

DISCUSSION

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Six commercially viable ways to remove CO₂ from the atmosphere and/or reduce CO₂ emissions

Roelof D Schuiling* and Poppe L de Boer

Abstract

Background: The burning of fossil fuels is the main cause of rising CO₂ levels of the atmosphere. This will probably result in climate change. Another consequence is ocean acidification. Although these consequences are not yet proven beyond doubt, the risk of doing nothing is too large. The simplest response is the removal and sustainable storage of CO₂. By reaction with basic minerals, nature has sequestered almost all of the CO₂ that has ever been released by the planet. This weathering continues to play a role but nature cannot cope with the ongoing much (30 to 60 times) higher rates of anthropogenic greenhouse gas emissions.

Results: In this paper six approaches are described which take advantage of the natural process of weathering and solve other problems as well, thereby making them cost-effective. All six make the maximum use of natural conditions (climate, tides, currents), natural materials (olivine, serpentine), and organisms (diatoms, hyperaccumulator plants).

Conclusions: Impacts on the environment are minimized or even turned into benefits.

Keywords: Nickel farming; Biodiesel from diatoms; Forest fires; Supergreen energy; Coastal protection; High-energy shallow seas

Background

Almost all of the CO₂ that has ever leaked out of the planet has been removed from the atmosphere and the ocean, and sustainably stored in rocks, mainly by weathering, and also in the later part of the Earth's history by storage as organic carbon. During weathering, which is the reaction of rocks with CO₂ and water, CO₂ is first converted to bicarbonate solutions. In the ocean corals, shellfish, and plankton convert them to carbonate sediments, which form the ultimate sustainable storage of CO₂ (Figure 1).

Six solutions

Six low-cost or financially self-supporting ways are described in which we can store large volumes of CO₂ and/or significantly diminish CO₂ emissions:

1. A switch from nickel mining, ore dressing, and nickel recovery to nickel farming by the use of nickel hyperaccumulator plants. This switch will cut down CO₂ emissions because it avoids the energy-intensive

steps in the nickel cycle and enhances the weathering of olivine or serpentine which captures additional CO₂.

2. Diatoms contain approximately 50% of lipids, which makes them an ideal starting material for the production of biodiesel. They grow fast, provided they have a source of silica. They do not suffer from drawbacks of land-grown biofuel crops. They do not occupy vast tracts of land that are urgently needed for food production, and they do not require vast amounts of scarce irrigation water and fertilizer. The use of biodiesel from diatoms will reduce the CO₂ emissions from fossil fuels.
3. Quenching of forest fires. Forest fires are the second largest emitter of CO₂, after fossil fuels. It was demonstrated that quenching such fires with a slurry of serpentine powder is considerably more effective than quenching with water. This reduces the emissions of CO₂ by the fires and the associated financial losses. The serpentine that was calcined by the fire reacts very fast with CO₂ and water afterwards, thereby compensating part of the emitted CO₂ during the fire. A better and quicker mastery over forest fires may also help to save lives.

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Figure 1 A Karst landscape in China is one of the many stores for CO₂ of the world.

4. If the heat that is released by the weathering of olivine is trapped, this would represent a huge alternative source of energy that additionally captures large volumes of CO₂, hence the name supergreen energy. A basic scenario is described how this could be achieved.
5. When olivine is used for coastal protection (breakwaters, artificial reefs, sand replenishment on beaches) this has a direct effect against ocean acidification. CO₂ is absorbed as bicarbonate, and the pH of the surrounding waters rises.
6. Olivine in high-energy marine environments. Large areas of shallow seas are subjected to strong currents that can transport gravel. When olivine grit is spread on the sea floor, the grains are kept in motion and bump and rub against each other. This destroys reaction-limiting silica coatings on the grain surfaces and releases micron-sized slivers that rapidly react with sea water. It is the most direct way to counter ocean acidification.

Nickel farming

All mining operations have an impact on the environment. This also holds for nickel, independent of the type of ore, whether nickel laterite or nickel sulfide. Nickel laterites must be leached and nickel sulfides must be roasted and dissolved. These steps are energy-intensive and polluting. These disadvantages can be reduced if part of the world nickel production is gradually replaced by a switch to nickel farming. A fairly large number of plant species from different families are known to exhibit the remarkable property that they very effectively extract nickel from nickel-rich soils and store it in their

tissues (Figure 2). Soils on serpentinized peridotites often contain no more than 0.2% of nickel, but the ash of these plants may contain 10% or more of nickel, much richer than the richest nickel ores. If some NPK fertilizer is spread over nickel-rich soils and such plants

