CLIMATE RESTORATION:

SOLUTIONS TO THE GREATEST THREAT FACING HUMANITY AND NATURE TODAY

THE FOUNDATION FOR CLIMATE RESTORATION
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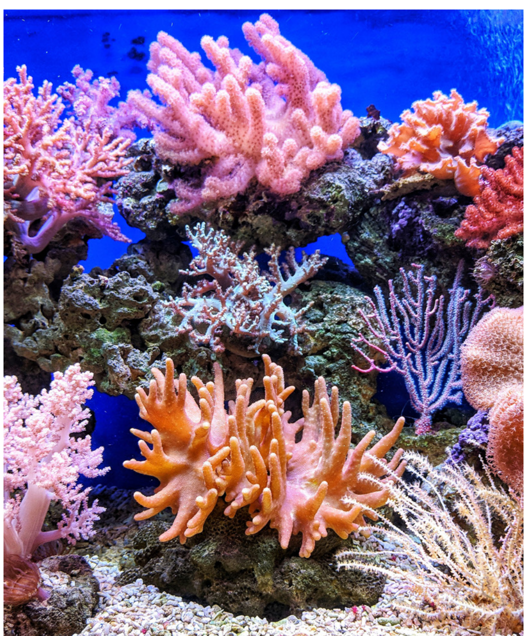

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INTRODUCTION TO CLIMATE RESTORATION

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_2 at well over 450 parts per million (ppm) in 2050 (IPCC, 2018: Global Warming of 1.5°C). This level of CO_2 is 50 percent higher than human beings have ever survived long-term. We have always, until last century, lived in a world where CO_2 levels were at most 300 ppm.

The last time CO_2 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.[1] The climate crisis is already having severe impacts on our income, health, economic prospects, development opportunities, and (planetary) security.

[1]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.

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 POWER OF AN EXPLICIT GOAL

The emerging field of Climate Restoration sets a new goal: Ensure the survival of humanity by restoring CO_2 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. 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_2 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_2 by 115 ppm by 2050 requires sequestering one trillion tons of carbon dioxide (see Appendix 3). The task—capturing a trillion tons of CO_2 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_2 BY 2050

In 2017, a Swiss start-up company launched the world's first commercial plant to pull CO_2 out of the air. The company, Climeworks, has developed scalable, low-energy, CO_2-filtering machines that can operate anywhere (Rathi, 2017).

In Iceland, the CarbFix project has for years been capturing CO_2 from a geothermal plant and pumping it deep into formations of porous basalt (Matter et al., 2011). The CO_2 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_2 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_2 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_2 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_2 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_2 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_2. Climeworks expects that to drop to $100/ton by 2025 (Climeworks, 2019) (Peters, 2019). At $100/ton, deep-underground sequestration of all excess CO_2 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).

The project shows that we could use today's technology and finance to remove and permanently sequester all the excess CO_2 in our atmosphere by 2050.

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_2-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_2 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_2 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_2 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_2 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_2; carbon-neutral fuels, which can replace fossil fuels but do not sequester CO_2; "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_2 per year. With this requirement, even if only two solutions reached full scale, 50 GT of CO_2 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_2 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_2 levels.

The solutions mimic how nature has recovered from previous mass extinction events associated with increases in CO_2 levels, and are designed to accelerate the timeline. In nature, atmospheric CO_2 drops as it is sequestered into limestone and into underwater biocarbon stores (Dutkiewicz, 2019).

Solutions that meet all three criteria include mineralizing CO_2 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_2, profitably.

Other CO_2 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.

