New tools for Climate Repair: an introduction for Engineers

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Iron Salt Aerosol
a natural method to remove methane & other greenhouse gases

Renaud de RICHTER, Franz Dietrich OESTE, Tingzhen MING, Sylvain CAILLOL
Robert TULIP, John MACDONALD, Clive ELSWORTH, and the ISA Team...

http://www.ironsaltaerosol.com
renaud.derichter@gmail.com
Conductive thread

The Iron Salt Aerosol (ISA) method

1. why focus on methane
2. natural sinks for methane
3. how ISA generates Cl atoms
4. sources of ISA
   - Natural
   - Anthropogenic (man made)
   - Our proposals
5. critics compare ISA to OIF
6. safety, efficacy and field trials
7. conclusions
Why removing other GHGs than CO$_2$?

Consequently our team works on greenhouse gas removal.
Our publications on greenhouse gas removal


Why target methane (CH$_4$)?

Currently increasing fugitive emissions from fossil fuels, livestock, wetlands, rice paddies, ... Accelerating **permafrost thawing** might release large amounts of methane and CO$_2$.

Submarine reserves of **methane-hydrates** could release large quantities of methane in a short time.

The global warming potential of methane is **86 times greater than CO$_2$** on a 20 year time horizon.

Some scientists talk of a **methane time-bomb**...
The permafrost timebomb

1. Global warming causes surface temperatures to rise.
2. Permafrost warms up.
3. Frozen organic matter thaws and decays.
4. Carbon is released into the atmosphere as the greenhouse gases CO₂ and methane.
5. Emissions from permafrost accelerate global warming, which then accelerates the permafrost melt. Global warming could be much worse than predicted.

Permafrost is perenially frozen ground covering a quarter of land in the Northern Hemisphere.

It contains 1,500 billion tonnes of carbon, 2x more than is currently in the atmosphere.

Forecasts for CH₄ release over the next 200 years in billions of tonnes:
- 43-135
- 246-415

Source: UNEP, Woods Hole Research Center
Destabilisation of submarine Methane-Hydrates time-bomb
How can we remove methane? Answer: by enhancing natural CH$_4$ Sinks

- The biggest **natural** methane sink in the troposphere is the hydroxyl radical HO° (~90%)
- The 2$^{\text{nd}}$ **natural** methane sink in the troposphere is the chlorine atom Cl (3-4%)
- There are other smaller CH$_4$ sinks: the oceans UV photolysis, minerals, plants, bacteria…

Iron Salt Aerosol can enhance both natural sinks: **the hydroxyl radical sink and the chlorine sink**
Enhancing the generation of chlorine atoms is the most efficient way to remove tropospheric methane.

The speed of reaction of Cl atoms with methane is 16 times faster than with the hydroxyl radical HO°.

How ISA generates Cl atoms?

Key discovery: generation of chlorine atoms is induced by Iron (III)


The ideas and the funding of this work comes from our German colleagues Ernst Ries and Franz Oeste.
How does ISA remove methane?

NaCl → acidity → Fe → sunlight → Cl ⇌ CH₄ oxidation

Sodium Chloride from natural sea salt spray naturally generates hydrogen chloride (hydrochloric acid) when it encounters natural or pollution-related acidity.

Hydrogen chloride reacts with soluble iron hydroxides to form the Iron Salt Aerosol: iron chloride (FeCl₃).

Under sunlight, iron chloride generates chlorine atoms (Cl) which oxidize methane (CH₄).

Photocatalytic Fe(III)/Fe(II) regenerates the Cl atoms very rapidly all day long.
ISA also generates bromine atoms


\[ \text{NaBr} \xrightarrow{\text{acidity + Fe + sunlight}} \text{Br} \]

Bromine atoms are known to destroy tropospheric ozone


Consequently, the Iron Salt Aerosol method can also fight global warming by removing (surface) tropospheric ozone O$_3$
Iron Salt Aerosols are Natural

Iron is the 4th most abundant element in the Earth’s crust. Natural dusts always contain iron.