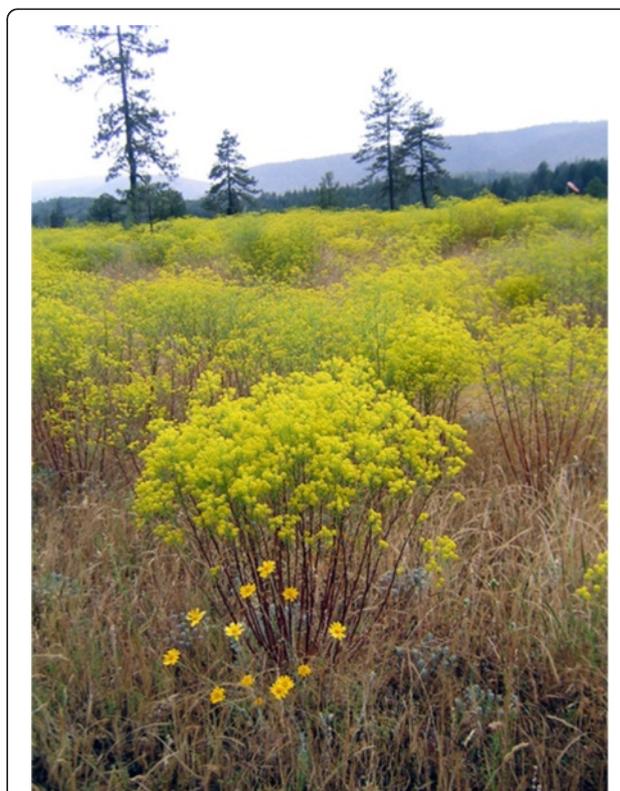


Figure 2 *Alyssum corsicum*, a nickel hyperaccumulator.

are sown, these nickel hyperaccumulator plants can be harvested at the end of the growing season, and their nickel content can be recovered after ashing. Several of these plants are perennial, so they do not need to be sown every year.

A first estimate [1] shows that the recovery of nickel by using these plants will cost no more than the current way of nickel production. This means that all the savings on CO₂ expenditure and CO₂ storage are essentially cost-free. In instances where an appropriate value may be associated with the CO₂ savings compared to conventional nickel production, nickel farming may economically outcompete incumbent nickel production processes.

Once such nickel hyperaccumulation systems will have been fully developed and become deployable, it is hoped that governments adopt incentive structures that oblige mining companies with nickel mining assets to conduct at least part of their businesses with these methods and that associated CO₂ savings and removals are quantified and verified. In addition, because the nickel obtained from phytomining is not extracted from nickel ores but from common peridotite rocks, nickel farming will extend the lifetime of nickel ore deposits.

Biodiesel from diatoms

Diatoms (siliceous algae) make up a large part of the biomass in the oceans. They consist for about 50% of lipids, which makes them an ideal raw material for the production of biodiesel. The process to make biodiesel from algae is already known. They grow fast and can outcompete their competitors in the algal world in the fight for food, provided that there is sufficient silica available in their environment. Diatoms need silica for the construction of their silica skeleton (Figure 3). An extensive discussion of the role of dissolved silica in promoting the growth of diatoms at the cost of other plankton like dinoflagellates can be found in [2].

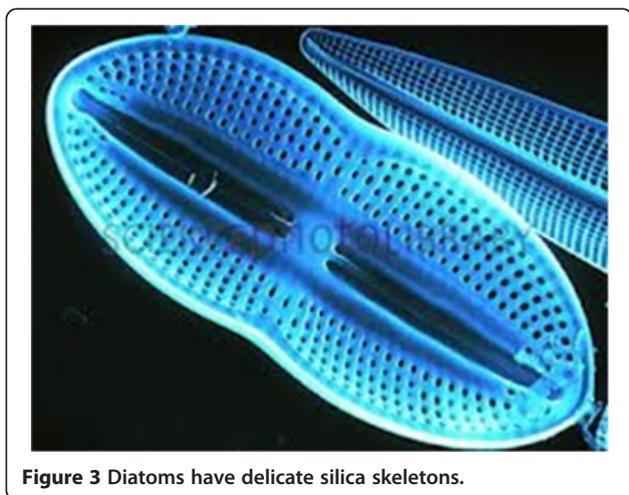


Figure 3 Diatoms have delicate silica skeletons.

Land-grown biofuels (among others oil palm, sugarcane, sweet sorghum, soybean, maize) occupy vast tracts of land that would normally be used for food production, or land that used to be the territory of threatened species like the orangutan. They also need vast volumes of scarce irrigation water and fertilizer. This results in higher prices for these fertilizers, which will push up their price as well as the price of food.

