-private partnerships, but these are not currently in place.	Varies depending on intervention type and environmental conditions.	Improves soil health and productivity, increasing global food supply and livelihood for farmers.
<b>OCEAN DOWNWELLING</b> (Preuss, 2001), (de Figueiredo, n.d.). <sup>10</sup>	Could be >25 GT CO <sub>2</sub> / year, but net CO <sub>2</sub> removal is unproven.	No, could be financed through coordinated public-private partnerships, but these are not currently in place.	May be 100 yrs+, but unproven. More research needed.	NA

# GETTING BACK TO 300 PPM: CLIMATE RESTORATION SOLUTIONS THAT ARE PERMANENT, SCALABLE, AND FINANCEABLE

## 1. SYNTHETIC ROCK FOR CONSTRUCTION AND PAVING

Carbon dioxide can be mineralized above ground as well as in deep basalt. In recent years, companies in the U.K., U.S., and Australia have developed ways to use captured CO<sub>2</sub> in the production of concrete and other building materials ([Davidson, 2017](#)).

Concrete is composed of sand and gravel aggregate (60–75 percent), cement (10–15 percent), and water (15–20 percent) ([Portland Cement Association, n.d.](#)).<sup>11</sup> Synthetic limestone can replace the quarried rock traditionally used for aggregate and road beds, which has a trillion-dollar market ([Synapse, 2017](#)). Silicon Valley-based startup [Blue Planet](#) combines CO<sub>2</sub> with calcium to create synthetic limestone that is carbon-negative. The process mimics how

shellfish make seashells from calcium and CO<sub>2</sub> dissolved in seawater ([Pultarova, 2019](#)). In this case, the calcium can come from recycled materials such as concrete from demolished buildings, fly ash from power plants, other industrial waste, and common rock such as basalt. In 2016, workers poured carbon-negative concrete for a boarding area at San Francisco International Airport, demonstrating its viability for paving and building (O’Heir, 2016).

By 2030, substituting synthetic limestone for quarried aggregate could pull 50 GT of CO<sub>2</sub> per year from the atmosphere.<sup>12</sup> Permanent carbon storage would thus be financed by the market—simply through the purchase of rock and aggregate.

<sup>2</sup>Quarried rock purchased for concrete, road base and other building materials can be replaced with synthetic limestone. The market buys 55 GT rock/year, expected to increase to 110 GT/ year in 2030 ([Kuhar, 2014](#)). Limestone (calcium carbonate) is 44% CO<sub>2</sub> by weight. It can be produced from CO<sub>2</sub> and environmental calcium sources, with low energy chemistry similar to how clams produce their shells. Pioneered by [Blue Planet Ltd.](#)

<sup>3</sup>Also called OIF, a minimal intervention method similar to volcanic and dust storm ocean fertilization. First discussed by [John Martin \(1988\)](#).

<sup>4</sup>Artificial upwelling used to grow kelp and other seaweed in ocean-based grid structures called [Marine Permaculture Arrays](#) ([Brian von Herzen](#) and the [Climate Foundation](#)).

<sup>5</sup>There are financeable DAC applications which are not scalable or not permanent, such as Enhanced Oil Recovery (EOR), production of consumable products such as carbonated drinks, jet fuel, and fertilizers.

<sup>6</sup>[Significant startup funding](#) has been committed and invested.

<sup>7</sup>Non-commercial CDR costs are about 1–3% of global GDP for 30 years, assuming CDR costs of \$30–\$100/t CO<sub>2</sub>. However there is no existing budget or firm plan to develop that budget out of public funds. Therefore it is not considered financeable at this time.

<sup>84</sup>In pathways limiting global warming to 1.5 degrees C with limited or no overshoot, BECCS deployment is projected to range from ...0–8 GT CO<sub>2</sub> yr<sup>-1</sup> in... 2050...The upper end of these deployment ranges by mid-century exceeds the BECCS potential of up to 5 GT CO<sub>2</sub> yr<sup>-1</sup>” ([IPCC, 2018, 17](#)).

<sup>94</sup>In pathways limiting global warming to 1.5 degrees C...agriculture, forestry and land-use (AFOLU) related CDR measures are projected to remove 1–11 GT CO<sub>2</sub> yr<sup>-1</sup> in 2050 (medium confidence)...The upper end of these deployment ranges by mid-century exceeds the...afforestation potential of up to 3.6 GT CO<sub>2</sub> yr<sup>-1</sup>” ([IPCC, 2018, 17](#)).

<sup>10</sup>Downwelling is an emerging method of carbon sequestration, which pumps CO<sub>2</sub>-rich surface ocean water into the depths where it may remain sequestered. It is being developed by [Ocean-Based Climate Solutions](#).

<sup>11</sup>Companies have also demonstrated how cement, the most energy-intensive component of concrete, can be made carbon neutral ([Harvey, 2018](#)).

<sup>12</sup>Current rock production is given as 53 GT projected in 2017 from RockProducts’ 2014 summary with growth rates about 7.7% per year, or doubling every 10 years ([Kuhar, 2014](#)).

Policy could accelerate the use of carbon-storing materials, through procurement rules requiring them for new projects.

The largest risk in building materials is compromised quality: No one wants bridges or buildings to fall down. Fortunately, synthetic limestone has undergone and earned high scores in safety tests from independent third parties like the California Department of Transportation and concrete and construction companies in California and Canada ([Blue Planet, 2019](#)).

#### **AN ENERGYSTAR® FOR STORED CARBON**

A quantitative standard and certification program is being developed to certify the amount of CO<sub>2</sub> sequestered in building materials. Similar to the EnergyStar® program, “CarbonStar®” is expected to facilitate the adoption of carbon-negative building materials by governments and the private sector.

With these innovations in Climate Restoration technology, every gravel roadbed, paved road, and concrete bridge and building could contribute to restoring our climate ([Kennedy, 2017](#)).

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**“By 2030, substituting carbon-negative limestone for quarried aggregate could pull 50 GT of CO<sub>2</sub> per year from the atmosphere. Permanent carbon storage would thus be financed by the market—simply through the purchase of rock and aggregate.”**

## **STORING CARBON, RESTORING OCEANS**

Photosynthesis in the ocean appears to be the fastest biological way to remove atmospheric CO<sub>2</sub>. On land, most plants sequester carbon for a few decades or less before they burn or rot, returning CO<sub>2</sub> to the atmosphere. In the ocean, most plants sink, carrying their CO<sub>2</sub> to the depths. Once below 500 m, they can remain there for a millennium ([Smetacek et al, 2012](#)).

Covering 71 percent of the planet ([USGS, 2019](#)), the ocean presents as much as ten times more area for photosynthesis than does arable land ([Levin, 2019](#)), so ocean photosynthesis does not compete with food production. On the contrary: it produces food ([Duarte, 2009](#)). And underwater forests never burn.

The growth rate of underwater forests is remarkable: Giant kelp can grow up to two feet per day ([Monterey Bay Aquarium Foundation, 2019](#)). Seaweed forests develop entire ecosystems, from phytoplankton to fish to marine mammals.

As to the safety of ocean restoration interventions: promoting photosynthesis helps support a healthy ocean—one that hosts a plethora of fish and other sea-life in robust ecosystems. The widely used Ocean Health Index uses eight goals<sup>13</sup> to evaluate ocean health. They assess trends in each category to calculate an overall score ([Ocean Health Index, 2015](#)). Ocean restoration supports several of these goals and is based on biomimicry and geomimicry, replicating natural processes.

Numerous scientific studies have isolated conditions in which the proposed ocean-restoration methods fail. These conditional failures can be over-generalized as fundamental failures. However, the carbon-removal methods copy natural processes which do work; successful replication depends in part on selecting or providing the right conditions.

Removing enough CO<sub>2</sub> to restore the climate could be accomplished with intentional management of just 1–2 percent of the ocean ([Y Combinator, n.d.](#)).

## MARINE PERMACULTURE

Fisheries the world over are in trouble, and ocean deserts—the least productive areas of oceans, which are clear blue rather than photosynthetic green—are expanding (Renfrew, 2019). Marine ecosystems depend on key nutrients “upwelling” from the depths to the surface, and natural upwelling is slowing in some areas due to warming waters (Dawicki, 2013) (Oyarzún and Brierley, 2019).

Taking advantage of the photosynthesis capacity of kelp and other seaweed, marine permaculture is being developed both to feed communities and to sequester CO<sub>2</sub>. Marine permaculture involves intentionally growing (or regrowing) underwater forest ecosystems that store large amounts of CO<sub>2</sub>

and provide food and shelter to revive fisheries (Froehlich et al, 2018). Marine permaculture involves simulating natural upwelling with the use of a small pump that runs on wave energy (Bates & Draper, 2018) (Hawken, 2017).

To expand beyond coastal areas, marine biologists are building “Marine Permaculture Arrays”—light, latticed structures to which kelp and other seaweed can attach. The arrays, with pump and pipe for upwelling, can be navigated out to sea, where they can foster dynamic ecosystems and fisheries in what are now ocean deserts (Climate Foundation, 2019).

## OCEAN FERTILIZATION WITH IRON

Ocean iron fertilization (OIF) also promotes rapid sea-based photosynthesis to store CO<sub>2</sub> and restore fisheries. OIF mimics the distribution of minerals from volcanoes—along with upwelling, a major source of ocean nutrients. Large volcanic eruptions (like Pt. Pinatubo in 1991) not only reduce CO<sub>2</sub> levels for about a year by scattering nutrients; they also reflect solar radiation and thereby decrease average temperatures by about 1°F (Climate Institute, 2018).<sup>14</sup>

A report by the National Academy of Science (2015) describes the biological pump that allows for CO<sub>2</sub> sequestration in the oceans: phytoplankton and other microscopic plants take up CO<sub>2</sub> at the ocean surface, and convert it to biocarbon, some of which is deposited and sequestered in the deep ocean (National Research Council, 2015a).<sup>15</sup>

Researchers have found iron to be the limiting nutrient in many areas of the ocean (Martin,

1992). In OIF demonstrations, after implementers sprinkle a tiny amount of that mineral in an area of water, it blooms with phytoplankton, fish, and other flora and fauna (de Baar et al, 2005) (Boyd et al, 2007) (Smetacek et al, 2012) (Martin et al, 2013). However, questions remain about whether this increase in marine life translates to high quantities of sequestered carbon in the deep ocean (Smetacek et al, 2012) (Yoon, 2018).

The ideal setting for OIF is in discrete ocean “pastures” about 60 miles (100 km) in diameter, located within ocean gyres. Circling currents keep the iron in place for several months—as opposed to days, like in much of the open ocean—while plankton grows and fish feast (Boudreau, 2018). After the iron dissipates, the pasture reverts from green—indicating a profusion of photosynthesis—back to ocean-desert blue. Conducting OIF in swirling gyres reduces the need to re-apply iron frequently to maintain optimal levels (Yoon, 2018).

<sup>13</sup>Food provision, artisanal fishing opportunities, carbon storage, coastal protection, livelihood and economies, tourism and recreation, sense of place, clean waters, and biodiversity.

<sup>14</sup>“The only time that the upward trend line of atmospheric CO<sub>2</sub> [Keeling curve] significantly halted was following the Mount Pinatubo eruption” (Climate Institute, 2018).

<sup>15</sup>NRC estimates that “variations in the magnitude and geographic patterns of the biological pump could drive changes in atmospheric CO<sub>2</sub> of a few tens to perhaps more than 100 ppm.” (National Research Council, 2015a, p. 56)

Just as successful farmers, for economic and environmental reasons, use the minimum amount of fertilizer and fallow their land frequently, OIF pastures, too, receive the minimum intervention and are left “fallow” most of the time.

Experiments have shown that it takes an application of only 10 pounds of iron-ore dust per square mile to create phytoplankton blooms (Zubrin, 2014).<sup>16</sup> In comparison, farmers annually

dust 90,000 pounds of fertilizer on one square mile of corn—9,000 times more (Cornell, n.d.).

Since 1990, 13 OIF experiments have been carried out around the world. Most did not demonstrate an increase in carbon sequestration, potentially due to poor experimental conditions including non-optimal location, insufficient duration, and various monitoring issues. While it seems logical to assume that OIF should work when done properly, there

## BOX 2. HANG ON...IS THIS GEOENGINEERING?

“Geoengineering” refers to deliberate, large-scale intervention in natural systems to counteract climate change (Oxford University, 2018).

The thought of intentional, large-scale involvement in the atmosphere and ocean raises alarm bells, especially for those passionate about the environment. Many ask, “Isn’t mucking around with the Earth’s systems the way we got into this mess in the first place?” (Yes, in fact, our climate crisis is the result of over a hundred of years of negative geoengineering.)

“Geoengineering,” though, also encompasses proposals for massive tree-planting, adopting regenerative agriculture, rebuilding ecosystems, and turning large amounts of biomass into charcoal to make the soil more CO<sub>2</sub>-rich.

The IPCC now prefers the term “carbon-dioxide removal” (CDR) to refer to large-scale efforts to remove carbon dioxide from the air or industrial emissions (IPCC, 2014), and “solar radiation management” (SRM) for reflecting sunlight back to space (Solar Radiation Management Governance Initiative, 2019). Because of their specificity, we prefer these terms as well. The American Geophysical Union proposes the neutral phrase, “climate intervention” (Landau, 2018).

### IT’S NOT JUST WHAT YOU DO, IT’S HOW YOU DO IT

Tree-planting sounds natural and benign. But plant the wrong type in the wrong place—especially on a large scale—and you can seriously harm ecosystems, wildlife, crops, and even water cycles (Jackson, 2005) (Maathai, 2011) (Parr & Lehmann, 2012).

BECCS and other proposals to grow “biomass” to absorb carbon can also take up precious cropland—problematic in a world trying to grow food for nearly eight billion people (Bailey, 2018).

High-tech as some may sound, most Climate Restoration methods are actually based on “biomimicry” or “geomimicry” of natural processes (Zari, 2010).

For instance, creating synthetic limestone (calcium carbonate) mimics how shellfish build seashells from calcium and CO<sub>2</sub>, and how corals build reefs. All methods of SRM under serious consideration are modeled on a daily natural occurrence—volcanic eruption. Ocean iron fertilization, too, is based on the distribution of volcanic dust (Tripp, 2014).

are still questions about what variables need to be in place for this to occur. The scale, duration, expense, and monitoring required to conduct OIF effectively, along with negative perceptions of it, have hindered progress in research and testing (Yoon, 2018).