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

HOW CO_2 REMOVAL-AND-STORAGE METHODS COMPARE ON THE THREE CLIMATE RESTORATION CRITERIA

CO_2 SEQUESTRATION METHOD	SCALABILITY (>25 GT CO_2/YR)	FINANCEABILITY (FUNDING AVAILABLE NOW)	PERMANENCE (100 YRS +)	OTHER BENEFITS
SYNTHETIC LIMESTONE (Blue Planet, 2019)[2]	Yes, can scale to >25 GT CO_2/yr.	Yes, can be paid for by the construction industry buying product they would buy anyway.	Yes, CO_2 is sequestered for >100 yrs.	Resulting limestone is well suited to construction needs. Reduces the need for quarries.
OCEAN IRON FERTILIZATION (Martin, 1988)[3]	Yes, can scale to >25 GT CO_2/yr.	Yes, can be paid for through sales of commercial fishing licenses and taxes as fisheries rebound.	Yes, CO_2 is sequestered for >100 yrs.	Can revitalize marine ecosystems, providing food and livelihoods for struggling coastal communities.
MARINE PERMACULTURE/ RESTORING PRIMARY PRODUCTIVITY OF OCEANS (The Drawdown Agenda, 2018)[4]	Yes, can scale to >25 GT CO_2/yr.	Yes, can be paid for through sales of kelp and commercial fishing licenses.	Yes, CO_2 is sequestered for >100 yrs.	Provides important food source for marine life, improving ecosystem health.
DIRECT AIR CAPTURE (DAC) WITH CO_2 PUMPED UNDERGROUND (Doukas, 2017)[5]	Yes, can scale to >25 GT CO_2/yr.	No, would require government or donor funding, currently unbudgeted (Temple, 2019).[6]	Yes, CO_2 is sequestered for >100 yrs	N/A
OCEAN ALKALINIZATION (Ilyina et al, 2013)	Yes, can scale to >25 GT CO_2/yr.	No, would require government or donor funding, currently unbudgeted (Wang, 2012).[7]	Yes, CO_2 is sequestered for >100 yrs.	Reduces ocean acidity.
BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS) (IPCC, 2018)[8]	No, can scale to 0-8 GT CO_2/yr.	No, cost of biofuel exceeds the market price for renewables, and growing biofuel competes with acreage for food crops and forests.	Yes, CO_2 is sequestered for >100 yrs.	Provides clean energy.
AGRICULTURE, FORESTRY, AND IMPROVED LAND USE (AFOLU); (IPCC, 2018).[9]	No, can scale to 1-11 GT CO_2/yr.	No, could be financed through coordinated public-private partnerships, but these are not currently in place.	Varies depending on interven-tion type and environmental conditions.	Improves soil health and productivity, increasing global food supply and livelihood for farmers.
OCEAN DOWNWELLING (Preuss, 2001), (de Figueiredo, n.d.).[10]	Could be >25 GT CO_2 / year, but net CO_2 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_2 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.).[11] 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_2 with calcium to create synthetic limestone that is carbon-negative. The process mimics how shellfish make seashells from calcium and CO_2 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_2 per year from the atmosphere.[12] Permanent carbon storage would thus be financed by the market—simply through the purchase of rock and aggregate.

[2]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_2 by weight. It can be produced from CO_2 and environmental calcium sources, with low energy chemistry similar to how clams produce their shells. Pioneered by Blue Planet Ltd.

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

[4]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).

[5]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.

[6]Significant startup funding has been committed and invested.

[7]Non-commercial CDR costs are about 1–3% of global GDP for 30 years, assuming CDR costs of \$30-\$100/t CO_2. 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.

[8]"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_2 yr−1 in... 2050...The upper end of these deployment ranges by mid-century exceeds the BECCS potential of up to 5 GT CO_2 yr-1" (IPCC, 2018, 17).

[9]"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_2 yr−1 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_2 yr-1" (IPCC, 2018, 17).

[10]Downwelling is an emerging method of carbon sequestration, which pumps CO_2-rich surface ocean water into the depths where it may remain sequestered. It is being developed by Ocean-Based Climate Solutions.

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

[12]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_2 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).