Diatoms do not have these drawbacks, but before they can be used as an alternative source of biofuel, the problems of mass culturing and harvesting them must be solved. A large-scale mariculture of diatoms might take the following shape. An artificial lagoon can be sectioned off by a dike around a sector of shallow seawater in front of a beach section.

The beach between the low-tide mark and the high-tide mark must be covered by a layer of olivine sand with a thickness of about 0.5 m. One or more U-shaped tubes are left in the dike that connects the lagoon with the open sea, permitting the tide to reach the lagoon and to alternatively wet and drain the olivine beach. These tubes should be closed by a perforated metal plate covered with a plankton net. This would permit the exchange of water, but prevent the diatoms to be carried out of the lagoon by the ebb. The olivine will weather, and the weathering solution, including the silica that is set free during the olivine reaction, will be distributed in the lagoon. In addition, the bicarbonate that is captured during olivine weathering will be used by the diatoms for photosynthesis.

When the silica limitation is removed, diatoms will form a quasi-monoculture in the lagoon. Nutrients should, of course, be added, mainly for their ammonia and phosphate requirements. A cheap way to do this would be by the use of struvite, an ammonium-magnesium phosphate that is produced by a simple and robust technology in the treatment of organic wastes, including manure, urban waste, and urine [3]. Struvite is a slow-release fertilizer that will steadily add ammonium and phosphate to the lagoon. The addition of nutrients should be limited, however, because diatoms react to a slight starvation by raising their lipid content, which increases their value for biodiesel production. The diatom production can be increased by underwater lighting at night.

Harvesting the diatoms efficiently is a major problem. The following possibility may provide a solution. Dig a hole inside the lagoon. Dead diatoms will collect in this pit, also thanks to the fact that they are relatively heavy due to their silica skeletons. From time to time, this mass of dead diatoms can be sucked up, drained and transported to the biofuel plant.

When the culture and harvesting of vast volumes of diatoms can be successfully accomplished, this application will become financially self-supporting and will

reduce CO₂ emissions from the burning of fossil fuels. It can be set up in any country with marine coastlines, preferentially in dry climate zones with abundant sunshine.

Fire fighting

Forest fires (Figure 4) are the largest CO₂ emitters after the burning of fossil fuels. Forest fires and, to a lesser extent, other forest losses account annually for about 6 Gt of extra CO₂ emissions on a total of somewhat more than 30 Gt of human CO₂ emission [4]. They cause every year not only huge financial losses but also the deplorable loss of human lives. Experimental fires at the test site of Brandbeveiliging BV (Fire Protection) in the Netherlands were considerably faster and completely extinguished by spraying with a suspension of serpentine powder than with plain water. Serpentine powder from the PASEK mine in North-West Spain and from the Isomag Mine in Austria was used with equally positive results.

Serpentine can be considered the hydrated equivalent of olivine. Huge massifs of serpentine are formed by the interaction of olivine with hydrothermal waters and also on the ocean floor along mid-ocean ridges. Serpentine is a soft rock and serpentine is similar to a clay mineral. Like any other clay, it can be baked into a hard, brick-like substance. When this calcined serpentine is pulverized, it turns out that the powder reacts fast with CO₂ and water, considerably faster even than olivine. It would be an excellent material to rapidly remove CO₂ from the atmosphere, but baking it costs a lot of energy and associated CO₂ emission. So, it is a pity, but using calcined serpentine against climate change is out..., except in cases where one wants to quickly remove as much heat as possible, like in extinguishing forest fires.

When serpentine slurries were tested in test fires, they not only removed a considerable amount of heat from the fire, but they displayed another property which is probably more decisive. The serpentine that was sprayed over the fire turned into a thin baked impermeable skin that prevented the access of oxygen to the burning material, and also prevented the emission of the inflammable gases from the burning wood.

So, when forest fires are raging, the spraying of serpentine slurries (almost as simple as spraying water, because a 40% serpentine slurry is still very fluid) can reduce the extent and severity of such fires. When a reduction of 10% in forest losses could be achieved worldwide, this would already be a major breakthrough, since this represents a reduction of 0.6 Gt of CO₂ emissions each year.

Moreover, after extinction of the fire, the calcined serpentine will quickly react with CO₂ and the first rainwater, thereby compensating part of the CO₂ that was emitted by the fire. It is clear that the spraying of serpentine (serpentine powder is a cheap and ubiquitous material) is a very cost-effective way of reducing the huge financial losses from forest fires, and it holds the promise of reducing losses of life as well. It pays amply for the reduction in CO₂ emission by limiting the areal extent of burnt forest and by the capture of CO₂ by the reaction of the calcined serpentine afterwards. It also limits the required volumes of water considerably, which is important in hot dry summers in countries that are most vulnerable for forest fires and have only limited fresh water resources.