**“Researchers have found iron to be the limiting nutrient in many areas of the ocean. In OIF demonstrations, after implementers sprinkle a tiny amount of that mineral in an area of water, it blooms with phytoplankton, fish, and other flora and fauna.”**

OIF success depends on maximizing the amount of CO<sub>2</sub> that sinks below 500m, and only a few of the 13 published experiments showed good results (Yoon, 2018). Notably, a 2012 study showed that about 70 percent of biocarbon sinks below 500 m, where it can remain for about a thousand years (Smetacek et al, 2012).<sup>17</sup> (About 10 percent of the biocarbon reaches the ocean floor.)

The cost of CO<sub>2</sub> sequestration associated with OIF is about one dollar per ton. An OIF demonstration in Alaska cost about \$2.5 million and is reported to have sequestered 80 million tons of CO<sub>2</sub>. However, that sequestration number has not been verified since scientific funding was discontinued after a widely disseminated newspaper article reported (incorrectly) that required permits had not been obtained (Lukacs, 2012). Future tests can be verified with modern

satellite carbon-measurement techniques that measure ocean carbon down to 1000 m below the surface (NOAA, 2017).

**“It takes only 10 pounds of iron-ore dust per square mile to create phytoplankton blooms. In comparison, farmers annually dust 90,000 pounds of fertilizer on one square mile of corn—9,000 times more.”**

Small island nations are increasingly expressing interest in OIF (private communication, 2019). Further efforts may be conducted by island or coastal nations with collapsing fisheries, as public-private partnerships. Rebounding fish populations can bring jobs back to the local fishing industry. Revenue from taxes or fishing licenses flows to the government, which can fund the OIF by sharing a portion of revenue with the companies that conduct the process and monitor results.

For an island or coastal state to restore its fisheries would likely require activities at about 30 pastures, with half fertilized and half fallow in a given year. Each pasture, about 60 miles (100 km) in diameter, can remove about 200 million tons of CO<sub>2</sub> per year. Therefore 300 pastures could sequester 50 GT CO<sub>2</sub>/year.

How safe is it? OIF mimics the localized and intermittent dispersal of dust from volcanoes. Nature has adapted well to the volcanic process over the last three billion years; a volcano erupts on

<sup>16</sup>Calculated based on the figures in this article. 120 tons/10,000 km<sup>2</sup> converted to miles.

<sup>17</sup>“...at least half the bloom biomass sank far below a depth of 1,000 metres and... a substantial portion is likely to have reached the sea floor. Thus, iron-fertilized diatom blooms may sequester carbon for timescales of centuries in ocean bottom water and for longer in the sediments” (Smetacek et al, 2012).

average once per week (USGS, 2011). In addition, only when OIF enables the rebounding of healthy fish will it be economically sustainable; diverse, plentiful, and healthy fish are also indicators of a healthy marine environment (Ocean Health Index, 2019). So feedback is built into the system.

**“Small island nations are increasingly expressing interest in OIF. Further efforts are likely to be conducted as public-private partnerships by island or coastal nations that want to revive their collapsing fisheries.”**

Some reviewers have publicized a concern about drastic alteration, saying OIF could “turn the ocean into pea soup” (Powell, 2008). Yet in reality, dangerous algae blooms occur in coastal areas where runoff deposits too many nutrients (NOAA, 2016)—not in the deep ocean, where OIF would be most useful. OIF treatments are short-lived, so if thick algal blooms were to occur, they would disperse within a few months as currents restore the previous chemistry and ecology. No dangerous blooms have been reported resulting from volcanic OIF events, though short-term healthy blooms have resulted (Kinver, 2013).

In addition, no one foresees iron fertilization throughout the oceans. In fact, pasturing only about 1 percent of the ocean, intermittently, would be sufficient to sequester all excess carbon dioxide (Y Combinator, n.d.).

### BOX 3. HOW DID OIF BECOME CONTROVERSIAL?

Several factors converged to cast doubt on OIF and keep it from being widely researched.

First, key carbon traders opposed it early on. Carbon removal for less than \$1 per ton, when carbon credits were trading for around \$50, threatened to ruin the carbon market and harm developing countries dependent on revenue from carbon trading. It would also put carbon traders out of business (R. George, personal communication, 2019).

Some green organizations objected to OIF and other large-scale CO<sub>2</sub> removal methods on the grounds that “They are a dangerous distraction providing governments and industry with an excuse to avoid reducing fossil fuel emissions,” in the words of one activist (Worstell, 2014).

Many climate specialists also appeared to misunderstand how OIF is practiced, expressing fear that it would affect most of the ocean continuously, not 1-2 percent intermittently.

OIF skeptics also cite concerns about causing areas of low oxygen when organisms die and decay. Lower oxygen levels do occur any time there is a large amount of biological growth, including following fertilization by volcanic eruption. Natural processes have evolved over geologic time to adapt to such events. We know of no reports or even hypotheses of long-term damage related to intermittent, short-term ocean fertilization.

Finally, in the absence of early, peer-reviewed research, scientists questioned the amount of CO<sub>2</sub> actually sequestered. However, a 2012 study of OIF reported that

“...at least half the bloom biomass sank far below a depth of 1,000 metres and... a substantial portion is likely to have reached the sea floor. Thus, iron-fertilized diatom blooms may sequester carbon for timescales of centuries in ocean bottom water and for longer in the sediments.” (Smetacek et al, 2012).

## COMPLEMENTARY CARBON-REMOVAL APPROACHES

A number of methods remove atmospheric CO<sub>2</sub> but do not (yet) satisfy the three Climate Restoration criteria. Converting CO<sub>2</sub> into jet fuel, for instance, is scalable, financeable, and an important opportunity to contribute to net zero emissions, but it is not permanent. CO<sub>2</sub> returns to the atmosphere when the fuel burns (Keith, 2018). Other carbon-removal methods sequester some carbon and could be considered complementary to the large-scale Climate Restoration solutions. Here we consider a few of the better known methods.

**DIRECT AIR CAPTURE (DAC).** This approach is widely discussed since it removes CO<sub>2</sub> from the atmosphere and can be safely deployed to any scale (Sanz-Pérez et al., 2016). The Climeworks project mentioned above sequesters the CO<sub>2</sub> permanently after DAC, but it is the exception. Most DAC projects use captured CO<sub>2</sub> to produce jet fuel, fizzy drinks, and other consumer products.

Funding for these companies in the last year exceeded \$100M<sup>18</sup> (Crunchbase.com, n.d.) largely from oil companies planning to use the CO<sub>2</sub> for enhanced oil recovery. Competition is increasing and DAC costs are falling rapidly (Carbon Engineering, 2019) (Peters, 2019). This process is expected to sequester perhaps 10 million tons of CO<sub>2</sub> a year (National Energy Technology Laboratory, 2010)—less than one thousandth of the 25 GT needed to make real Climate Restoration progress (DOE, 2010).

**ALKALINIZATION.** Several researchers have proposed carbon-storage methods that also neutralize some of the ocean's acidity. Ground alkaline rock, placed in the ocean, may sequester CO<sub>2</sub> at a cost of approximately \$100/ton (Paquay, 2013). Alkalinization does not result in a commercial product, however, so it would likely compete with underground mineralization for government funding, were such funding available (Rau, 2011).

**BIOENERGY WITH CARBON CAPTURE AND SEQUESTRATION (BECCS).** BECCS is a variation on DAC, in which the energy and chemistry required to concentrate CO<sub>2</sub> comes from certain agricultural crops. This provides the benefit of being able to sell excess energy to help defray costs. The energy produced is too expensive to be competitive with commercial energy sources, so BECCS would compete against DAC for government funding. Current costs of BECCS are comparable to DAC, and the method has also garnered much attention. BECCS has disadvantages besides cost: It would compete against food production for land and water, if done at scale (Heck, 2018). It also encourages monoculture cropping which can be environmentally harmful (Dooley, 2017).

**AGRICULTURE, FORESTRY, AND IMPROVED LAND USE (AFOLU).** These approaches include reforestation, afforestation, and methods that increase CO<sub>2</sub> storage in the soil, such as biochar (Cummins, 2017) (Hawken, 2017). Many techniques, such as regenerative agriculture, provide important environmental and health benefits. However, estimates of how much carbon they can actually capture vary widely. While there are several techniques that could sequester hundreds of gigatons of CO<sub>2</sub> per year, they would need to be used across all agricultural land worldwide to reach those scales (Regeneration International, 2018). The logistical challenge of scaling new agricultural practices is considerable: Farmers, especially in poor regions, tend to be risk averse. It is unlikely that all farmers would engage in the retraining, retooling, and capital investment required to engage in improved land management practices that increase CO<sub>2</sub> storage. In addition, approaches like reforestation have long lead times, and the cost per ton of CO<sub>2</sub> stored is typically high, although some claim that CO<sub>2</sub> can be removed for \$15/ton (Indigo, 2019).

<sup>18</sup> Carbon Engineering (\$68M), Climeworks (\$31M), Global Thermostat, Inventys (\$26M), and Silicon Kingdom/Lackner (\$2M?)

**OCEAN DOWNWELLING.** Water near the surface contains more CO<sub>2</sub> than deeper water, due to contact with the atmosphere. The idea behind downwelling is to pump surface seawater down below 1000 feet, where it might stay for centuries or millennia. Pumps can be powered by ocean waves and density differences and require little to

no energy, so CO<sub>2</sub> sequestration costs would be well below \$100/ton. However the theory of how much CO<sub>2</sub> is sequestered is complicated and needs additional testing (Brewer, 2003).

## CLIMATE RESTORATION INCLUDES ARCTIC RESTORATION

Refreezing the Arctic may be essential to ensuring the long-term survival of humanity, along with pulling CO<sub>2</sub> from the air (Fiekowsky, 2019). Some 3.5 million years ago, the last time CO<sub>2</sub> was at today's level, the planet was in a state called "hothouse earth" with alligators and camels at the poles, and sea levels many meters higher than they are now (see Appendix 2). The transition back to the planet's interglacial state, "icehouse earth" took about 2 million years (Figure 1). Humans evolved after the transition, in the icehouse/interglacial state we have known until recently.

Our planet is now mostly transitioned to hothouse once again, with CO<sub>2</sub> at hothouse levels and

80 percent of Arctic sea-ice already melted (Wadhams, 2017). Removing excess CO<sub>2</sub> from the atmosphere will reduce the warming we're experiencing now and expecting to continue for decades to come.

However, it's too late for that reduced CO<sub>2</sub> to prevent the loss of our polar ice caps, which reflect heat away from Earth and stabilize weather patterns. Restoring the climate requires both restoring CO<sub>2</sub> levels and accelerating the transition back to the icehouse state, especially by rebuilding the polar ice caps. We probably can't wait 2 million years for nature to restore a favorable climate for us again.

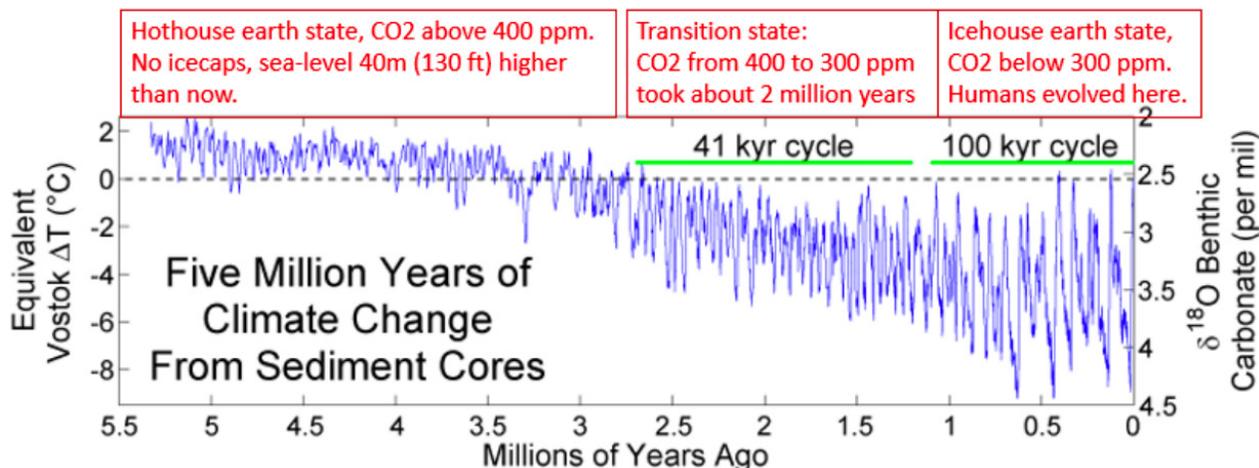


Figure 1. Five million years of climate change: It took 2 million years to transition from hothouse back to the icehouse/interglacial state (between about 3.5 to about 1.5 million years ago.)

Credit: [https://en.wikipedia.org/wiki/Geologic\\_temperature\\_record](https://en.wikipedia.org/wiki/Geologic_temperature_record).

## WE NEED TO ACCELERATE THE TRANSITION BACK TO AN ICEHOUSE/INTERGLACIAL STATE

As the global community mobilizes to rapidly remove CO<sub>2</sub> and we expect temperatures to drop, refreezing the Arctic will become critical. Without required CO<sub>2</sub> removal, refreezing the Arctic would be short-lived and thus of limited value.

The threats of a melting Arctic are well documented (Wadhams, 2017). Less well known is the fact that research teams have proposed or developed a number of options to keep the Arctic reflective and limit methane emissions.

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**“Restoring the climate requires both restoring CO<sub>2</sub> levels and accelerating the transition back to the icehouse state, especially by rebuilding the polar ice caps. We probably can’t wait 2 million years for nature to restore a favorable climate for us again.”**

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### REFLECTIVE SAND

One method uses reflective sand made from hollow microspheres of silica, a material abundant in the ocean. When sprayed over ice, the silica sand reflects sunlight, slowing ice melt (Field, 2018). In demonstrations by the nonprofit Ice911 Research, treated ice lasted several weeks longer into spring than untreated (Ice911, 2019). When the weather warms and melting begins, the silica floats, remaining reflective like ice itself.

The microspheres measure about 50 microns in diameter; anything larger than 10 microns is considered safe. The material has been shown to be safe to animals as it is chemically the same as sand.

The amount required to cover critical large areas is low, since it works with a layer 1/3 mm thick.

Strategic use of reflective sand could cool the fast-warming Siberian continental shelf in the Arctic, where seabed permafrost stores as much methane as all the land permafrost of the Arctic-- and is in danger of releasing it ten times faster (P. Wadhams, personal communication, 2019).

This one method could scale to avoid disastrous permafrost melting, for an estimated \$1–5 billion per year (Leslie Field, personal communication, 2019).