Desert dust storms occur frequently and produce aerosols.
Iron enables photosynthesis

Over ~25% of soils are chalky (calcareous), causing iron deficiency (plant chlorosis).

*Root and leaf iron fertilization addresses plant chlorosis and enhances crops and orchards yields.*


**Desert dust Iron fertilizes the Amazon rain forest**

Phytoplankton blooms remove CO$_2$ from the atmosphere.

A phytoplankton bloom in the North Sea off the east coast of Scotland, UK, in 2008. Image from ESA.
Iron enables photosynthesis

Iron deficiency limits phytoplankton growth rates over much of the world ocean, particularly in the high nutrient, low chlorophyll (HNLC) regions.


Ocean Iron Fertilization (OIF) scientific experiments have resulted in phytoplankton blooms


The iron of desert dust fertilizes the oceans


Consequently, the Iron Salt Aerosol method can also enhance carbon dioxide uptake by plants and phytoplankton
The iron content of desert dust fertilizes the oceans and the forests.
Anthropogenic (man-made) ISA emissions

There is extensive scientific evidence that large-scale, open-field ISA emissions are already occurring, mainly from the steel industry, the fossil fuel power plants and from other combustion processes.

**Anthropogenic aerosol** associated with coal burning would be the major bioavailable iron source in the surface water of the oceanic regions.


**Anthropogenic iron emissions** mainly from coal power plants and from steel making plants are responsible for a very significant part of the oceans productivity because the form of iron released is soluble and bio-available.


...higher than previously estimated Fe emission from coal combustion implies a **larger atmospheric anthropogenic input of soluble Fe** to the northern Atlantic and Pacific Oceans, which is expected to **enhance the biological carbon pump** ...


ISA could expand this “inadvertent fertilization” into deliberate climate remediation
Human made ISA emissions already occur

“Acid dissolution of Fe in particles from the steel industry and deserts due to anthropogenic acidic gas emissions will certainly add more soluble Fe to the oceans.”
Li, W., et al. (2017). Air pollution–aerosol interactions produce more bioavailable iron for ocean ecosystems. Science advances, 3(3), e1601749.

“Combustion processes currently contribute from 20 to 100% of the soluble iron deposition over many ocean regions.”

In contrast to natural desert dust deposition that occurs infrequently, the iron emissions from fossil fuel power plants and steel industry are continuous throughout the year.

Soluble bioavailable iron from industrial pollution and fossil fuels enhances biological productivity

They can be replaced with ISA.
Global shipping also generates ISA

Cargo vessels burn bunker fuel which contains iron

“...model results suggest that deposition of soluble iron from ships in 2100 will contribute 30–60% of the soluble iron deposition over the high-latitude North Atlantic and North Pacific.”

Ito A. et al. (2013). Global modeling study of potentially bioavailable iron input from shipboard aerosol sources to the ocean. *Global Biogeochem Cycles*, 27(1),1-10.
A 1\textsuperscript{st} possible ISA dispersion method is by enhancing iron emissions by global shipping in order to reduce pollution.

It is known since the 1970’s that adding metals like iron to fuel additives improves motor performance and reduces BC emissions, CO & VOCs emissions…
A 2\textsuperscript{nd} possible ISA dispersion method

This ISA dispersion method allows targeting of localized CH\textsubscript{4} emission sources before its dilution into the atmosphere.
For ex. “Walter Energy Inc”, ALABAMA 35244; USA
this open pit coal mine
releases 166 000 tons CH$_4$/yr

With ISA we can also target “CH$_4$ leaks”
For ex. in 2015-2016, in 4 months near Los Angeles, a leak in the reservoir of Aliso Canyon has released 100 000 tons CH$_4$
Several other possible localized ISA applications

- Underground coal mine aeration-ventilation systems
- Tropical hydroelectric dams
- Greenhouses dedicated to sludge drying
- Livestock farms venting systems
- Leakage at hydraulic fracturing sites to extract shale gas
- Destabilization of oceanic methane-hydrates
- Siberia and Northern Canada, if permafrost melts and massive CH$_4$ releases occur
- Leakage of gas reservoirs
- Open pit coal mines
- Etc.