It should be considered whether the spraying of serpentine slurries can also be used in the containment of tunnel fires.



Figure 4 Forest fires are the second largest emitter of CO₂ in the world.

grains, leaving the olivine surfaces free for continued reaction.

Coastal protection

Olivine can be used in several ways to protect coastlines against erosion. Olivine is considerably heavier than normal quartz sand (specific masses of 3,400 versus 2,650 kg/m³), which makes it more resistant to physical erosion. Olivine blocks can be used in the construction of permeable breakwaters. In a permeable triangular breakwater, pointing into the sea, the force of the longshore (flood and ebb) currents is weakened because part of the water passes through the breakwater and loses momentum in doing so, while another part is deviated from the coast. Both effects reduce coastal erosion. If the sections at either side of the breakwater are covered with olivine sand, it will resist erosion even better. Another way of using olivine for coastal protection is the construction of olivine reefs at strategic points to keep waves and currents away from the coast. If the seawater that is enclosed in the reefs is only slowly refreshed, its pH will rise as a consequence of the olivine reaction. This may lead to the precipitation of calcite, so that these reefs are self-cementing. They will become hatching and hiding places for fish and a place for mussels and oysters to settle (Figure 6).

Stretches of beach that lose sand can be restored by spreading olivine sand on the beaches. Olivine sand on beaches feels well, and children love to build their sand castles with it and make sand sculptures of dolphins and seals (Figure 7).

Very rough coastal stretches can be covered with olivine grit, preferably of various sizes. In imitated surf experiments, we have shown that mixtures of different

grain sizes become rounded and are abraded faster than single grain sizes by the multiple grain-to-grain collisions [7]. During this polishing in the surf, small micron-sized slivers of olivine are knocked off (see also Section 'Olivine in high-energy marine environments'). These slivers react very rapidly with sea water and add alkalinity to counteract ocean acidification. It was even found that brucite (Mg(OH)₂) formed already after a few days in experiments with olivine and seawater. From the observations on white smokers [8], it is known that brucite is rapidly transformed into aragonite (Figure 8).

Coastal protection with olivine, instead of with the usual basalt blocks, will add alkalinity to the ocean and also provide places of interest to tourists. This makes this combined function of CO₂ capture and alkalinity provider also financially attractive. Rough stretches of beach covered with olivine grit can serve as natural tumbling devices, where nicely rounded green grit can be produced by the surf. These may serve for applications as diverse as chicken grit and covering material for driveways. Tourists may also find these polished marbles attractive collector's items. Using the surf which is free of charge, instead of mechanical crushing and tumbling devices, is an additional modest saving. Another financial advantage is that olivine cargo ships can unload their olivine directly in front of the coast, thus avoiding harbor dues.

Olivine in high-energy marine environments

It is a paradigm that weathering on land, and under marine conditions, always would be a slow process. When olivine grains, preferably of different sizes, are



Figure 6 The sea as a threat: the Hondsbossche Zeewering along the Dutch Coast.



Figure 7 The sea as an ally. Children making sand sculptures of olivine sand that will merge with the sea at high tide and help in counteracting ocean acidification.

free to be kept in motion by currents, their weathering is a fast process. The grains are quickly rounded and abraded by mutual collisions (Figure 9), producing myriads of micron-sized slivers (see picture in Additional file 1; see also [9]).

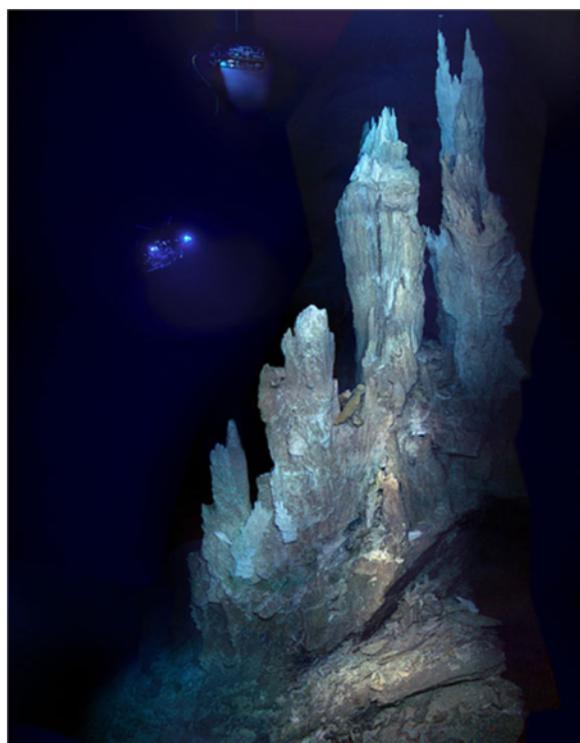


Figure 8 Sixty-meter tall aragonite (replacing brucite) chimneys on Lost City Seamount.