## MARINE-CLOUD BRIGHTENING (MCB)

As ships crisscross the ocean, sulfates in the exhaust rise to become tiny seed crystals that brighten marine clouds slightly, increasing their reflectivity a few percent. Scientists have replicated this effect, atomizing seawater to use salt instead of sulfates ([The Economist, 2014](#)) ([Leavenworth, 2017](#)).

Costs for implementing MCB at global scale range from less than \$100M/year (Armand Neukermans personal communication 2019) ([Salter et al, 2008](#)) to \$5B/year ([National Research Council, 2015b](#)). While some proof-of-concept work has been accomplished, virtually no funds are currently budgeted for further development.

## IRON SALT AEROSOL (ISA)

Iron salt aerosol combines the benefits of marine cloud brightening and ocean iron fertilization (Oeste, 2017). By adding miniscule amounts of iron to ship or power-plant fuel, iron salts can be sent into the sky, where they have many positive effects. In the atmosphere, ISA can:

- Eliminate atmospheric methane—the iron salt aerosol catalyzes it into CO<sub>2</sub> and water;
- Increase cloud brightness, similar to marine-cloud brightening; and
- Increase ocean (and land) photosynthesis, similar to ocean iron fertilization, potentially removing half our excess trillion tons of CO<sub>2</sub> by 2050.

Costs for implementing ISA at global scale are estimated to be \$1–5 billion per year (Oeste, personal communication, 2019). If testing confirms the efficacy of ISA, this will be added to the list of viable solutions. Currently, however, no funds are known to have been allocated for testing and development.

## SEA-ICE THICKENING

Oil companies have thickened sea-ice for decades to build ice roads and islands for oil production (Ekelund, 1980). Seawater, pumped onto existing ice in winter's -40°C temperatures, can freeze in an hour. Adding a meter of new ice could ensure the ice remains frozen through the summer ([Desch, 2017](#)). Arctic restoration researchers project that thickening ice in 10 percent of the Arctic would be enough to prevent catastrophic methane release.

The method is well proven, although oil companies use diesel to power the pumps—a nonstarter for Climate Restoration. Arizona State University researchers suggest wind turbines—about 10 million of them (similar to the number of cars in New York or Los Angeles) ([Desch, 2017](#)). Oil companies have cautiously expressed interest in contributing their experience and resources to the effort (Private communication, 2019).

#### BOX 4. STRATOSPHERIC SUNBLOCK: SOLAR RADIATION MANAGEMENT

Solar radiation management (SRM) represents a range of rapid but temporary cooling methods that reflect a small percentage of sunlight away from earth and back to space. These approaches could be used for 10-15 years after the global community has mobilized to restore healthy levels of CO<sub>2</sub> and Arctic ice. SRM could save hundreds of millions of lives during the time it takes for CO<sub>2</sub> to drop back to healthy levels.

One of the better-known SRM methods, stratospheric aerosol injection (SAI), mimics the scattering of volcanic dust in the upper atmosphere (stratosphere). The particles could be sulfates or calcium carbonate. While sending sulfates to the stratosphere may sound drastic, an effective sulfur-aerosol project would add only a tiny fraction of the sulfates already in the air.

For some context: SAI may involve spraying 0.5 million tons/year of sulfates or carbonates for 10-15 years, in targeted areas. Mount Pinatubo released 17 million tons of sulfates in 1991 (Smith et al, 2011). Coal plants emit 100 million tons of sulfates to the lower atmosphere every year (Klimont et al, 2013). In other words, SAI would add 0.5 percent to the amount produced by coal plants.

Calcium carbonate is also being considered as an alternative to sulfates, since there is concern that stratospheric sulfates could harm the ozone layer (Keutsch Research Group, n.d.).

Although SRM can rapidly lower temperatures, it does not remove CO<sub>2</sub>. Therefore, we suggest that it is premature to focus on SRM other than for research and avoiding emissions from permafrost, until we commit to restoring safe levels of CO<sub>2</sub>.

#### NANOBUBBLES

Seafoam brightens the ocean surface and can be artificially generated. The smaller the bubbles, the longer they last: Bubbles smaller than 5 microns persist for days or weeks, slightly brightening the ocean surface. Devices called “fluidic oscillators”

produce nano bubbles at low cost (Seitz, 2011) (Clark, 2018). Currently no projects are funded to advance this technology.

## STRATEGY AND COST OF CLIMATE RESTORATION

***“We always overestimate the change that will occur in the next two years and underestimate the change that will occur in the next ten. Don’t let yourself be lulled into inaction.”***

**–Bill Gates**

Climate restoration is planned in three phases:

■ **2019–20:** Agree on the goal, organize initial funding, declare a “Decade of Climate Restoration,” and forge a Climate Restoration Coalition

■ **2021–30:** “Decade of Climate Restoration:” Select, pilot, implement, and scale solutions to 100% needed capacity

■ **2031–50:** Rapidly remove CO<sub>2</sub> and restore Arctic ice as CO<sub>2</sub> returns to below 300 ppm and the climate returns to health

Considering objectives and costs by phase highlights an idea integral to climate restoration: As with the moonshot of the 1960s, it is declaring the goal that initiates action. Activities and financing follow.

Managed well, Climate Restoration could be relatively inexpensive—especially compared to the cost and societal disruption of inaction. The costs and returns-on-investment (ROI) given for Climate Restoration solutions below are best estimates grounded in what practitioners know now. As Gates reminds us, technology advances faster than we would estimate over 10 years; we can expect costs to drop correspondingly.

**A TRILLION TONS OF CO<sub>2</sub> REMOVED BY 2050.** Our best estimates given current knowledge is:

Public funding of \$30 million per year for science, monitoring and oversight through 2050 would ensure safety and pay for oversight and create buy-in.

Commercial investment requirements through 2030 vary widely depending on the method selected, from \$300 million to \$250 billion per year.

Buyers of products derived from Climate Restoration (e.g., synthetic limestone, fish) would pay directly for carbon removal, to be completed by 2050.

#### **ARCTIC ICE RESTORATION.**

Public investment of \$5–20 billion per year may be sufficient to restore Arctic ice in time to avoid or remove catastrophic methane release from permafrost.

#### **OVERALL.**

Climate Restoration would require as little as \$300 million or as much as \$250 billion in private investment per year through 2050. Meanwhile, climate-related losses cost the world \$160 billion in 2018, as calculated by Swiss Re, one of the world's largest reinsurers ([Energize Weekly, 2019](#)).

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**Restoring the climate by 2050, with the solutions we have now, could require as little as \$300 million or as much as \$250 billion per year in private investment, with an estimated IRR of 15 percent. For context: climate-related losses in 2018 alone cost the world \$160 billion.**

### **COST BY CLIMATE RESTORATION OPTION**

Here we consider the primary climate-restoration solutions, each scaled to sequester 50 GT CO<sub>2</sub> per year (in case only one is employed). The scale-up costs are estimates made by the authors in discussion with the solutions' inventors, based on best current knowledge. These are all “back of the envelope calculations” because there is no funding, or even public encouragement, yet for scale-up to 50 GT/year. Thus these are not intended for comparison or evaluation. They show that the

financing is entirely possible, even if the cost were 5x more or 5x less than estimates.

#### **ESTIMATED COSTS FOR EXCESS CO<sub>2</sub> REMOVAL, PER YEAR**

Because of the preliminary nature of these figures, they are not intended for comparison or evaluation. Bill Gates' observation above reminds us that, for technology, costs often turn out to be lower than those estimated.

**TABLE 2**

SOLUTION, SCALED UP TO 50 GT CO <sub>2</sub> /YR	NATURAL PROCESS IT MIMICS	PUBLIC FINANCING REQUIRED	INVESTMENT PER YEAR (FOR 10 YEARS) AND IRR*	ESTIMATE BASIS	NOTES
<b>CARBON-NEGATIVE BUILDING MATERIALS</b>	Shellfish build shells from CO <sub>2</sub> and Calcium	N/A	\$250 B/yr to build up capacity by 5 billion tons/ year  IRR = 15%	Blue Planet Ltd—business plan	\$50/ton/ year at capacity;  Quarried stone costs \$30–200/ ton
<b>OCEAN FERTILIZATION</b>	Volcanic dust fertilizes the ocean	\$20 M/yr for monitoring, public oversight	\$300 M/yr for 10 years;  IRR = 20%	Pasture Partners - business plan	300 pastures per year  Removes ⅓ GT of CO <sub>2</sub> /yr/ pasture
<b>PERMACULTURE ARRAYS WITH UPWELLING</b>	Kelp forests near natural upwelling sites	\$10 M/ yr for monitoring, public oversight	\$100 B/yr for 10 years;  IRR = 15%	Climate Foundation-business plan	To build arrays to cover 1 million km <sup>2</sup> per year, for 10 years.
<b>TOTAL</b>		\$30 million a year for 30 years			

\*IRR = internal rate of return, or annualized rate of earnings on an investment

**BOX 5. CALCULATING CARBON SOLUTION COSTS**

**CARBON-NEGATIVE BUILDING MATERIALS:** synthetic limestone. To sequester 50 GT CO<sub>2</sub> per year would require building 5,000 plants per year over ten years: 50,000 by 2030. Each would have the capacity to capture a million tons of CO<sub>2</sub> per year, and produce 2 million tons of limestone.

At scale, plants are expected to cost about \$50 million each, so investment needs total \$250 billion per year, for ten years. Costs include the carbon capture.

Since transport is the major cost of rock, it makes sense to build the 50,000 mostly where the rock is needed, in and near cities.

**OCEAN FERTILIZATION.** The process as tested in the Gulf of Alaska in 2012 would use government-funded science to monitor the performance and health of the “pastures” being restored.

Each pasture, about 60 miles (100 km) in diameter, can remove about 200 million tons of CO<sub>2</sub> per year. Therefore 300 pastures could sequester 50 GT CO<sub>2</sub>/year.

It would cost an estimated \$1 million to fertilize a pasture for a year. Pastures would remain fallow half the time to allow the chemistry and biome to return to baseline.

If 20 island and coastal states each decided to restore their fisheries, and managed 30 pastures (follow half the time), these activities would store the target of 50 GT CO<sub>2</sub> per year, at a cost of \$30 million.

**MARINE PERMACULTURE ARRAYS** are expected to remove about 500 tons of CO<sub>2</sub> per year. That scale would require building 1 million km<sup>2</sup> of arrays each year, at an anticipated cost of \$10,000 per km<sup>2</sup>.

## COSTS FOR ARCTIC ICE RESTORATION

For each option, we have calculated costs as if it would be the only method used. Of course, if a

combination of methods were used, the cost of each would be lower.

**TABLE 3**

METHOD	PUBLIC FUNDING	START-UP FUNDING	PERSISTENCE (YEARS)	NOTES
ICE THICKENING	\$10B/year	\$5M	1 year	Sea ice only
FLOATING SAND	\$5B/year	\$2M	0.5 year	Mainly sea ice, maybe glaciers
MARINE CLOUD BRIGHTENING (MCB)	\$100M/year	\$10M	0.1 year	
IRON SALT AEROSOL (ISA)	\$50M/year	\$2M	0.1 year	Also removes methane & fertilizes ocean
STRATOSPHERIC AEROSOL INJECTION (SAI)	\$5B/year	complete	1.5 year	Can also be used to cool the tropics and improve crops and save lives
NANO-BUBBLE FOAM (SEITZ, 2011, CLARKE, 2018) <sup>19</sup>		\$3M	0.1 year	
<b>TOTAL</b>	<b>\$20.15 billion/year</b>	<b>\$22 million</b>		

<sup>19</sup>Bubbles smaller than 5 microns last days or weeks, brightening the ocean surface, (Seitz, 2010); [Bright Water](#) (Harvard 2010), [Design for a Marine Nanobubble Generator](#) (Sev Clark 2018)

## POLICY TO ACCELERATE CLIMATE RESTORATION

***“Nothing is more powerful than an idea whose time has come.”***

**–Victor Hugo**

Government policy has tremendous leverage to accelerate progress in fields requiring collective action, such as Climate Restoration. At the same time, a coalition will be needed to align goals and action. Here we propose ways for policy to promote the goal of reducing atmospheric CO<sub>2</sub>

below 300 ppm by 2050, through methods that are scalable, financeable, and permanent. This would serve as a compass for investors, private sector, financiers, civil society groups, and scientists to support the solutions that will actually produce the needed results.

### EARLY-STAGE CLIMATE RESTORATION POLICY: AGREE ON THE GOAL, BOLSTER CONFIDENCE IN THE SOLUTIONS AND DECLARE A “DECADE OF CLIMATE RESTORATION”

**The objective through 2020 is to make Climate Restoration “an idea whose time has come.”** This means generating broad and explicit agreement on the goal of climate restoration and ensuring the survival and flourishing of humanity. This agreement must include key communities including the UN, religious, political, policy, environmental, education, economics, finance, business, technical, building, and others. Most of these communities have traditions of focusing on immediate goals and assuming that the future will take care of itself, an assumption that is no longer true.

Such agreement would be expressed as membership in the Climate Restoration Coalition and as significant funding for relevant programs in each community. Early-stage policy should also promote research and development on methods and safety, setting the stage for investment and implementation.

**CLIMATE RESTORATION RESOLUTIONS** allow climate advocates to call on public officials and other leaders to explicitly commit to the survival and flourishing of humanity. Several Members of Congress have introduced Climate Restoration resolutions so far ([H.Con.Res 35](#) and [H.Con.Res 52](#), U.S. Congress 2019). At least one U.S. county, Santa Clara County in California, recently pledged support for climate restoration. ([Santa Clara, 2019](#))

#### LAUNCHING A “DECADE OF CLIMATE RESTORATION,” 2021–2030

During this decade, investors and implementers will refine and scale up carbon removal and Arctic restoration solutions to 100 percent of capacity required to achieve restoration by 2050.

This period also coincides with the completion of the [Sustainable Development Goals](#) (SDGs). Global warming makes most of the SDGs nearly impossible to achieve: it exacerbates hunger, drought, poverty, illness, and displacement. Conversely, repairing the climate has many benefits, including that it can restore the dependability of farming seasons; allow would-be climate refugees to stay in their homes; and limit the spread of disease-carrying insects.

#### FORMING THE GLOBAL PARTNERSHIP FOR CLIMATE RESTORATION (GPCR)

Loosely modeled after the Global Fund to Fight AIDS, Tuberculosis and Malaria, the GPCR will help mobilize support and investment for Climate Restoration. It will create standards for and guide organizations conducting carbon-removal projects; oversee safety and results monitoring; and coordinate public and private stakeholders.

## FUNDING FOR RESEARCH AND DEVELOPMENT

Funding for Climate Restoration research and development would engage university researchers leverage academic and philanthropic support and private investment. Of particular interest is modeling to show how ice caps and oceans react as CO<sub>2</sub> returns to safe levels, so we can fine-tune restoration efforts.