"By 2030, substituting carbon-negative limestone for quarried aggregate could pull 50 GT of CO_2 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_2. On land, most plants sequester carbon for a few decades or less before they burn or rot, returning CO_2 to the atmosphere. In the ocean, most plants sink, carrying their CO_2 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[13] 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_2 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_2. Marine permaculture involves intentionally growing (or regrowing) underwater forest ecosystems that store large amounts of CO_2 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_2 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_2 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).[14]

A report by the National Academy of Science (2015) describes the biological pump that allows for CO_2 sequestration in the oceans: phytoplankton and other microscopic plants take up CO_2 at the ocean surface, and convert it to biocarbon, some of which is deposited and sequestered in the deep ocean (National Research Council, 2015a).[15]

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).

[13]Food provision, artisanal fishing opportunities, carbon storage, coastal protection, livelihood and economies, tourism and recreation, sense of place, clean waters, and biodiversity.

[14]"The only time that the upward trend line of atmospheric CO_2 [Keeling curve] significantly halted was following the Mount Pinatubo eruption" (Climate Institute, 2018).

[15]NRC estimates that "variations in the magnitude and geographic patterns of the biological pump could drive changes in atmospheric CO_2 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).[16] 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_2-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_2, 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_2 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).[17] (About 10 percent of the biocarbon reaches the ocean floor.)

The cost of CO_2 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_2. 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_2 per year. Therefore 300 pastures could sequester 50 GT CO_2/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

[16]Calculated based on the figures in this article. 120 tons/10,000 km2 converted to miles.

[17]"...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_2 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 (Worstall, 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_2 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_2 but do not (yet) satisfy the three Climate Restoration criteria. Converting CO_2 into jet fuel, for instance, is scalable, financeable, and an important opportunity to contribute to net zero emissions, but it is not permanent. CO_2 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_2 from the atmosphere and can be safely deployed to any scale (Sanz-Pérez et al., 2016). The Climeworks project mentioned above sequesters the CO_2 permanently after DAC, but it is the exception. Most DAC projects use captured CO_2 to produce jet fuel, fizzy drinks, and other consumer products.

Funding for these companies in the last year exceeded $100M[18] (Crunchbase.com, n.d.) largely from oil companies planning to use the CO_2 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_2 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_2 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_2 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_2 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_2 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_2 storage. In addition, approaches like reforestation have long lead times, and the cost per ton of CO_2 stored is typically high, although some claim that CO_2 can be removed for $15/ton (Indigo, 2019).

[18] Carbon Engineering ($68M), Climeworks ($31M), Global Thermostat, Inventys ($26M), and Silicon Kingdom/ Lackner ($2M?)

OCEAN DOWNWELLING. Water near the surface contains more CO_2 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_2 sequestration costs would be well below $100/ton. However the theory of how much CO_2 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_2 from the air (Fiekowsky, 2019). Some 3.5 million years ago, the last time CO_2 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_2 at hothouse levels and 80 percent of Arctic sea-ice already melted (Wadhams, 2017). Removing excess CO_2 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_2 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_2 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.