Iron Salt Aerosol emissions will be localized
ISA is very different to OIF

ISA provides iron that is 100 to 1000 times more diluted than OIF.

Analogy to irrigation of crops fields and orchards

- OIF is like a flood followed by four months of drought
- ISA is like daily drip irrigation...

ISA also has atmospheric co-benefits such as methane, tropospheric ozone and BC removal.

ISA is economical, safer, better distributed & far easier for plankton uptake.

Estimated ISA cost is well below 10 dollars per ton of CO$_2$-eq removed.
There are many criticisms of OIF

- disturbing marine ecosystems;
- favoring toxic algae or micro-organisms;
- producing toxic levels of domoic acid;
- lowering $O_2$ levels in the deep ocean;
- lowering bioavailable nutrients (P, N,...);
- increasing oceanic CH$_4$ or N$_2$O emissions
- etc.

There is no evidence that currently existing inadvertent anthropogenic ISA emissions might have similar deleterious effects
The main criticism of OIF (and ISA?)

No proof of C storage, CO$_2$ probably goes back to the atmosphere...

No proof yet because the marine food web & the oceanic C cycle are quite complex...

Let us test first the methane removal effect and discuss ocean carbon storage later.
Is the Iron Salt Aerosol method safe?

Assessment of risks and benefits of the ISA method requires scientific evaluation of safety and efficiency. Field trial and computer modelling research are needed to evaluate the effects of iron aerosols on:

- all parts of the biosphere
- atmospheric chemistry
- and living organisms.
Iron Salt Aerosol field trial proposal

After all legal authorizations are granted, **and funding found**, we plan ISA field trial research.

Field trials will be:
- done with marine biologists and climate modelers
- evaluated by satellite measurements as well as ground and ocean-based analytical instrumentation.

**ISA field trials are under discussion in Australia and the Arctic Ocean.**

Scientific cooperation proposals are welcomed...

… as well as funding suggestions £ $ € ¥

http://www.ironsaltaerosol.com  
renaud.derichter@gmail.com  
John Macdonald  john@ironsaltaerosol.com  
Robert Tulip  robert@rtulip.net
CONCLUSIONS

• ISA is already occurring by inadvertent man made Iron emissions from combustion sources (coal, fuel) & steel industry, as well as by desert dust acidic-processing

• Iron in natural desert dust and in ISA fertilizes both the oceans and the continents enhancing primary productivity

• Currently occurring inadvertent anthropogenic ISA emissions have only shown “cooling” effects

• ISA can reduce atmospheric levels of CH$_4$, tropospheric O$_3$, some halocarbons, black carbon, VOCs, … and CO$_2$

• ISA can help address the “methane time bomb” risks (methane-hydrates destabilization, melting permafrost)

ISA is the cheapest method proposed to fight global warming but we need funding for research and to assess its safety and efficiency
The Iron Salt Aerosol Method

Based on: *Earth System Dynamics*, 2017, 8(1), 1-54. *Climate engineering by mimicking natural dust climate control: the iron salt aerosol method*, by Oeste F. D., de Richter R., Ming T., & Caillol S.

Additional ISA Technical Slides and bibliography

Thank You!

The End...

Any Questions?
Additional ISA
Bibliography and Technical Slides
Conclusion for Iron Salt Aerosol


- It shows that ISA could be the best value and most effective global method for climate restoration.
- No need to build new infrastructure or develop new technologies: ISA uses existing ones
- ISA is not a panacea or a silver bullet likely to provide the whole answer to GW, but deserves to be part of the portfolio of technologies studied and fully evaluated
- The next steps from this technical analysis are computer modeling and field trials.
- We warmly welcome further discussion and interest. We seek scientific, political and industrial partners.