## GRAND CHALLENGES AND PRIZES

Well-publicized, substantial prizes specifically for large-scale carbon removal and storage can generate excitement and encourage teams to develop new solutions. The Carbon XPRIZE (XPRIZE, 2019) is an example. New challenges

could encourage technologies that meet the three Climate Restoration criteria.

## CARBON TAXES

A tax on emissions, already enacted in about 60 countries, has successfully promoted emissions reductions in some and demonstrates a commitment to climate action (World Bank, 2018). Now that the cost for new renewable energy generation has fallen well below those for new fossil fuels infrastructure in most of the world, we expect renewables to accelerate their rapid expansion—with or without carbon taxes (Motyaka, 2019). However carbon tax revenue used to accelerate Climate Restoration development would be logical and productive.

## MIDDLE-STAGE POLICY, 2021–30: SCALING UP CLIMATE RESTORATION TECHNOLOGIES

The Decade of Climate Restoration will see the demonstration and scale-up of carbon-removal capacity. The objective of middle-stage policy is to increase both the robustness of Climate Restoration methods and the private investment to develop them.

To date, climate-fund managers say they have eager investors waiting, but not enough projects ready to handle the \$10-million minimum investment that institutional investors often prefer.

Policy tools for rapidly growing investment in carbon removal include:

### INVESTMENT TAX CREDITS.

Build a tax credit, and investors will come. To significantly promote Climate Restoration, incentives must be carefully targeted to solutions that meet the criteria of being scalable, permanent and financeable.

For instance, a recent U.S. tax credit for sequestered carbon called “45Q” quickly boosted investment in DAC projects that withdraw CO<sub>2</sub> from the atmosphere (Carbon180, 2019) (US Code, 2018). Yet most of that CO<sub>2</sub> is being used to increase oil production through “enhanced oilfield

recovery” (Doukas, 2017). This well intentioned credit has yielded counterproductive benefits that reduce the cost of oil but add little benefit for climate restoration projects.

On the other hand, well designed investment credits for ocean-fishery restoration and carbon-negative building materials would rapidly boost the investment needed to build these new industries.

### CARBONSTAR® RATING FOR BUILDING MATERIALS.

Inspired by Energy Star®, a CarbonStar® system will certify that carbon-negative materials store as much carbon as they claim. It should be in place in early 2020, after which procurement rules can move the building material markets rapidly.

### PROCUREMENT RULES.

Procurement rules can have a big impact. CarbonStar® will enable effective procurement policies that require building materials be made from carbon-negative materials wherever possible. If adopted globally, by 2050 all the excess CO<sub>2</sub> could be sequestered into buildings and roads. These rules would be adopted by cities, counties, states, nations, and groups like the Green Building Council, LEED, and Architecture 2030.

## A SIMILAR CARBON CERTIFICATION FOR FISH.

Certification that fish were grown in carbon sequestration areas must be designed and proposed. (Efforts are under way to develop similar certification for carbon-negative food from farms.)

## POLICY PROMOTING GOVERNANCE AND COORDINATION.

New environmental policies must be designed which balance the survival of future generations against the short and medium term goals of today's corporations and individuals. These policies must be developed by non-profits such as Greenpeace, Sierra Club, WWF, etc, as well as official agencies such as Environmental Protection Agencies.

## ARCTIC RESTORATION POLICY AND BUDGETS

Streamlined permitting for testing of low-risk biomimicry and geomimicry materials should be designed, adopted, and promoted in the US and other countries. Research and development budgets for Arctic restoration techniques should be developed and adopted, whether or not they are likely to lead to profitable industries. This is similar to budgets for public education which benefit future generations, and benefit current businesses that provide materials and service..

### BOX 6. OPPORTUNITIES TO CONTRIBUTE

#### What can governments do?

- Develop policy to encourage research into Climate Restoration and the survival of humanity
- Policy to encourage the use of carbon-negative construction materials
- Policy to encourage marine-fishery restoration.

#### What can companies & organizations do?

- Advocate for public investment in Climate Restoration policy and projects
- Develop procurement policies that favor carbon-negative construction materials
- Let policymakers know that you hold them accountable for the survival of humanity

#### What can investors do?

- Invest in and guide companies working on Climate Restoration solutions

#### What can scientists and researchers do?

- Model pathways to restoration: regarding energy, economics, resources, oceans, agriculture, environment, health
- Test the models, spotlight challenges for technologists to solve

#### What can individuals do?

- Tell policymakers that we want humanity to survive and that we're holding them accountable
- Research the most impactful things you can do to lower your carbon footprint.

## LATE STAGE POLICY, 2031–50: REMOVING CARBON AT SCALE AS THE CLIMATE RETURNS TO HEALTH

In these decades we should expect to see carbon-dioxide removal at rates required for CO<sub>2</sub> levels to drop below 300 ppm by 2050, approximately 50 GT per year. Late-stage policy will focus on monitoring and continuous refinement as well

as ensuring reliable financing to complete the process. It should also encourage new technologies and efficient, low cost paths to reducing consumption of natural resources.

## CONCLUSION

We do not need to leave dangerous, unprecedented conditions to our progeny. We have the technology and financing, now, to reclaim the climate of over a century ago. What we need is the commitment to do so.

While new carbon removal and storage methods will surely emerge, the world already possesses the ability to restore an optimal climate for humanity by 2050. Although skeptics will point out that there is no proof that we will succeed until we're done, clear goals and sound, flexible management can get us there—as they did in overcoming smallpox and for the moon mission.

Restoring the climate will allow us to commit to other issues critical to the survival and flourishing of humanity, such as eliminating extreme poverty and restoring the environment.

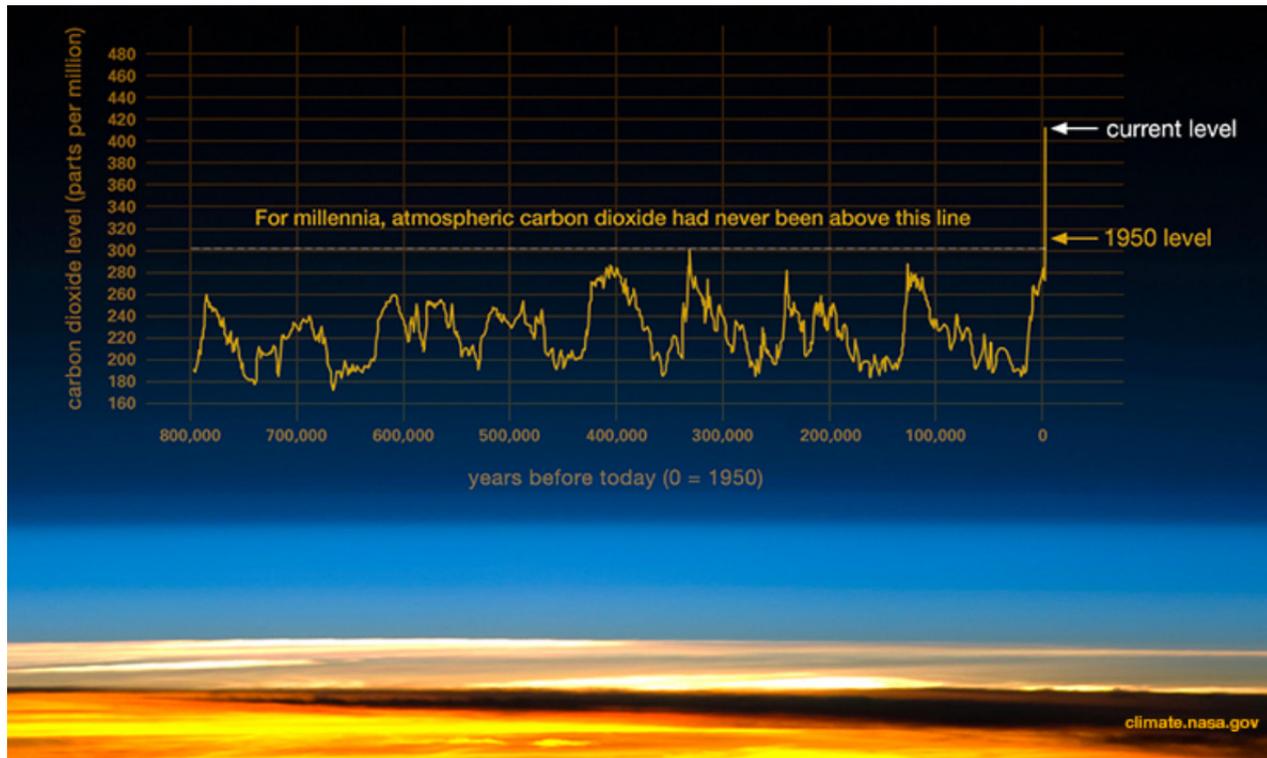
We can and must begin today. What's needed is to collectively commit to restore the climate—and let that commitment attract the investment needed.

If you would like to be a *Restorationist*, join the Global Coalition for Climate Restoration at [F4CR.org/coalition](https://www.f4cr.org/coalition)



Credit: Ben Chapman

## Appendix 1: The Current Climate Trajectory



Credit: [NOAA](#)

Data from: Luthi, D., et al. 2008; Etheridge, D.M., et al. 2010; Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO<sub>2</sub> record. Some description adapted from the Scripps CO<sub>2</sub> Program website, “Keeling Curve Lessons.”

In 2019, carbon dioxide in the air reached 415 ppm, far above the highest level (300 ppm) since homo sapiens evolved. A time lag exists between carbon additions and temperatures as the oceans warm, but the trends are clear.

The last time atmospheric CO<sub>2</sub> exceeded 400 ppm was between 3 and 4 million years ago (NASA, 2013). Camels and horses roamed the Arctic. Palm trees grew in the Arctic. Ocean waves lapped shores 40 meters (131 feet) higher than today’s. Forests and grasslands likely covered the Sahara (Wallace-Wells, 2019). Homo sapiens had yet to evolve.

Temperatures hovered on average 2-3° Celsius (3.6-5.4° Fahrenheit) warmer than today; 10° Celsius warmer in the Arctic.

In such a world, some humans might survive. But billions of people, mostly the poorer among us, are likely to perish as ecosystems collapse (Ellison, 1991), food production falls (Rosenzweig et al., 2001), the sea engulfs coastal cities (Nicholls, 2010), hundreds of millions move away from unlivable homes (Piguet, 2008), and conflicts erupt (World Bank, 2009) over water, land, and other resources (Ellison, 1991). All these are already beginning to happen.

Today, despite laudable progress in renewables and climate action taken by countries and cities across the world, CO<sub>2</sub> trends show us now heading for an even hotter future.

Already, at 415 ppm CO<sub>2</sub>, unprecedented heat waves on every continent are making food harder to grow and leading to a surge in heat-related deaths. Insect populations, including pollinators needed to produce crops, are crashing, down 75% to 90% from 30 years ago (Carrington, 2019). Coral reefs and other ocean ecosystems are disappearing. Hotter temperatures enable the spread of disease-bearing mosquitoes and ticks. Weather-related disasters—floods, long-term droughts, wildfires, and monster storms—are on the rise.

The climate crisis is about the speed of change even more than the temperature. The planet is heating far faster than natural systems can adapt—10 times faster than it has before, with the notable exception of the five previous mass extinction periods. Indeed, many scientists claim we are in the midst of the sixth mass extinction—one that we could reverse.

## Appendix 2: On tipping points

### We've already tipped. But it's not irreversible

Think of a bookshelf, upright and stable. Push a bit and it will rock and return to vertical. Push hard enough, long enough, and it will reach a “tipping point” and fall over. Now it's stable again, horizontal on the floor.

Once the shelf is actually falling, it doesn't help much to stop pushing. You need to shift strategies when you recognize the change—run around to the other side and push it back up.

The climate literature is full of references to “avoiding (unspecified) irreversible tipping points.” The one of most concern to experts is the melting of the polar ice caps, and that is clearly reversible as shown in figure 1, although historically it has taken millions of years.

### Icehouse Earth, hothouse Earth

For instance, in geological time our planet alternates between two stable states—“icehouse earth” and “hothouse earth.” Icehouse earth features ice-covered poles, glaciers, and periodic ice ages: This is the climate in which we evolved (Steffen, 2018).

Sediment cores show that icehouse switches to hothouse when CO<sub>2</sub> exceeds 350–400 ppm. The last hothouse state prevailed between 3 and 5 million years ago. Visualize camels in the Arctic, lush forest near the South Pole.

You could say that we tipped in 2016 when CO<sub>2</sub> hit 400 ppm (Kahn, 2016), or earlier this century when it hit 350ppm. In any case, the bookcase is falling: We have transitioned most of the way from icehouse to hothouse. By now, 80% of Arctic sea-ice has melted. Arctic forests and peat are burning. Melting permafrost is pouring more CO<sub>2</sub> and methane—a shorter-lived but far more potent greenhouse gas—into the atmosphere (Wadhams, 2017).

Yet passing the tipping point is not necessarily irreversible. It means you have to run around to right the bookcase before it lands; or run around to get the CO<sub>2</sub> out while Earth is still transitioning. Refraining from pushing—or stopping emissions—alone won't set things right.

### Appendix 3: A Word on Climate Restoration Targets

Climate Restorationists use CO<sub>2</sub> ppm as a yardstick since it is simpler to measure and control than temperature levels.

Global winds keep CO<sub>2</sub> levels uniform around the planet, so readings from Mauna Loa, Hawaii accurately chart progress. In contrast, checking global average temperature requires calibrating and collating thousands of measurements.

We know how the composition of air has changed over the last 800,000 years. Scientists analyze air bubbles trapped in “ice cores”—samples of ice drilled miles down in the ice caps of Greenland and Antarctica. In those 800,000 years—longer than modern humans have existed—CO<sub>2</sub> levels have never strayed above 300 ppm for any significant length of time, until 1925.

In 2019, atmospheric carbon reached 415 ppm; it continues to rise 2.5 ppm per year.

The commonly discussed climate plans, such as the IPCC 1.5 report and Project Drawdown, call for attaining net zero CO<sub>2</sub> emissions by roughly 2050. If that happens, CO<sub>2</sub> will stabilize at 455 ppm, 50% higher than has been proven to be safe.

We can infer from historic climatic records that leaving CO<sub>2</sub> above 300 ppm long-term poses a significant risk that humanity may not survive. We are already getting a taste of the “natural” disasters, resource conflicts, droughts and ecosystem disruption that will only accelerate without active efforts to reduce atmospheric CO<sub>2</sub>.

Therefore the objective of Climate Restoration is to reduce CO<sub>2</sub> levels to below 300 ppm.