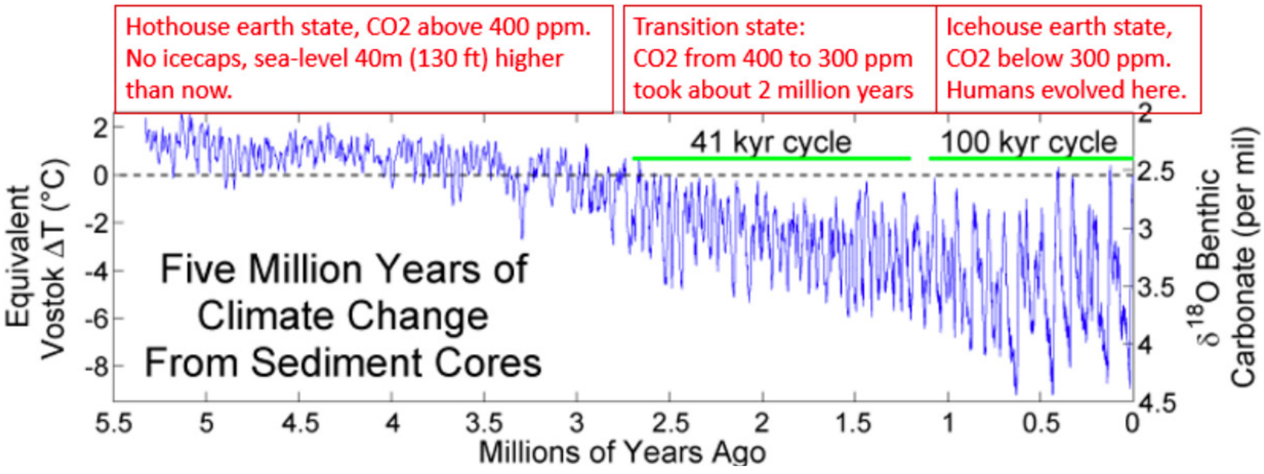


Figure 1. Five million years of climate change: It took 2 million years to transition from hothouse back to the icehouse/interglacial state (between about 3.5 to about 1.5 million years ago.)

Credit: https://en.wikipedia.org/wiki/Geologic_temperature_record.

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

As the global community mobilizes to rapidly remove CO_2 and we expect temperatures to drop, refreezing the Arctic will become critical. Without required CO_2 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.

“Restoring the climate requires both restoring CO_2 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.”

BOX 4. NAVIGATING A RE-FROZEN ARCTIC

Restoring Arctic sea-ice in international waters will require considerable international collaboration. As part of that collaboration An Arctic canal has been proposed as a tool to develop that cooperation (Maarten van Herpen, personal communication, 2019). The canal, either directly over the pole or around the Canadian or Siberian coasts, would allow ship traffic through the Arctic and to Russian ports year-round. Tolls for the canal, which would be competitive with the Suez and Panama canals, could generate annual revenue of several billion dollars, as long as the Arctic remains frozen. Canal tolls would incentivize the operators to support Arctic restoration, since the canal would not be used when the sea is clear of ice.

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 10microns 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 ⅓ 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_2 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_2 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 5. 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_2 and Arctic ice. SRM could save hundreds of millions of lives during the time it takes for CO_2 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 CO2. 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_2.

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_2 and restore Arctic ice as CO_2 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 CO2 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).

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_2 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_2 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_2/YR	NATURAL PROCESS IT MIMICS	PUBLIC FINANCING REQUIRED	INVESTMENT PER YEAR (FOR 10 YEARS) AND IRR*	ESTIMATE BASIS	NOTES
CARBON-NEGATIVE BUILDING MATERIALS	Shellfish build shells from CO_2 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
OCEAN FERTILIZATION	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_2 /yr/ pasture
PERMACULTURE ARRAYS WITH UPWELLING	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^2 per year, for 10 years.
TOTAL		$30 million a year for 30 years			

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

BOX 6. CALCULATING CARBON SOLUTION COSTS

CARBON-NEGATIVE BUILDING MATERIALS: synthetic limestone. To sequester 50 GT CO_2 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_2 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_2 per year. Therefore 300 pastures could sequester 50 GT CO_2/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 (fallow half the time), these activities would store the target of 50 GT CO_2 per year, at a cost of $30 million.

MARINE PERMACULTURE ARRAYS are expected to remove about 500 tons of CO_2 per year. That scale would require building 1 million km2 of arrays each year, at an anticipated cost of $10,000 per km^2.

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)[19]		$3M	0.1 year	
TOTAL	$20.15 billion/year	**$22 million**		

[19]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_2 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_2 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_2 from the atmosphere (Carbon180, 2019) (US Code, 2018). Yet most of that CO_2 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_2 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 7. 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_2 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.