Please contact me to discuss at renaud.derichter@gmail.com
Conclusion: Iron Salt Aerosol (ISA)

New GHG removal technology:
- science-based, innovative, quick, effective, economic, scalable, safe

Remove carbon dioxide CO₂, as well as other GHGs and climate forcers
- methane CH₄;
- Halo-methanes,
- tropospheric ozone O₃;
- black carbon…

Reduces CH₄ emissions from wetlands and rice paddies
Cools the ocean surface by enhancing DMS
Can Iron Salt Aerosols be toxic or harmful?

The toxic forms of iron, if they are inhaled and reach the lungs are **insoluble** Fe(III) oxides like Fe$_2$O$_3$.

A sensibility analysis has shown that even if all ISA (as it is planned) falls down as Fe$_2$O$_3$ (which is very improbable), the amount that can be breathed will be 1,000 to 10,000 times smaller than natural and anthropogenic sources of iron in dusts.

A lack of Iron is detrimental

According to WHO, nearly 2 billion humans (out of 7.4 billion) suffer iron deficiency anaemia, specially among women and women who already had a child.

=>$> $ Iron food fortification or enrichment is recommended by WHO & FAO as a public health strategy to improve the iron status of populations.

Serendipity, or too good to be true?

Iron addition to rice paddies, crops cultures or wetlands reduces CH$_4$ emissions by enhancing anaerobic CH$_4$ oxidation and inhibiting CH$_4$ production by methanotrophs


Iron compounds deposition enhance abiotic humification of organic matter and promotes its preservation


Cooling effects of ISA by DMS emissions

“The greatest climate effect of ocean iron fertilization may be in enhancing dimethyl sulfide (DMS) production…” // “… By fertilizing just a small portion (about 2%) of the Southern Ocean (SO) with iron, the natural sulfur cycle could be stimulated enough to produce extra (about 20%) dimethyl sulfide which could lead to an increase in cloud reflectivity that could cool the SO region”

* Wingenter O.W., Moore J., Elliot S.M., Blake D.R., Reversing sea level rise by enhancing the natural sulfur cycle, EGU Conf., Austria, April 2008.
* Wingenter O.W., Elliot S.M., Blake D.R., Lowering global temperature by enhancing the natural sulfur cycle, AGU, San Francisco Fall 2007.
The Paris Accord commitment to hold global warming \textbf{below 2°C} can only be met by reaching net zero GHGs emissions but also requires \textit{negative emission technologies (greenhouse gas removal GGR)}.

We need to stop Earth’s current thermal disequilibrium that would cause dangerous sea level rise, among other risks.

Our climate repair goal is to stop sea-level rise and restore a safe and healthy climate.
An ISA analog


Reducing BC emissions by **fuel additives** containing Iron

Organometallic compounds create hydroxyl radicals in flame gases, which react with soot precursors at high temperature & reduce black carbon. Fuel **Iron additives** reduce combustion temperature (-2.4%); NOx (-18%); BC (-40%); fuel consumption (-1.2%)


… metal based additive **FeCl$_3$** (20 µmol/L) is efficient in improving the properties of waste cooking palm oil-based biodiesel:
+6.3% thermal efficiency; -8.6% fuel consumption; - 52.6% CO;
- 6.9% BC (smoke emissions), - 26.6% total hydrocarbon emissions; compared to bio-diesel with no added Iron.

Krill as an example of the Marine Food Web complexity

Krill eats phytoplankton on the ocean surface, but then the krill swarms deep dive, up to 1000 m where they defecate and their feces pellets constitute an important part of the carbon bottom sediment.


Ocean de-stratification by the up- & down-movement of krill or their faeces is possible.


The iron content in krill muscle rises with the amount of ingested lithogenic particles and continue participating to the marine food web.


Integration of organic & inorganic carbon on the ocean crust

Some estimate the annual global volume of seafloor generation to 18.7±2.9 km$^3$ yr$^{-1}$ while for others the production of new oceanic crust at mid-ocean ridges is 20 km$^3$ yr$^{-1}$.