### Appendix 4: What about the 2°C and 1.5°C goals?

Policymakers generally consider global warming to be an economic issue described through “externalities”, to be solved with economic tools such as carbon taxes. Yale economist William Nordhaus, who won the Nobel Prize in economics in 2018, began proposing economic remedies in 1977, in “Economic Growth and Climate: The Carbon Dioxide Problem,” based on simple physics and economic models ([Nordhaus, 1977](#)).

Nordhaus, after weighing economic costs and benefits of decarbonizing society, concluded that 2°C warming would be an optimal target. In the years since, others have also settled on a 2° C goal ([Carbon Brief, 2014](#)).

An alternative way of looking at global warming is to consider it a problem related to the survival of humanity. Some economists might equate economics and survival, but timescales relevant to humanity’s survival exceed the decadal timelines that economics tends to consider. In addition, economic models do not generally consider environmental, economic or social collapse, and it’s not clear how they would be modeled.

Climate Restoration is based on our desire for humanity to survive and flourish, which is different than the economic criteria used for the 2° C goal.

Humans have never survived with CO<sub>2</sub> above 300 ppm before, and there is reason to predict that we will not in the future ([Gutterman, 2018](#)). To prevent environmental, social, political and economic collapse, we suspect we'll need to restore the climate by 2050 at the latest.

#### **Appendix 5: Can we restore the climate without a sea-change in consciousness and economic systems?**

Many writers call for fundamental economic change as a precondition for meaningful climate action. Climate activists often cite the quote: “We can’t solve problems by using the same kind of thinking we used when we created them.”

However, Climate Restoration does not come from the same kind of thinking that created the problem. Unstrategic, short-term thinking brought us here. Mature, collective action can lead us out.

There is no question that the current economic system creates huge inequities and burdens. Nevertheless, we can restore the climate now—either under the current system, or during profound social and economic change.

In fact Climate Restoration could give humanity the time we need to develop a more just and equitable society.

#### **Appendix 6: CarbonStar® rating for building materials**

CarbonStar® is a new rating system for building materials modeled after the international EnergyStar rating, which allows customers to compare products by energy consumption.

Currently being approved by the [Canadian Standards Association](#), it is expected to be available in 2020.

When carbon-negative building materials come on the market, CarbonStar will provide a uniform international metric for rating the amount of carbon in rock, concrete, and other materials. The rating system will help government officials, and architecture groups such as the [Green Building Council](#) and [Architecture 2030](#), implement requirements for low- or negative-carbon building materials.

CarbonStar® could make a major contribution to Climate Restoration since the quantity of building materials used each year is enormous: Seven tons for every person on the planet.

## THE FOUNDATION FOR CLIMATE RESTORATION (F4CR)

Our mission is to catalyze the commitment and action needed for Climate Restoration because we hold ourselves accountable for ensuring human survival and flourishing.

We encourage and spotlight achievable solutions to draw down excess CO<sub>2</sub> from the air and rebuild Arctic ice, engaging in dialogue and global initiatives to unite the public, policy-makers, and technical and business experts behind the common goal of reversing global warming and restoring a healthy climate for future generations.

The Foundation for Climate Restoration is a 501(c)3 charitable organization based in the United States.

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# BIBLIOGRAPHY

- Anderson, J. M. "The Effects of Climate Change on Decomposition Processes in Grassland and Coniferous Forests." *Ecological Applications* 1, no. 3. 1991: 326–47. <https://doi.org/10.2307/1941761>.
- ASU. "Lackner's Carbon-Capture Technology Moves to Commercialization." *ASU Now*, April 29, 2019. <https://asunow.asu.edu/20190429-solutions-lackner-carbon-capture-technology-moves-commercialization>.
- Atomic Heritage Foundation. "The Manhattan Project." May 12, 2017. <https://www.atomicheritage.org/history/manhattan-project>.
- de Baar, Hein J. W., Philip W. Boyd, Kenneth H. Coale, Michael R. Landry, et al. "Synthesis of iron fertilization experiments: From the Iron Age in the Age of Enlightenment." *Journal of Geophysical Research*, 110, September 28, 2005, C09S16. <https://doi.org/10.1029/2004JC002601>
- Baik, Ejeong, Daniel L. Sanchez, Peter A. Turner, Katharine J. Mach, Christopher B. Field, and Sally M. Benson. "Geospatial Analysis of Near-Term Potential for Carbon-Negative Bioenergy in the United States." *Proceedings of the National Academy of Sciences* 115, no. 13. March 27, 2018: 3290–95. <https://doi.org/10.1073/pnas.1720338115>.
- Bailey, Rob, and Richard King. "Betting on BECCS? Exploring Land-Based Negative Emissions Technologies." Hoffmann Centre for Sustainable Resource Economy, May 17, 2018. <https://hoffmanncentre.chathamhouse.org/article/betting-on-beccs-exploring-land-based-negative-emissions-technologies/>.
- Bastin, Jean-Francois, Yelena Finegold, Claude Garcia, Danilo Mollicone, et al. "The Global Tree Restoration Potential." *Science* 365, no. 6448. July 5, 2019: 76–79. <https://doi.org/10.1126/science.aax0848>.
- Bate, Mathew. "An Illustrated Guide to Seaweed Farming." *Matters Journal*, December 2018. <https://mattersjournal.com/stories/seaweedfarming>.
- Bates, Albert, and Kathleen Draper. *Burn: Using Fire to Cool the Earth*. White River Junction, Vermont: Chelsea Green Publishing, 2019.
- Berwyn, Bob. "Ice Loss and the Polar Vortex: How a Warming Arctic Fuels Cold Snaps." *Inside Climate News* (blog), September 28, 2017. <https://insideclimatenews.org/news/27092017/polar-vortex-cold-snap-arctic-ice-loss-global-warming-climate-change>.
- Bevis, Michael, Christopher Harig, Shfaqat A. Khan, Abel Brown, Frederik J. Simons, Michael Willis, Xavier Fettweis, et al. "Accelerating Changes in Ice Mass within Greenland, and the Ice Sheet's Sensitivity to Atmospheric Forcing." *Proceedings of the National Academy of Sciences* 116, no. 6. February 5, 2019: 1934–39. <https://doi.org/10.1073/pnas.1806562116>.
- Biello, David. *The Unnatural World: The Race to Remake Civilization in Earth's Newest Age*. 1st edition. New York: Scribner, 2016.
- Bishop, James K. B., Todd J. Wood, Russ E. Davis, and Jeffrey T. Sherman. "Robotic Observations of Enhanced Carbon Biomass and Export at 55°S During SOFeX." *Science* 304, no. 5669. April 16, 2004: 417–20. <https://doi.org/10.1126/science.1087717>.
- "Blue Planet | Economically Sustainable Carbon Capture," 2019. <http://www.blueplanet-ltd.com/>.
- Boudreau, Thomas. "The Earth's Atmosphere as a Global Trust: Establishing Proportionate State Responsibility to Maintain, Restore and Sustain the Global Atmosphere." *Environmental and Earth Law Journal (EELJ)* 7, no. 1. August 25, 2017. <https://lawpublications.barry.edu/ejej/vol7/iss1/2>.
- . "Blue Planet: Green Seas: Buying Time in the Current Climate Change Crisis through Negative Emissions." *MAHB* (blog), December 2018. <https://mahb.stanford.edu/blog/blue-planet-green-seas-global-strategy-carbon-sequestration/>.
- Boyd, P. W., T. Jickells, C.S. Law, S. Blain et al. "Mesoscale Iron Enrichment Experiments 1993–2005: Synthesis and Future Directions." *Science* 315, no. 5812. February 2007: 612–617. <https://doi.org/10.1126/science.1131669>
- Brewer, Peter, and Monterey Bay Aquarium Research Institute. "Sequestration in the Oceans." *The Carbon Dioxide Dilemma: Promising Technologies and Policies*. Washington, D.C.: National Academies Press, 2003. <https://doi.org/10.17226/10798>.
- Buesseler, K. O. "The Effects of Iron Fertilization on Carbon Sequestration in the Southern Ocean." *Science* 304, no. 5669 (April 16, 2004): 414–17. <https://doi.org/10.1126/science.1086895>.
- Burns, Wil, and Simon Nicholson. "Bioenergy and Carbon Capture with Storage (BECCS): The Prospects and Challenges of an Emerging Climate Policy Response." *Journal of Environmental Studies and Sciences* 7, no. 4 (December 2017): 527–34. <https://doi.org/10.1007/s13412-017-0445-6>.
- Caesar, L., S. Rahmstorf, A. Robinson, G. Feulner, and V. Saba. "Observed Fingerprint of a Weakening Atlantic Ocean Overturning Circulation." *Nature* 556, no. 7700 (April 2018): 191–96. <https://doi.org/10.1038/s41586-018-0006-5>.
- Carbon Brief. "Two Degrees: The History of Climate Change's 'Speed Limit'." December 8, 2014. <https://www.carbonbrief.org/two-degrees-the-history-of-climate-changes-speed-limit>.
- Carbon Engineering. "Carbon Engineering Concludes USD\$68 Million Private Investment Round and Proceeds with Commercialization of Carbon Dioxide Removal Technology." March 21, 2019. <https://carbonengineering.com/carbon-engineering-concludes-usd68-million-private-investment-round/>
- Carbon180. "45Q Creates Tax Credits for Carbon Capture. Who Benefits?" Medium, June 5, 2019. <https://medium.com/@carbon180/45q-creates-tax-credits-for-carbon-capture-who-benefits-731bf382ab1d>.
- Carrington, Damian. "Plummeting insect numbers 'threaten collapse of nature.'" *The Guardian*, February 10, 2019. <https://www.theguardian.com/environment/2019/feb/10/plummeting-insect-numbers-threaten-collapse-of-nature>

- Ceballos, G., Paul R. Ehrlich, Rodolfo Dirzo. "Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines." *Proceedings of the National Academy of Sciences of the United States of America*, (2017) 114, no. 30: E6089-E6096. <https://www.pnas.org/content/114/30/E6089>
- Center for Climate and Energy Solutions. "Enhanced Oil Recovery Overview." Factsheet, February 27, 2012. <https://www.c2es.org/document/enhanced-oil-recovery-overview/>.
- Clarke, Sev. "Design v1 for a Marine Nanobubble Generator or 'Fiztop.'" March 2018. <https://climategamechangers.org/wp-content/uploads/Fiztop.pdf>.
- "Climate Foundation: Marine Permaculture." Climate Foundation. Accessed August 27, 2019. <http://www.climatefoundation.org/marine-permaculture.html>.
- Climate Institute. "Expert Input to the Talanoa Dialogue," April 1, 2018. [https://unfccc.int/sites/default/files/resource/97\\_Talanoa%20Submission\\_climate%20institute.pdf](https://unfccc.int/sites/default/files/resource/97_Talanoa%20Submission_climate%20institute.pdf).
- Climeworks. [climeworks.com](http://climeworks.com), 2019
- Cornell University. "Fertilizers for Corn," n.d. <https://fieldcrops.cals.cornell.edu/corn/fertilizers-corn/>.
- Cornelissen, Joep. *Corporate Communication: A Guide to Theory and Practice*. 3rd ed. Thousand Oaks, CA: SAGE Publications, 2011.
- Crewdson, John . "How many people die on airplanes?" *Chicago Tribune*, 1996. <https://www.chicagotribune.com/news/ct-xpm-1996-06-30-9606300406-story.html>.
- Crunchbase. "Climeworks Overview; Total Funding Amount CHF33.5M," n.d.a <https://www.crunchbase.com/organization/climeworks#section-overview>.
- "Carbon Engineering Overview; Total Funding Amount USD107.4M," n.d.b <https://www.crunchbase.com/organization/carbon-engineering#section-overview>
- "Inventys Thermal Technologies Overview; Total Funding Amount USD33.6M," n.d.c <https://www.crunchbase.com/organization/inventys-thermal-technologies>
- Cummins, Ronnie. "Four for 1000': A Global Initiative to Reverse Global Warming Through Regenerative Agriculture and Land Use." *Regeneration International*, October 17, 2017. <https://regenerationinternational.org/2017/10/17/four-1000-global-initiative-reverse-global-warming-regenerative-agriculture-land-use/>.
- Davidson, Helen. "Australian Firm Unveils Plan to Convert Carbon Emissions into 'green' Concrete." *The Guardian*, August 24, 2017, sec. Environment. <https://www.theguardian.com/environment/2017/aug/25/green-building-materials-carbon-capture-technology-ready-by-2020-says-manufacturer>.
- Dawicki, Shelley. "Changing Sea Surface Temperatures and Water Circulation Patterns Affecting Food Supply for Young Atlantic Cod." *Research Communications*, NOAA Fisheries, June 20, 2013. [https://nefsc.noaa.gov/press\\_release/2013/SciSpot/SS1307/](https://nefsc.noaa.gov/press_release/2013/SciSpot/SS1307/)
- Deloitte., and Marlene Motyka. "Deloitte. 2019 Renewable Energy Industry Outlook My Take: Marlene Motyka." Deloitte, 2019. <https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-renewable-energy-industry-outlook.pdf>.
- Derra, Skip . Blog. Lackner's carbon-capture technology moves to commercialization. Arizona State University, April 29, 2019. <https://asunow.asu.edu/20190429-solutions-lackner-carbon-capture-technology-moves-commercialization>.
- Desch, Steven J., Nathan Smith, Christopher Groppi, Perry Vargas, Rebecca Jackson, Anusha Kalyaan, Peter Nguyen, et al. "Arctic Ice Management." *Earth's Future* 5, no. 1 (2017): 107–27. <https://doi.org/10.1002/2016EF000410>.
- DOE: National Energy Technology Laboratory. "Carbon Dioxide Enhanced Oil Recovery Untapped Domestic Energy Supply and Long Term Carbon Storage Solution." U.S. Department of Energy, The Energy Lab, March 2010. [https://www.netl.doe.gov/sites/default/files/netl-file/CO2\\_EOR\\_Primer.pdf](https://www.netl.doe.gov/sites/default/files/netl-file/CO2_EOR_Primer.pdf).
- Dooley, Kate, Peter Christoff, and Kimberly A. Nicholas. "Co-Producing Climate Policy and Negative Emissions: Trade-Offs for Sustainable Land-Use." *Global Sustainability* 1 (2018): e3. <https://doi.org/10.1017/sus.2018.6>.
- Doukas, Alex, Janet Redman, and Steve Kretzmann. "EXPANDING SUBSIDIES FOR CO2-ENHANCED OIL RECOVERY: A NET LOSS FOR COMMUNITIES, TAXPAYERS, AND THE CLIMATE." Oilchange International, October 2017. <http://priceofoil.org/content/uploads/2017/10/45q-analysis-oct-2017-final.pdf>.
- Duan, Lei, Long Cao, Govindasamy Bala, and Ken Caldeira. "Climate Response to Pulse Versus Sustained Stratospheric Aerosol Forcing." *Geophysical Research Letters* 0, no. 0 (August 5, 2019). <https://doi.org/10.1029/2019GL083701>.
- Drawdown Agenda. "Episode 8: Marine Permaculture with Brian Von Herzen." *The Drawdown Agenda* (blog), November 16, 2018. <http://www.thedrawdownagenda.com/episode-8-marine-permaculture-brian-von-herzen/>.
- Duarte, Carlos M., Marianne Holmer, Yngvar Olsen, Doris Soto, Núria Marbà, Joana Guiu, Kenny Black, and Ioannis Karakassis. "Will the Oceans Help Feed Humanity?" *BioScience* 59, no 11 (December 1, 2009): 967-76. <https://academic.oup.com/bioscience/article/59/11/967/251334>
- Duarte, Carlos M., Jiaping Wu, Xi Xiao, Annette Bruhn, and Dorte Krause-Jensen. "Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation?" *Frontiers in Marine Science* 4 (2017). <https://doi.org/10.3389/fmars.2017.00100>.
- Dutkiewicz, Adriana, R. Dietmar Müller, John Cannon, Sioned Vaughan, and Sabin Zahirovic. "Sequestration and Subduction of Deep-Sea Carbonate in the Global Ocean since the Early Cretaceous." *Geology* 47, no. 1 (January 1, 2019): 91–94. <https://doi.org/10.1130/G45424.1>.
- Ekelund, M. J., and D. M. Masterson. "Floating Ice Platforms for Oil Exploration in the Arctic Islands." *Arctic* 33, no. 1 (1980): 168–83.
- Ellison, Joanna C., and David R. Stoddart. "Mangrove Ecosystem Collapse during Predicted Sea-Level Rise: Holocene Analogues and Implications." *Journal of Coastal Research* 7, no. 1 (1991): 151–65.
- Energize Weekly. "Natural Disasters Caused \$160 Billion in Damages in 2018 with about Half Covered by Insurers." *EUCI* (blog), January 15, 2019. [CLIMATE RESTORATION: SOLUTIONS TO THE GREATEST THREAT FACING HUMANITY AND NATURE TODAY](https://www.euci.com/natural-disasters-</a></p>
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caused-160-billion-in-damages-in-2018-with-about-half-covered-by-insurers/.