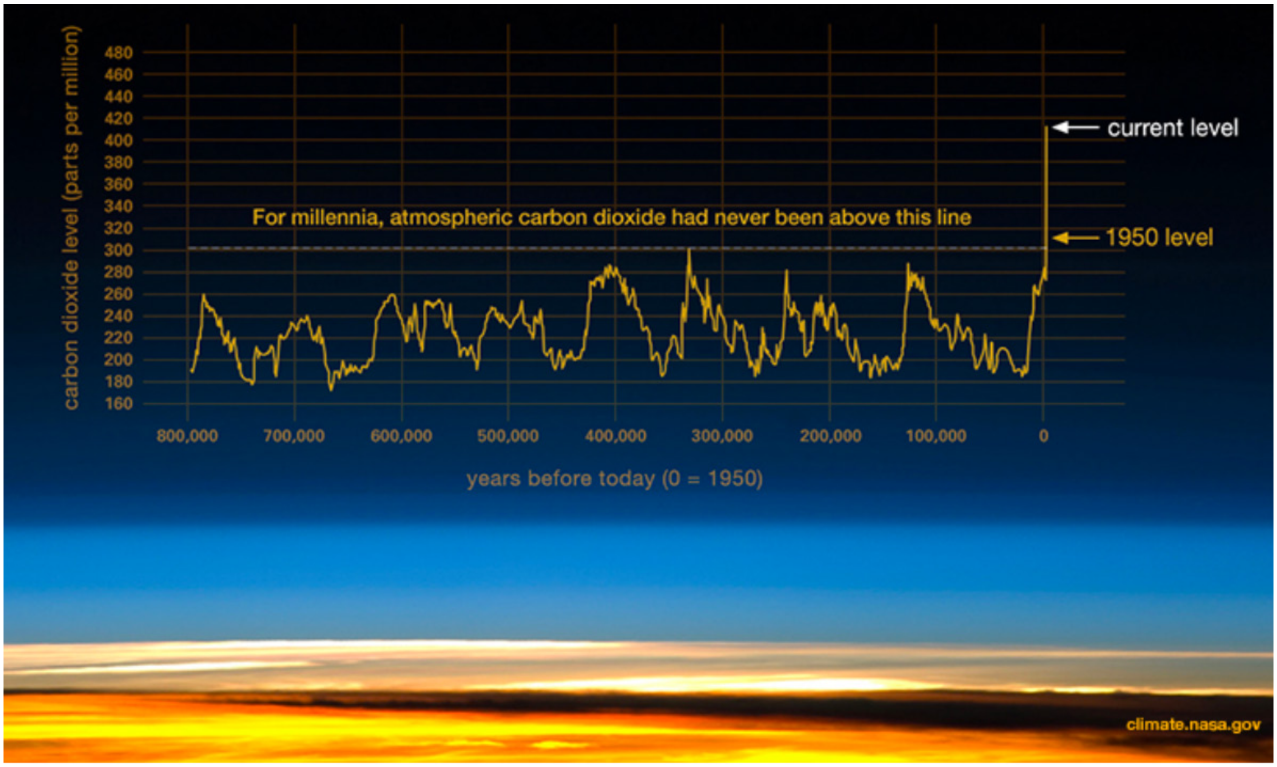
Restoring the climate will allow us to commit to other issues critical to the survival and flourishing of humanity, such as eliminating extreme poverty and restoring the environment.

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**

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_2 *record. Some description adapted from the Scripps* CO_2 *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_2 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_2 trends show us now heading for an even hotter future.

Already, at 415 ppm CO_2, 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_2 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_2 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_2 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_2 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_2 ppm as a yardstick since it is simpler to measure and control than temperature levels.

Global winds keep CO_2 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_2 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_2 emissions by roughly 2050. If that happens, CO_2 will stabilize at 455 ppm, 50% higher than has been proven to be safe.

We can infer from historic climatic records that leaving CO_2 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_2.

Therefore the objective of Climate Restoration is to reduce CO_2 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_2 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_2 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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