Cogné J.P. and E. Humler, *Trends and rhythms in global seafloor generation rate*. Geochemistry, Geophysics, Geosystems, 2006. 7(3).

Li M., et al., *Quantifying melt production and degassing rate at mid-ocean ridges from global mantle convection models with plate motion history*. *Geochemistry, Geophysics, Geosystems*, 2016. 17(7): p. 2884-2904

Big parts of the oceanic crust consist of pure mantle rock peridotite (mainly olivine, an alkaline rock) that will be transformed to serpentinite. Up to 100 billion m$^3$ day$^{-1}$ of ocean water are driven through the porous ocean crust by thermal upwelling where the inorganic carbon and salt content are reduced by high temperatures…


Cost estimation for ISA use for GGR/CDR (1)

**Redfield ratio** or stoichiometry is the consistent atomic ratio of carbon, nitrogen and phosphorus found in marine phytoplankton and throughout the deep oceans.

When nutrients are not limiting, the molar elemental ratio C:N:P:Fe in most phytoplankton is 106:16:1:0.001. Which means that with 1 mole of iron (55.85g) up to 106,000 x 12 = 1,272,000 g of carbon (1.27 tons C) can be fixed by phytoplankton, which represents a potential withdrawal of 106,000 x 44g = 4.67 tons of CO$_2$.

Our proposal consists in doubling the amount of current anthropogenic iron emissions from combustion sources and steel industry, which means the emission of 150,000 tons of iron ($2.69 \times 10^{12}$ moles) per year, that will in theory remove 12.54 Gtons of CO$_2$ per year by enhancing phytoplankton production.

A great part of the organic carbon can be safely stored in the oceans: as organic sediment + organic recalcitrant soluble carbon + soluble inorganic carbon (HCO$_3^-$) + inorganic carbon precipitate as carbonates and silicates + soluble CO$_2$ gas in deep cold oceanic water currents that puts at least 1,000 years to be released back to the atmosphere by upwelling.
Cost estimation for ISA use for GGR/CDR (2)

The phytoplankton generated will enter the marine full web and be eaten by zooplankton and krill, themselves by small fishes, etc. (Cf. food web slide). We will make the very conservative assumption that only $\frac{1}{10}$ of the 12 Gtons (i.e. 1.2 Gtons) of eq-CO$_2$ captured by the phytoplankton will be stored, even if we are convinced that $\frac{1}{2}$ is possible (i.e. 6 Gtons of eq-CO$_2$).

If ISA generation is made by combustion of ferrocene (or other organic iron complexes) by ships or by existing coastal thermal power plants it would cost nearly $20,000 by ton of Iron => $20,000 \times 150,000$ tons/yr = $3$ billion/yr. $\frac{3$ billion}{1.2 \text{ Gtons eq-CO}_2} = \$2.5$ per ton eq-CO$_2$.

If ISA generation is made by spraying an acidic aqueous solution of diluted FeCl$_3$, the estimated costs will be reduced by a factor of 5, as the iron compound is much cheaper, as well as the solvent (diluted aqueous HCl), but the nebulization and the infrastructure costs are higher: the estimated cost is then $0.5$/ton eq-CO$_2$.

But this estimation only accounts for the ocean iron fertilization effect, while ISA will also remove from the tropospheric atmosphere surface Ozone, CH$_4$ and some other GHGs. We have estimated to 6 Gtons eq-CO$_2$ the yearly ISA removal of the other GHGs, taking into account the global warming potential on a 100-years basis. There is no need of storage for these GHGs.
There is a link between the glacial cycles and the Milankovitch cycles due to the eccentricity, obliquity and precession of the Earth.

Several scientific articles evaluate to 60% their effects on glacials, 40% being due to Iron in dust.
Ice Age data show that dust cools the planet and removes carbon dioxide.

CO$_2$ + Low CO$_2$ + DUST

Low Temperature + High Dust Level

Temperature measured from the Vostok, Antarctica ice core.


Ice cores teach us that past temperatures and CO$_2$ concentrations are very well correlated.