- “ExxonMobil and Global Thermostat to Advance Breakthrough Atmospheric Carbon Capture Technology,” June 27, 2019. <https://www.businesswire.com/news/home/20190627005137/en/ExxonMobil-Global-Thermostat-Advance-Breakthrough-Atmospheric-Carbon>.
- Fiekowsky, Peter. “Restoring Arctic Ice Is the Key to Curbing Climate Change—So Why Are We Ignoring It?” *Pacific Standard*. March 18, 2019. <https://psmag.com/ideas/we-already-have-effective-ways-of-restoring-arctic-ice>.
- Field, L., D. Ivanova, S. Bhattacharyya, V. Mlaker, et al. “Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering.” *Earth’s Future*, No. 6 (June 2018): 882–901. <https://doi.org/10.1029/2018EF000820>.
- Figueiredo, M.A. de, D.M. Reiner, and H.J. Herzog. “Ocean Carbon Sequestration: A Case Study in Public and Institutional Perceptions.” M.I.T., n.d. <http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.208.568>
- Fisheries and Oceans Canada, Pacific Region. “Salmon Catch Statistics and Logbook Reports | Fisheries and Oceans Canada, Pacific Region,” May 14, 2013. <http://www.pac.dfo-mpo.gc.ca/fm-gp/species-especies/salmon-saumon/fisheries-peches/stats-donnees-eng.html>.
- Fountain, Henry. “How Oman’s Rocks Could Help Save the Planet.” *The New York Times*, April 26, 2018, sec. Climate. <https://www.nytimes.com/interactive/2018/04/26/climate/oman-rocks.html>
- Froehlich, H., Gentry, R., & Halpern, B. “Global change in marine aquaculture production potential under climate change.” *Nature Ecology & Evolution* 2, no. 11 (2018): 1745–1750. <https://doi.org/10.1038/s41559-018-0669-1>
- Fuss, Sabine, Josep G. Canadell, Glen P. Peters, Massimo Tavoni, Robbie M. Andrew, Philippe Ciais, Robert B. Jackson, et al. “Betting on Negative Emissions.” *Nature Climate Change* 4, no. 10 (October 2014): 850–53. <https://doi.org/10.1038/nclimate2392>.
- George, Russ. “Cannery Row At The Beginning Of The Story Of Ocean Pasture Collapse.” (blog), April 11, 2014. <http://russgeorge.net/2014/04/10/cannery-row/>.
- Gertner, Jon. “The Tiny Swiss Company That Thinks It Can Help Stop Climate Change.” *The New York Times*, February 12, 2019. <https://www.nytimes.com/2019/02/12/magazine/climeworks-business-climate-change.html>.
- . “Klaus Lackner Is Pulling CO<sub>2</sub> Out of Thin Air.” *Fast Company*, April 13, 2015. <https://www.fastcompany.com/3044272/clearing-the-air>.
- González, Miriam Ferrer, Tatiana Ilyina, Sebastian Sonntag, and Hauke Schmidt. “Enhanced Rates of Regional Warming and Ocean Acidification After Termination of Large-Scale Ocean Alkalinization: AOA Termination,” *Geophysical Research Letters* 45, no. 14 (July 28, 2018): 7120–29. <https://doi.org/10.1029/2018GL077847>.
- Grist Creative. “Stopping Climate Change Isn’t Enough—We Need to Reverse It.” *Grist* (blog), July 23, 2019. <https://grist.org/article/everyone-has-a-climate-plan-which-ones-get-us-to-a-livable-future/>.
- Gutterman, Sara. “Paul Hawken: How to Reverse Global Warming.” February 15, 2018. *Green Builder*. <https://www.greenbuildermedia.com/blog/paul-hawken-how-to-reverse-global-warming>.
- Hales, Burke, Lee Karp-Boss, Alexander Perlin, and Patricia A. Wheeler. “Oxygen Production and Carbon Sequestration in an Upwelling Coastal Margin: Coastal Margin Production and Sequestration.” *Global Biogeochemical Cycles* 20, no. 3 (September 2006): n/a–n/a. <https://doi.org/10.1029/2005GB002517>.
- Hansen, James, Makiko Sato, Pushker Kharecha, David Beerling, et al. “Target Atmospheric CO<sub>2</sub>: Where Should Humanity Aim?” *The Open Atmospheric Science Journal* 2, no. 1 (October 31, 2008): 217–31. <https://doi.org/10.2174/1874282300802010217>.
- Hanson, J. “Precautionary Principle.” *Encyclopedia of the Anthropocene*, 2018. <https://www.sciencedirect.com/topics/earth-and-planetary-sciences/precautionary-principle>
- Harvey, Chelsea. “Cement Producers Are Developing a Plan to Reduce CO<sub>2</sub> Emissions.” *Scientific American*, News, E&E, 2018. <https://www.scientificamerican.com/article/cement-producers-are-developing-a-plan-to-reduce-co2-emissions/>.
- Hawken, Paul, ed. *Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming*. New York, New York: Penguin Books, 2017.
- Heck, Vera, Dieter Gerten, Wolfgang Lucht, and Alexander Popp. “Biomass-Based Negative Emissions Difficult to Reconcile with Planetary Boundaries.” *Nature Climate Change* 8, no. 4 (April 2018): 345–345. <https://doi.org/10.1038/s41558-018-0107-z>.
- Hollis, Paul. “Fertilizer recommendations proving valid even with increasing corn yields.” *Farm Progress*, February 13, 2013. <https://www.farmprogress.com/grains/fertilizer-recommendations-proving-valid-even-increasing-corn-yields>
- Hooper, Rowan. “Refreezing the Arctic: How to Bring the Ice Back with Geoengineering.” *New Scientist*, August 28, 2019. <https://www.newscientist.com/article/mg24332450-700-refreezing-the-arctic-how-to-bring-the-ice-back-with-geoengineering/>.
- Hsiang, Solomon, Robert Kopp, Amir Jina, James Rising, Michael Delgado, Shashank Mohan, D. J. Rasmussen, et al. “Estimating Economic Damage from Climate Change in the United States.” *Science* 356, no. 6345 (June 30, 2017): 1362–69. <https://doi.org/10.1126/science.aal4369>.
- Ice911 Research. “Our Solution.” 2019. <https://www.ice911.org/beads>.
- Ilyina, Tatiana, Dieter Wolf-Gladrow, Guy Munhoven, and Christoph Heinze. “Assessing the Potential of Calcium-Based Artificial Ocean Alkalinization to Mitigate Rising Atmospheric CO<sub>2</sub> and Ocean Acidification: Modeling Mitigation Potential of AOA.” *Geophysical Research Letters* 40, no. 22 (November 28, 2013): 5909–14. <https://doi.org/10.1002/2013GL057981>.
- . “Assessing the Potential of Calcium-Based Artificial Ocean Alkalinization to Mitigate Rising Atmospheric CO<sub>2</sub> and Ocean Acidification: MODELING MITIGATION

- POTENTIAL OF AOA." *Geophysical Research Letters* 40, no. 22 (November 28, 2013): 5909–14. <https://doi.org/10.1002/2013GL057981>.
- Indigo. "The Terraton Initiative," 2019. <https://www.indigoag.com/the-terraton-initiative>.
- "Injury Facts Chart." National Safety Council, n.d. <https://www.nsc.org/work-safety/tools-resources/injury-facts/chart>.
- "Into the Great Wide Open." *The Economist*, December 11, 2014. <https://www.economist.com/science-and-technology/2014/12/11/into-the-great-wide-open>.
- IPBES, Josef Settele, Eduardo Brondízio, and Sandra Díaz. "IPBES Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services." 7th Session of the IPBES Plenary on 29 April – 4 May 2019. UNESCO world headquarters in Paris on 6 May 2019; UN, May 7, 2019.
- IPCC, 2013. *Climate Change 2013 - The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 2014. <https://doi.org/10.1017/CBO9781107415324>.
- 2018. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].
- 2018. "Summary for Policymakers of IPCC Special Report on Global Warming of 1.5°C Approved by Governments," 2018. <https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments/>.
- Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, et al. "Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change." Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.
- Ishimoto, Yuki, Masahiro Sugiyama, Etsushi Kato, Ryo Moriyama, Kazuhiro Tsuzuki, and Atsushi Kurosawa. "Putting Costs of Direct Air Capture in Context." *SSRN Electronic Journal*, 2017. <https://doi.org/10.2139/ssrn.2982422>.
- Jackson, R. B. "Trading Water for Carbon with Biological Carbon Sequestration." *Science* 310, no. 5756 (December 23, 2005): 1944–47. <https://doi.org/10.1126/science.1119282>.
- Jackson, R B, J G Canadell, S Fuss, J Milne, N Nakicenovic, and M Tavoni. "Focus on Negative Emissions." *Environmental Research Letters* 12, no. 11 (November 1, 2017): 110201. <https://doi.org/10.1088/1748-9326/aa94ff>.
- Jones, Nicola. "How the World Passed a Carbon Threshold and Why It Matters." *Yale E360* (blog), January 26, 2017. <https://e360.yale.edu/features/how-the-world-passed-a-carbon-threshold-400ppm-and-why-it-matters>.
- Joyce, Christopher. "Arctic Is Warming Twice as Fast as World Average." NPR.org, 2014. <https://www.npr.org/2014/12/18/371438087/arctic-is-warming-twice-as-fast-as-world-average>
- Kahn, Brian. "Antarctic CO2 Hit 400 PPM For First Time in 4 Million Years." *Climate Central*, 2016. <https://www.climatecentral.org/news/antarctica-co2-400-ppm-million-years-20451>
- Kahn, Matthew E., Kamiar Mohaddes, Ryan N. C. Ng, M. Hashem Pesaran, Mehdi Raissi, and Jui-Chung Yang. "Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis." *SSRN Electronic Journal*, 2019. <https://doi.org/10.2139/ssrn.3428610>.
- Keith, David W., Geoffrey Holmes, David St. Angelo, and Kenton Heidel. "A Process for Capturing CO2 from the Atmosphere." *Joule* 2, no. 8 (August 2018): 1573–94. <https://doi.org/10.1016/j.joule.2018.05.006>.
- Kennedy, Sarah. "Company Converts CO2 into Building Material » Yale Climate Connections." *Yale Climate Connections* (blog), February 26, 2019. <https://www.yaleclimateconnections.org/2019/02/company-converts-carbon-dioxide-into-building-material/>.
- Keutsch Research Group. "SCoPEX: Stratospheric Controlled Perturbation Experiment." Accessed August 31, 2019. <https://projects.iq.harvard.edu/keutschgroup/scopex>
- Kinver, Mark. "Iceland Volcano Ash Cloud Triggers Plankton Bloom." *BBC News*. April 10, 2013. <https://www.bbc.com/news/science-environment-22045941>
- Klimont, Z., S.J. Smith, J. Cofala. "The Last Decade of Global Anthropogenic Sulfur Dioxide: 2000–2011 Emissions." *Environmental Research Letters* 8, no. 1 (January 9, 2013): <https://iopscience.iop.org/article/10.1088/1748-9326/8/1/014003>
- Kriebel, D, J Tickner, P Epstein, and J et al Lemons. "The Precautionary Principle in Environmental Science." *Environmental Health Perspectives* 109, no. 9 (September 2001): 871–76. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1240435/>
- Kuhar, Mark S. "World Aggregates Market." *Rock Products*, 117, no. 2 (2014): 52-55.
- Lam, Phoebe J., Scott C. Doney, and James K. B. Bishop. "The Dynamic Ocean Biological Pump: Insights from a Global Compilation of Particulate Organic Carbon, CaCO<sub>3</sub>, and Opal Concentration Profiles from the Mesopelagic." *Global Biogeochemical Cycles* 25, no. 3 (2011). <https://doi.org/10.1029/2010GB003868>.
- Landau, Elizabeth. "Revised AGU Position Statement Addresses Climate Intervention." *The American Geophysical Union*, January 8, 2018. <https://eos.org/agu-news/revised-agu-position-statement-addresses-climate-intervention>.
- Lexico Dictionary. "Definition of Safety." Accessed August 21, 2019. <https://www.lexico.com/en/definition/safety>.
- Leavenworth, Stuart. "We Can Brighten Clouds to Reflect Heat and Reduce Global Warming. But Should We?" *McClatchy* . November 8, 2017. <https://www.mcclatchydc.com/news/nation-world/national/article183547911.html>.