In experiments where modest current action was imitated by letting olivine grains rotate slowly along the bottom of an Erlenmeyer, the water had become opaque white after a few days of rotation, the pH of the solution had gone up, and neoformed grains of brucite, a mineral known to transform into carbonate fast, had evolved.

Many shallow sea floors are covered with gravel. When 700,000 km² of such sea bottoms are covered each year with a 1-cm thick layer of olivine grit, this would compensate the *entire* anthropogenic CO₂ emissions, and raise the pH of the oceans. To make it more concrete, the following example may serve. Part of the continental shelf between the Shetland Isles and France, i.e. the Southern Bight of the North Sea, the English Channel and the Irish Sea, is covered with sand waves, and in and around the Channel, an area of well over 100,000 km² experiences bed stresses capable of transporting gravel [10,11]. If a volume of 0.35 km³ coarse olivine is spread over 35,000 km² of this area, this would compensate 5% of the world's CO₂ emissions, that is more than the combined emissions of the adjoining countries, the UK, France, Ireland, Belgium and the Netherlands together [9].

Another site where the spreading of coarse olivine grit may work out well is the Maelstrom, with very strong tidal current in the Lofoten Islands, Norway, and there are many more suitable areas in shallow shelf seas.

The alkalinity brought in by the olivine is of great importance. It counteracts ocean acidification, and the contained bio-limiting nutrients, Si and Fe, enhance marine productivity thereby capturing additional CO₂. Another factor that makes this approach low-cost is that large



Figure 9 Angular olivine grains are quickly rounded and abraded by mutual collisions when kept in motion.

carriers can bring the olivine directly to the place of use, where they are discharged, thus avoiding harbor dues and additional transport costs.

Discussion

A preliminary volume and cost-benefit estimate

At this early stage, it is virtually impossible to provide accurate estimates of the volumes of CO₂ involved for each of the options, and of the amount of money potentially won or lost. Table 1 should, therefore, be taken as a not-too-educated guess of the orders of magnitude involved in each of the six options. The large spread in the numbers for the first five options is caused by the uncertainty whether the particular activity will be executed in a few tests on essentially pilot scale, or as a worldwide activity.

The cost of the olivine in high-energy shallow seas is calculated as the total costs of spreading 25 Gt of crushed olivine in shallow high-energy seas. When compared to carbon capture and storage (CCS), it should not be marked as a cost of 500 billion euro, but as a benefit of 700 billion euro.

Table 1 Estimated order of magnitude of CO₂ capture and/or emission reduction and money involved

	CO ₂ capture or emission reduction	Cost or benefit
Unit	1 Million ton	1 Million euro
Options		
Nickel farming	1 to 50	0 to +200
Biodiesel from diatoms	50 to 1,000	+10 to +500
Quenching forest fires	100 to 1,000	+200 to +2,000
Supergreen energy	20 to 1,000	+50 to +5,000
Coastal protection	10 to 1,000	-1 to +100
Olivine in high-energy waters	25,000	-500,000 ^a

^aIf the figure of 500 billion euro of costs for the option in the last row is compared to the cost of the CCS-option, the deficit changes into a benefit of 700 billion euro [cf. 12].

Conclusions

It is likely that the first five examples of large-scale applications of the olivine option that are presented in this paper will all turn out to be profitable or, at least, financially self-supporting without requiring subsidies or carbon credits. The costs/benefits of the spreading of olivine in high-energy shallow seas depend on the way to calculate it. If it is just the cost of the operation itself, this total solution of the climate problem and ocean acidification costs a lot of money (order of 15% of the price of the equivalent amount of crude oil), but if it is compared to the costs of the CCS alternative, which is still on the agenda of several governments, it will save a huge amount of money. The major obstacle may well be that the unusual character of the proposals will delay their introduction because parties have a tendency to shy away from untested innovative approaches. Each of the six represents a major breakthrough in the attempts to control climate change and ocean acidification.

Additional file

Additional file 1: Mitigation of CO₂ emissions by stimulated natural rock weathering—fast weathering of olivine in high-energy shallow seas.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

RDS developed ideas about the use of stimulated olivine weathering as a means to counter human CO₂ emissions. PDB carried out flume experiments. Both authors contributed to, read and approved the final manuscript.

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