The more dust (thus Fe) the lower the atmospheric [CO$_2$] & [CH$_4$]

The correlation between past temperatures and CH$_4$ concentrations are also very good.
In volcanic plumes O$_3$, CH$_4$ and VOCs depletions occur. When the ash falls in the ocean plankton booms occur.


• Based on these Cl abundances, a potential –chlorine-induced – depletion of tropospheric methane (CH$_4$) in the plume was investigated. CH$_4$ lifetimes between 14 h (at 1 ppb O$_3$) and 47 days (at 80 ppb O$_3$) were derived. Gliss, Jonas, et al. "OCIO and BrO observations in the volcanic plume of Mt. Etna–implications on the chemistry of chlorine and bromine species in volcanic plumes." Atmospheric Chemistry and Physics 15.10 (2015): 5659-5681.

• Depletions of ozone were seen at all in-plume measurement locations, with average O$_3$ depletions ranging from 11–35 nmol mol$^{-1}$ (15–45 %). Atmospheric processing times of the plume were estimated to be between 1 and 4 min. Surl, L., Donohoue, D., Aiuppa, A., Bobrowski, N., & von Glasow, R. (2015). *Quantification of the depletion of ozone in the plume of Mount Etna*. Atmospheric Chem & Phys 15(5), 2613-2628.


How Iron Salt Aerosol Works

- Burning iron organic complexes, makes oxidic Iron aerosol in the flue gases, which reacts in the air with hydrogen chloride to make ISA.
- ISA makes low altitude clouds that cool both the sea and the land.
- ISA breaks down greenhouse gases in the troposphere such as methane, ozone, Halo-methanes.
- ISA falls in rain as a safe and widely dispersed fertilizer, adding iron as the vital missing trace element for both oceanic plankton and continental plant growth.
- The resulting photosynthesis sucks CO$_2$ out of the air and the sea.
- ISA is a quick, safe, scalable, low cost way to slow and reverse global warming, by mimicking the natural cooling process seen in ice ages.

Can ISA generate tropospheric ozone inside cities?

Cl might increase morning O$_3$ in coastal polluted regions

(except if Br and I are present)
Previous studies suggested that the inclusion of chlorine in air quality models leads to the generation of ozone in urban areas through photolysis of nitryl chloride (ClNO2). However, we find that **when considering the chemistry of Cl, Br and I together the net effect is a reduction of surface ozone concentrations.**

GGR effects (tropospheric O$_3$ depletion, accelerated VOCs oxidation)

“… source for reactive iodine in the marine boundary layer is the photodegradation of iodinated organic compounds (such as CH$_3$I, CH$_2$I$_2$, CH$_2$IBr and CH$_2$ICl) produced by macroalgae and phytoplankton in the ocean…”

Halogenated methanes “**production was also greatly enhanced during the Southern Ocean Iron Enrichment Experiments** (SOFeX), producing new aerosol particles…”
Methane, the main ingredient of natural gas, is a potent greenhouse gas that has more than 80 times the warming impact of carbon dioxide over the first 20 years after its release. The new study estimates total US emissions at 2.3 percent of production, enough to erode the potential climate benefit of switching from coal to natural gas over the past 20 years. The significantly, researchers found most of the emissions came from leaks, equipment malfunctions and other "abnormal" operating conditions. The climate impact of these leaks in 2015 was roughly the same as the climate impact of carbon dioxide emissions from all all U.S. coal-fired power plants operating in 2015, they found.

**Very Strong Atmospheric Methane Growth in the 4 Years 2014–2017: Implications for the Paris Agreement**

However, anthropogenic methane emissions are relatively very large and thus offer attractive targets for rapid reduction, which are essential if the Paris Agreement aims are to be attained.