- Lempert, Robert J., Giacomo Marangoni, Klaus Keller, and Jessica Duke. "Is Climate Restoration an Appropriate Climate Policy Goal?" Santa Monica: Rand Corporation, 2018. [https://www.rand.org/pubs/research\\_reports/RR2442.html](https://www.rand.org/pubs/research_reports/RR2442.html).
- Levin, Kelly, and Sarah Parsons. "7 Things to Know About the IPCC's Special Report on Climate Change and Land." World Resources Institute, August 8, 2019. <https://www.wri.org/blog/2019/08/7-things-know-about-ipcc-special-report-land-and-climate>.
- Lopez, Gabriel, Zack Abbott, Greg Rau, Leonid Kozhukh, and Sam Altman. "Ocean Phytoplankton | YC Request for Startups." Y Combinator, n.d. <http://carbon.ycombinator.com/ocean-phytoplankton/>.
- Lukacs, Martin. "World's Biggest Geoengineering Experiment 'violates' UN Rules." *The Guardian*, October 15, 2012. <https://www.theguardian.com/environment/2012/oct/15/pacific-iron-fertilisation-geoengineering>.
- Maathai, Wangari. "Silent Forests and Famine in East Africa | Wangari Maathai." *The Guardian*, November 25, 2011, sec. Opinion. <https://www.theguardian.com/commentisfree/2011/nov/25/silent-forests-famine-east-africa>.
- "Mapping The Potential Economic Effects Of Climate Change." NPR.org, 2017. <https://www.npr.org/sections/thetwo-way/2017/06/29/534896130/mapping-the-potential-economic-effects-of-climate-change>.
- Tripp, Emily. "Scientists Use Volcanic Eruption to Study Iron Fertilization," (blog). August 27, 2014. <http://marinesciencetoday.com/2014/08/27/scientists-use-volcanic-eruption-to-study-iron-fertilization/>
- Martin, John H. "Iron as a Limiting Factor in Oceanic Productivity." In *Primary Productivity and Biogeochemical Cycles in the Sea*, edited by Paul G. Falkowski, Avril D. Woodhead, and Katherine Vivirito, 123–37. Environmental Science Research. Boston, MA: Springer US, 1992. [https://doi.org/10.1007/978-1-4899-0762-2\\_8](https://doi.org/10.1007/978-1-4899-0762-2_8).
- Martin, John H., and Steve E. Fitzwater. "Iron Deficiency Limits Phytoplankton Growth in the North-East Pacific Subarctic." *Nature* 331, no. 6154 (January 1988): 341–43. <https://doi.org/10.1038/331341a0>.
- Martin, Patrick, Michiel Rutgers van der Loeff, Nicolas Cassar, Pieter Vandromme, et al. "Iron fertilization enhanced net community production but not downward particle flux during the Southern Ocean iron fertilization experiment LOHAFEX." *Global Biogeochemical Cycles*, 27, August 8, 2013: 871–881. <https://doi.org/10.1002/gbc.20077>
- Matter, Juerg M., W. S. Broecker, M. Stute, S. R. Gislason, E. H. Oelkers, A. Stefansson, D. Wolff-Boenisch, E. Gunnlaugsson, G. Axelsson, and G. Björnsson. "Permanent Carbon Dioxide Storage into Basalt: The CarbFix Pilot Project, Iceland" *Energy Procedia*, 1(2009), pp. 3641–3646.
- Matter, Juerg M., W. S. Broecker, S. R. Gislason, E. Gunnlaugsson, E. H. Oelkers, M. Stute, H. Sigurdardóttir, et al. "The CarbFix Pilot Project—Storing Carbon Dioxide in Basalt." *Energy Procedia*, 10th International Conference on Greenhouse Gas Control Technologies, 4 (January 1, 2011): 5579–85. <https://doi.org/10.1016/j.egypro.2011.02.546>.
- Metz, Bert, and Intergovernmental Panel on Climate Change, eds. *IPCC Special Report on Carbon Dioxide Capture and Storage*. Cambridge: Cambridge University Press, for the Intergovernmental Panel on Climate Change, 2005.
- Mevorach, Ian. "Can We Restore Our Climate? Science and Faith Say Yes." *HuffPost*, June 27, 2017. [https://www.huffpost.com/entry/can-we-restore-our-climate-science-and-faith-say-yes\\_b\\_5952cd81e4b0c85b96c65d7b](https://www.huffpost.com/entry/can-we-restore-our-climate-science-and-faith-say-yes_b_5952cd81e4b0c85b96c65d7b).
- "Mineral Carbonation International." Mineral Carbonation International, 2019. <https://www.mineralcarbonation.com/>.
- Monroe, Rob. "What Does This Number Mean?" *The Keeling Curve* (blog), May 12, 2015. <https://scripps.ucsd.edu/programs/keelingcurve/2015/05/12/what-does-this-number-mean/>.
- Monterey Bay Aquarium Foundation. "Giant Kelp, Kelp Forest, Plants & Algae, Macrocytist Pyrifera at the Monterey Bay Aquarium," 2019. <https://www.montereybayaquarium.org/animals-and-exhibits/animal-guide/plants-and-algae/giant-kelp>.
- Motyka, Marlene. "Renewable Energy Industry Outlook." Deloitte, 2019. <https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-renewable-energy-industry-outlook.pdf>.
- NASA. "An Ocean Full of Deserts" *Earthdata*. May 8, 2019. <https://earthdata.nasa.gov/learn/sensing-our-planet/an-ocean-full-of-deserts>.
- "The Relentless Rise of Carbon Dioxide." Climate Change: Vital Signs of the Planet, n.d. [https://climate.nasa.gov/climate\\_resources/24/graphic-the-relentless-rise-of-carbon-dioxide](https://climate.nasa.gov/climate_resources/24/graphic-the-relentless-rise-of-carbon-dioxide).
- "Scientists React to 400 ppm Carbon Milestone." Climate Change: Vital Signs of the Planet, 2013. <https://climate.nasa.gov/400ppmquotes>.
- National Academies of Sciences, Engineering, and Medicine. *Bioenergy with Carbon Capture and Storage Approaches for Carbon Dioxide Removal and Reliable Sequestration: Proceedings of a Workshop—in Brief*. Washington, DC: The National Academies Press, 2018. <https://doi.org/10.17226/25170>.
- Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press, 2019. <https://doi.org/10.17226/25259>.
- National Energy Technology Laboratory. "Carbon Dioxide Enhanced Oil Recovery: Untapped Domestic Energy Supply and Long Term Carbon Storage Solution." *The Energy Lab*, 2010. [https://www.netl.doe.gov/sites/default/files/netl-file/CO2\\_EOR\\_Primer.pdf](https://www.netl.doe.gov/sites/default/files/netl-file/CO2_EOR_Primer.pdf)
- National Research Council (U.S.). *Advancing the Science of Climate Change. America's Climate Choices*. Washington, D.C: National Academies Press, 2010.
- *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. Washington, D.C: National Academies Press, 2015a.
- *Climate Intervention: Reflecting Sunlight to Cool Earth*. Washington, DC: The National Academies Press, 2015b. <https://doi.org/10.17226/18988>.

- National Safety Council (NSC), 2017. "Injury Facts Chart." <https://www.nsc.org/work-safety/tools-resources/injury-facts/chart>
- National Snow and Ice Data Center (NSIDC). "Arctic Amplification." *NSIDC Highlights*. September 2009. <https://nsidc.org/about/monthlyhighlights/2009/09/arctic-amplification>.
- Nicholls, Robert J., and Anny Cazenave. "Sea-Level Rise and Its Impact on Coastal Zones." *Science* 328, no. 5985 (June 18, 2010): 1517–20. <https://doi.org/10.1126/science.1185782>.
- NOAA. "NOAA Ocean Acidification Program Home," n.d. <https://oceanacidification.noaa.gov/Home.aspx>.
- . "The Relentless Rise of Carbon Dioxide." *Climate Change: Vital Signs of the Planet*, 2008. [https://climate.nasa.gov/climate\\_resources/24/graphic-the-relentless-rise-of-carbon-dioxide](https://climate.nasa.gov/climate_resources/24/graphic-the-relentless-rise-of-carbon-dioxide).
- . "NOAA Observing Buoys Validate Findings from NASA's New Satellite for Measuring Carbon Dioxide." *NOAA Research News*, October 12, 2017. <https://research.noaa.gov/article/ArtMID/587/ArticleID/23/NOAA-observing-buoys-validate-findings-from-NASA's-new-satellite-for-measuring-carbon-dioxide>.
- . "To bloom or not to bloom: Research continues on the causes of harmful algal blooms." April 27, 2016. <https://www.noaa.gov/what-is-harmful-algal-bloom>
- . "Ocean Acidification," PMEL Carbon program, n.d. <https://www.pmel.noaa.gov/co2/story/Ocean+Acidification>.
- Nordhaus, William D. "Economic Growth and Climate: The Carbon Dioxide Problem." *American Economic Review* 67, no. 1 (1977): 341–46.
- Ocean-based Climate Solutions. "<http://www.ocean-based.com/>.
- Ocean Health Index. 2015 *Global Scores*. 2015. <http://www.oceanhealthindex.org/region-scores/annual-scores-and-rankings>
- Oeste, Franz Dietrich, Renaud de Richter, Tingzhen Ming, and Sylvain Caillol. "Climate Engineering by Mimicking Natural Dust Climate Control: The Iron Salt Aerosol Method." *Earth System Dynamics* 8, no. 1 (January 13, 2017): 1–54. <https://doi.org/10.5194/esd-8-1-2017>.
- O'Heir, Jeff. "Turning CO2 Into Concrete." *Mechanical Engineering*, August 2016: 25–26.
- OR. "CarbFix and Climeworks join forces with the world's first negative emission plant using direct air capture." [www.or.is](http://www.or.is), October 12, 2017. <https://www.or.is/en/projects/carbfix/news/carbfix-and-climeworks-join-forces-worlds-first-negative-emission-plant>.
- Oreskes, Naomi, Michael Oppenheimer, and Dale Jamieson. "Scientists Have Been Underestimating the Pace of Climate Change." *Scientific American Blog Network*, August 19, 2019. <https://blogs.scientificamerican.com/observations/scientists-have-been-underestimating-the-pace-of-climate-change/>.
- Oxford Geoengineering Programme. "What Is Geoengineering?," 2018. <http://www.geoengineering.ox.ac.uk/www.geoengineering.ox.ac.uk/what-is-geoengineering/what-is-geoengineering/>.
- Oyarzún, Damián, and Chris M. Brierley. "The Future of Coastal Upwelling in the Humboldt Current from Model Projections." *Climate Dynamics* 52, no. 1 (January 1, 2019): 599–615. <https://doi.org/10.1007/s00382-018-4158-7>.
- Panko, Ben. "First 'Negative Emissions' Plant Opens in Iceland, Turning Atmospheric CO<sub>2</sub> Into Stone." *Smithsonian*, October 19, 2017. <https://www.smithsonianmag.com/smart-news/first-negative-emissions-plant-opens-iceland-180965270/>
- Paquay, François S., and Richard E. Zeebe. "Assessing Possible Consequences of Ocean Liming on Ocean PH, Atmospheric CO<sub>2</sub> Concentration and Associated Costs." *International Journal of Greenhouse Gas Control* 17 (September 2013): 183–88. <https://doi.org/10.1016/j.ijggc.2013.05.005>.
- Parr, Catherine L., Emma F. Gray, and William J. Bond. "Cascading Biodiversity and Functional Consequences of a Global Change-Induced Biome Switch: Savanna Biome Switch." *Diversity and Distributions* 18, no. 5 (May 2012): 493–503. <https://doi.org/10.1111/j.1472-4642.2012.00882.x>.
- Parr, Kate, and Caroline Lehmann. "When Tree Planting Actually Damages Ecosystems." *The Conversation*, July 26, 2019. <http://theconversation.com/when-tree-planting-actually-damages-ecosystems-120786>.
- Peters, Adele. "We Have the Tech to Suck CO<sub>2</sub> from the Air—but Can It Suck Enough to Make a Difference?" *Fast Company*, June 11, 2019. <https://www.fastcompany.com/90356326/we-have-the-tech-to-suck-co2-from-the-air-but-can-it-suck-enough-to-make-a-difference>.
- Piguet, Etienne. "Climate Change and Forced Migration; New Issues in Refugee Research." Policy Development and Evaluation Service United Nations High Commissioner for Refugees, January 2008. <http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.430.9162>.
- Pilot, Otto. "The Population Bomb, 50 Years Later: A Conversation with Paul Ehrlich." *Climate One*, April 27, 2018. <https://climateone.org/audio/population-bomb-50-years-later-conversation-paul-ehrllich>.
- Plumer, Brad, and Nadja Popovich. "As Climate Changes, Southern States Will Suffer More Than Others." *The New York Times*, June 29, 2017. <https://www.nytimes.com/interactive/2017/06/29/climate/southern-states-worse-climate-effects.html>.
- Porter, Eduardo. "To Curb Global Warming, Science Fiction May Become Fact." *The New York Times*, April 4, 2017, sec. Business. <https://www.nytimes.com/2017/04/04/business/economy/geoengineering-climate-change.html>.
- Portland Cement Association. "How Concrete is Made." n.d. Accessed August 30, 2019. <https://www.cement.org/cement-concrete-applications/how-concrete-is-made>
- Powell, Hugh. "Fertilizing the Ocean with Iron." *Woods Hole Oceanographic Institution*, November 13, 2007. <https://www.whoi.edu/oceanus/feature/fertilizing-the-ocean-with-iron/>.
- . "Fertilizing the Ocean with Iron: Is This a Viable Way to Help Reduce Carbon Dioxide Levels in the Atmosphere?," *Woods Hole Oceanographic Institution*, 2008. <https://www.ocean.washington.edu/courses/oc400/Oceanus1.pdf>.
- . "What Are the Possible Side Effects?; The Uncertainties and Unintended Consequences of Manipulating Ecosystems." *Woods Hole Oceanographic Institution (blog)*, January 8, 2008. <https://www.whoi.edu/oceanus/feature/what-are-the-possible-side-effects/>.