**Plain Language Summary** The rise in atmospheric methane (CH₄), which began in 2007, accelerated in the past 4 years. The growth has been worldwide, especially in the tropics and northern midlatitudes. With the rise has come a shift in the carbon isotope ratio of the methane. The causes of the rise are not fully understood, and may include increased emissions and perhaps a decline in the destruction of methane in the air. Methane's increase since 2007 was not expected in future greenhouse gas scenarios compliant with the targets of the Paris Agreement, and if the increase continues at the same rates it may become very difficult to meet the Paris goals. There is now urgent need to reduce methane emissions, especially from the fossil fuel industry.
Why targeting methane in particular? (3)
Because emissions are still growing fast


China’s coal mine methane regulations have not curbed growing emissions

Anthropogenic methane emissions from China are likely greater than in any other country in the world. The largest fraction of China’s anthropogenic emissions is attributable to coal mining, but these emissions may be changing; China enacted a suite of regulations for coal mine methane (CMM) drainage and utilization that came into full effect in 2010. Here, we use methane observations from the GOSAT satellite to evaluate recent trends in total anthropogenic and natural emissions from Asia with a particular focus on China. We find that emissions from China rose by $1.1 \pm 0.4 \text{Tg CH}_4 \text{yr}^{-1}$ from 2010 to 2015, culminating in total anthropogenic and natural emissions of $61.5 \pm 2.7 \text{Tg CH}_4$ in 2015. The observed

*On a 20 years basis => 0.0615 x 86 = 5.3 Gt eq-CO₂*
The Iron Salt Aerosol method

=> MCB + OIF + CDR + GGR + direct & indirect SRM + …

### Principal NETs (negative emissions technologies)

<table>
<thead>
<tr>
<th>NATURAL FORESTRY/AGRICULTURAL</th>
<th>COMBINED NATURAL+TECHNOLOGICAL</th>
<th>TECHNOLOGICAL ENERGY/INDUSTRY</th>
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</thead>
<tbody>
<tr>
<td>Afforestation/Reforestation</td>
<td>Bioenergy with Carbon Capture and Storage (BECCS)</td>
<td>Accelerated Weathering</td>
</tr>
<tr>
<td>Tree growth takes up CO₂ from the atmosphere</td>
<td>Plants turn CO₂ into biomass that fuels energy systems; CO₂ from conversion is stored underground</td>
<td>Natural minerals react with CO₂ and bind them in new minerals</td>
</tr>
<tr>
<td>Biochar</td>
<td>Engineered Wood</td>
<td>Direct Air Capture</td>
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<tr>
<td>Partly burnt biomass is added to soil absorbing additional CO₂</td>
<td>Trees that have died due to warming or that need to be thinned to enhance forest health and prevent fire can be engineered into products that replace carbon-intensive building products such as cement and steel</td>
<td>CO₂ is removed from ambient air and stored underground</td>
</tr>
<tr>
<td>Soil Carbon Sequestration</td>
<td></td>
<td>Ocean Alkalinity Enhancement</td>
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<tr>
<td>Land management changes increase the soil carbon content, resulting in a net removal of CO₂ from the atmosphere</td>
<td></td>
<td>Alkaline materials are added to the ocean to enhance atmospheric drawdown and negate acidification</td>
</tr>
<tr>
<td>Other Land-Use/Wetlands</td>
<td></td>
<td>CO₂ to Durable Carbon</td>
</tr>
<tr>
<td>Restoration or construction of high carbon density, anaerobic ecosystems</td>
<td></td>
<td>CO₂ is removed from the atmosphere and bound in long-lived materials</td>
</tr>
</tbody>
</table>

- Less costly
- Closer to deployment
- More vulnerable to reversal
- More costly
- Greater R&D needs
- Less vulnerable to reversal

Note: This figure includes the major strategies that have been discussed in the literature so far (Minx et al., 2017).
Scientific literature on halogen chemistry (1)

Allan, W., H. Struthers, and D. C. Lowe. "Methane carbon isotope effects caused by atomic chlorine in the marine boundary layer: Global model results compared with Southern Hemisphere measurements."  

Lawler, M. J., et al. "HOCl and Cl₂ observations in marine air."  

Sommariva R & von Glasow R. "Multiphase halogen chemistry in the tropical Atlantic Ocean."  