- . “Will Ocean Iron Fertilization Work?” *Woods Hole Oceanographic Institution* (blog), 2008. <https://www.whoi.edu/oceanus/feature/will-ocean-iron-fertilization-work/>.
- Pultarova, Tereza. “Six ideas for CO2 reuse: a pollutant or a resource?” *Engineering and Technology*, February 19, 2019. <https://eandt.theiet.org/content/articles/2019/02/six-ideas-for-co2-reuse-a-pollutant-or-a-resource/>
- Rathi, Akshat. “World’s First ‘Negative Emissions’ Plant Turns Carbon Dioxide into Stone.” *Quartz*. August 8, 2017. <https://qz.com/1100221/the-worlds-first-negative-emissions-plant-has-opened-in-iceland-turning-carbon-dioxide-into-stone/>.
- Rau, Greg H. “CO 2 Mitigation via Capture and Chemical Conversion in Seawater.” *Environmental Science & Technology* 45, no. 3 (February 2011): 1088–92. <https://doi.org/10.1021/es102671x>.
- Regeneration International. “Reversing Climate Change through Regenerative Agriculture.” September 21, 2018. <https://regenerationinternational.org/2018/09/21/reversing-climate-change-regenerative-agriculture/>
- Renfrow, Stephanie. “An Ocean Full of Deserts.” *NASA Earthdata*,” May 8, 2019. <https://earthdata.nasa.gov/learn/sensing-our-planet/an-ocean-full-of-deserts>.
- Rockström, Johan, Owen Gaffney, Joeri Rogelj, Malte Meinshausen, Nebojsa Nakicenovic, and Hans Joachim Schellnhuber. “A Roadmap for Rapid Decarbonization.” *Science* 355, no. 6331 (March 24, 2017): 1269–71. <https://doi.org/10.1126/science.aah3443>.
- Rosenzweig, Cynthia, Ana Iglesias, X.B. Yang, Paul R. Epstein, and Eric Chivian. “Climate Change and Extreme Weather Events; Implications for Food Production, Plant Diseases, and Pests.” *Global Change and Human Health*, 2001. <https://link.springer.com/article/10.1023%2FA%3A1015086831467?LI=true#citeas>.
- “Santa Clara Co. Supervisors Declare Climate Crisis, Pledge Resources To Global Warming,” August 27, 2019. <https://sanfrancisco.cbslocal.com/2019/08/27/santa-clara-co-supervisors-declare-climate-crisis-mobilize-resources-toward-global-warming/>.
- Sanz-Pérez, Eloy S., Christopher R. Murdock, Stephanie A. Didas, and Christopher W. Jones. “Direct Capture of CO2 from Ambient Air.” *Chemical Reviews* 116, no. 19 (October 12, 2016): 11840–76. <https://doi.org/10.1021/acs.chemrev.6b00173>.
- Schiffman, Robert. “Why CO2 ‘Air Capture’ Could Be Key to Slowing Global Warming.” *Yale E360* (blog), May 23, 2016. [https://e360.yale.edu/features/pulling\\_co2\\_from\\_atmosphere\\_climate\\_change\\_lackner](https://e360.yale.edu/features/pulling_co2_from_atmosphere_climate_change_lackner).
- Schmidt, Charles W. “Keeping Afloat: A Strategy for Small Island Nations.” *Environmental Health Perspectives* 113, no. 9 (September 2005): A606–9. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1280424/>
- Scripps Oceanographic Institute. “Carbon Dioxide Levels Hit Record Peak in May: Monthly average surpassed 414 parts per million at Mauna Loa Observatory,” June 4, 2019. <https://scripps.ucsd.edu/news/carbon-dioxide-levels-hit-record-peak-may>
- Seitz, Russell. “Bright Water: Hydrosols, Water Conservation and Climate Change.” *Climatic Change* 105, no. 3–4 (April 2011): 365–81. <https://doi.org/10.1007/s10584-010-9965-8>.
- Shahbandeh, M. “Global seafood market value worldwide from 2016 to 2023.” *Statista*. Accessed August 30, 2019. <https://www.statista.com/statistics/821023/global-seafood-market-value/>
- Silver, Mary W., Sibel Bargu, Susan L. Coale, Claudia R. Benitez-Nelson, Ana C. Garcia, Kathryn J. Roberts, Emily Sekula-Wood, Kenneth W. Bruland, and Kenneth H. Coale. “Toxic Diatoms and Domoic Acid in Natural and Iron Enriched Waters of the Oceanic Pacific.” *Proceedings of the National Academy of Sciences* 107, no. 48 (November 30, 2010): 20762–67. <https://doi.org/10.1073/pnas.1006968107>.
- SIPRI. *SIPRI YEARBOOK 2019: Armaments, Disarmament and International Security*. Oxford University Press, 2019. <https://www.sipri.org/yearbook/2019>
- Smetacek, Victor, Christine Klaas, Volker H. Strass, Philipp Assmy, Marina Montresor, Boris Cisewski, Nicolas Savoye, et al. “Deep Carbon Export from a Southern Ocean Iron-Fertilized Diatom Bloom.” *Nature* 487, no. 7407 (July 2012): 313–19. <https://doi.org/10.1038/nature11229>.
- Smith, Pete, Jeff Price, Amy Molotoks, Rachel Warren, and Yadvinder Malhi. “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, no. 2119 (May 13, 2018): 20160456. <https://doi.org/10.1098/rsta.2016.0456>.
- Smith, Rob. “This Is the First Time a Tanker Has Crossed the Melted Arctic in Winter Unassisted.” *World Economic Forum*. February 16, 2018. <https://www.weforum.org/agenda/2018/02/tanker-crossed-arctic-in-winter-unassisted-first-time/>.
- Smith, S. J., J. van Aardenne, Z. Klimont, R. J. Andres, A. Volke, and S. Delgado Arias. “Anthropogenic Sulfur Dioxide Emissions: 1850–2005.” *Atmospheric Chemistry and Physics* 11, no. 3 (February 9, 2011): 1101–16. <https://doi.org/10.5194/acp-11-1101-2011>.
- Steffen, Will, Johan Rockström, Katherine Richardson, Timothy M. Lenton, Carl Folke, Diana Liverman, Colin P. Summerhayes, et al. “Trajectories of the Earth System in the Anthropocene.” *Proceedings of the National Academy of Sciences* 115, no. 33 (August 14, 2018): 8252–59. <https://doi.org/10.1073/pnas.1810141115>.
- Solar Radiation Management Governance Initiative. “What Is SRM?” 2019. <http://www.srmgi.org/what-is-srm/>.
- Stoy, Paul C., Selena Ahmed, Meghann Jarchow, Benjamin Rashford, David Swanson, Shannon Albeke, Gabriel Bromley, et al. “Opportunities and Trade-Offs among BECCS and the Food, Water, Energy, Biodiversity, and Social Systems Nexus at Regional Scales.” *BioScience* 68, no. 2 (February 1, 2018): 100–111. <https://doi.org/10.1093/biosci/bix145>.
- Syed, Matthew. *Black Box Thinking: Why Most People Never Learn from Their Mistakes--But Some Do*. 1st edition. New York, New York: Portfolio, 2015.
- Synapse. *Blue Planet: A biomimicry case study*. Biomimicry Business Intelligence, 2017. <https://biomimicrybusinessintelligence.com>
- Temple, James. “Startups Looking to Suck CO2 from the Air Are Suddenly Luring Big Bucks.” *MIT Technology Review*, May

2019. <https://www.technologyreview.com/s/613447/startups-looking-to-suck-c02-from-the-air-are-suddenly-luring-big-bucks/>.
- Trusel, Luke D., Sarah B. Das, Matthew B. Osman, Matthew J. Evans, Ben E. Smith, Xavier Fettweis, Joseph R. McConnell, Brice P. Y. Noël, and Michiel R. van den Broeke. "Nonlinear Rise in Greenland Runoff in Response to Post-Industrial Arctic Warming." *Nature* 564, no. 7734 (December 2018): 104–8. <https://doi.org/10.1038/s41586-018-0752-4>.
- Tulip, Robert. "Model for Marine Algae HTL System for Carbon Dioxide Removal." Google Groups, 2014. <https://groups.google.com/forum/#!topic/geoengineering/FqyulyOTQK4>.
- United Nations. "UN Report: Nature's Dangerous Decline 'Unprecedented'; Species Extinction Rates 'Accelerating.'" *United Nations Sustainable Development* (blog), May 6, 2019. <https://www.un.org/sustainabledevelopment/blog/2019/05/nature-decline-unprecedented-report>.
- University of Newcastle. "Mineral Carbonation Plant Opens at University of Newcastle," 2017. <https://www.sustainabilitymatters.net.au/content/sustainability/case-study/mineral-carbonation-plant-opens-at-university-of-newcastle-1093160688>.
- USGS. "Volcano Hazards Program FAQ." 2011. [https://volcanoes.usgs.gov/vsc/file\\_mgr/file-153/FAQs.pdf](https://volcanoes.usgs.gov/vsc/file_mgr/file-153/FAQs.pdf)
- "How Much Water Is There on Earth?," 2019. [https://www.usgs.gov/special-topic/water-science-school/science/how-much-water-there-earth?qt-science\\_center\\_objects=0#qt-science\\_center\\_objects](https://www.usgs.gov/special-topic/water-science-school/science/how-much-water-there-earth?qt-science_center_objects=0#qt-science_center_objects).
- U.S. Code. "26 USC 45Q: Credit for carbon oxide sequestration." Accessed August 30, 2019. [https://uscode.house.gov/view.xhtml?req=\(title:26%20section:45Q%20edition:prelim\)](https://uscode.house.gov/view.xhtml?req=(title:26%20section:45Q%20edition:prelim))
- Vidal, John. "Geoengineering Side Effects Could Be Potentially Disastrous, Research Shows." *The Guardian*, February 25, 2014, sec. Environment. <https://www.theguardian.com/environment/2014/feb/25/geoengineering-side-effects-potentially-disastrous-scientists>.
- Wadhams, Peter. *A Farewell to Ice: A Report from the Arctic*. 1 edition. New York: Oxford University Press, 2017.
- Wallace-Wells, David. *The Uninhabitable Earth: Life After Warming*. 1st Edition edition. New York: Tim Duggan Books, 2019.
- Waller, Rhian. "Iron Fertilization: Savior to Climate Change or Ocean Dumping?" *National Geographic Society Newsroom*, October 18, 2012. <https://blog.nationalgeographic.org/2012/10/18/iron-fertilization-savior-to-climate-change-or-ocean-dumping/>.
- Wang, Brian. "Iron Fertilization of the Ocean Is as Natural as Whale Poop and It Can Save the Planet – NextBigFuture.Com," January 2018. <https://www.nextbigfuture.com/2018/01/iron-fertilization-of-the-ocean-is-as-natural-as-whale-poop-and-it-can-save-the-planet.html>.
- . "Solutions for Ocean Acidification – NextBigFuture.Com," June 30, 2012. <https://www.nextbigfuture.com/2012/06/solutions-for-ocean-acidification.html>.
- "War Powers Act of 1941." In *Wikipedia*, March 8, 2019. [https://en.wikipedia.org/w/index.php?title=War\\_Powers\\_Act\\_of\\_1941&oldid=886719984](https://en.wikipedia.org/w/index.php?title=War_Powers_Act_of_1941&oldid=886719984).
- Welch, Craig. "Some Arctic Ground No Longer Freezing—Even in Winter." *Environment* (blog), August 20, 2018. <https://www.nationalgeographic.com/environment/2018/08/news-arctic-permafrost-may-thaw-faster-than-expected/>.
- Wilson, Bradley J. *Corp Reputation Rev* (2018) 21: 179. <https://doi.org/10.1057/s41299-018-0055-6>
- Wolovick, Michael J., and John C. Moore. "Stopping the Flood: Could We Use Targeted Geoengineering to Mitigate Sea Level Rise?" *The Cryosphere* 12, no. 9 (September 20, 2018): 2955–67. <https://doi.org/10.5194/tc-12-2955-2018>.
- Wong, Kathleen. "Bobbing for Carbon." *Research UC Berkeley*, n.d. <https://vcresearch.berkeley.edu/news/bobbing-carbon>.
- Woods Hole Oceanographic Institute. *Annual Report*. 1999.
- . "Will Ocean Fertilization To Remove Carbon Dioxide From The Atmosphere Work?" *ScienceDaily*, April 10, 2003. <https://www.sciencedaily.com/releases/2003/04/030410073330.htm>.
- World Bank, Robin Mearns, Andrew Norton. *The Social Dimensions of Climate Change: New Frontiers of Social Policy*. The World Bank, 2009. <https://doi.org/10.1596/978-0-8213-7887-8>.
- World Bank, and Ecofys. "State and Trends of Carbon Pricing 2018," 2018. <https://www.readkong.com/page/state-and-trends-of-carbon-pricing-2018-7043488>.
- World Economic Forum (2018). "The world's \$80 trillion economy in one chart." <https://www.weforum.org/agenda/2018/10/the-80-trillion-world-economy-in-one-chart/>
- World Health Organization (WHO). "Ambient (Outdoor) Air Quality and Health." Accessed September 3, 2019. [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health).
- Worstell, Tim. "Iron Fertilisation of the Oceans Produces Fish and Sequesters Carbon Dioxide. So Why Do Environmentalists Oppose It?" *Forbes*, April 28, 2014. <https://www.forbes.com/sites/timworstell/2014/04/28/iron-fertilisation-of-the-oceans-produces-fish-and-sequesters-carbon-dioxide-so-why-do-environmentalists-oppose-it/#37b53f1b7419>
- XPRIZE. "Ten Teams from Five Countries Advance to Finals of \$20M NRG COSIA Carbon XPRIZE," April 9, 2018. <https://www.xprize.org/articles/ten-teams-from-five-countries-advance-to-finals-of>.
- Y Combinator. Request for Startups: Ocean Phytoplankton. N.D <http://carbon.ycombinator.com/ocean-phytoplankton/>
- Yoon, Joo-Eun, Kyu-Cheul Yoo, Alison M. Macdonald, Ho-Il Yoon, Ki-Tae Park, Eun Jin Yang, Hyun-Cheol Kim, et al. "Reviews and Syntheses: Ocean Iron Fertilization Experiments – Past, Present, and Future Looking to a Future Korean Iron Fertilization Experiment in the Southern Ocean (KIFES) Project." *Biogeosciences* 15, no. 19 (October 5, 2018): 5847–89. <https://doi.org/10.5194/bg-15-5847-2018>.
- Zari, Maibritt Pedersen. "Biomimetic Design for Climate Change Adaptation and Mitigation." *Architectural Science Review* 53, no. 2 (May 2010): 172–83. <https://doi.org/10.3763/asre.2008.0065>.
- Zubrin, Robert. "The Pacific's Salmon Are Back – Thank Human Ingenuity." *National Review* (blog), April 22, 2014. <https://www.nationalreview.com/2014/04/pacifics-salmon-are-back-thank-human-ingenuity-robert-zubrin/>.



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