CARBON CAPTURE BY SHELLFISH

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From peer-reviewed and open access publications
developed with researchers in UK, Finland, Italy and USA

Our carbon problem

- The global carbon cycle was in equilibrium since the dawn of man.
- Since the industrial revolution and the advent of intensive agriculture, the atmospheric carbon dioxide level has nearly doubled, provoking an imbalance, a dysfunction.
- The impact of GHGs is already a reality today. Raising temperatures, forced species migration, more frequent, longer and more intense extreme weather events.
- A major concern are the famous **tipping points**. Points of no return to the actual climate system: continental ice melting, forests die-off, methane-hydrate and permafrost thawing.
- These could cause runaway climate change. Dramatic sea level rise, extension of uncultivable areas, mass extinction of species.
- **NOW** we need to reduce our GHG emissions to net zero with renewable energy **AND** to remove CO_2 from the atmosphere with carbon sinks.

What are carbon sinks?

- Carbon sinks refer to flows of atmospheric carbon sequestered for the long term in reservoirs, ideally during thousands to millions of years. By extension, a reservoir with an inflow of carbon is also called a carbon sink, but this is confusing.
- Long term carbon reservoirs interact barely with the atmosphere, **unless disturbed.** Fossil fuel reserves until extraction and combustion, soil humus until intensive agriculture, anoxic marine sediments until bottom trawling, fossil limestone deposits until use in cement industry.
- Carbon sources are processes that emit carbon into the atmosphere. I've just mentioned a few, all anthropogenic.
- A given reservoir can act as a carbon sink or a carbon source, **it depends.** Forests for example are sinks as long as they are growing and producing humus. Forests become sources when photosynthesis stops (at night, too hot, too dry) or when they wither (diseases, parasites, fires).
- The effectiveness of a carbon sink is determined by the **persistence** of carbon sequestration (at least one thousand years) and its **scale** (in relation to the hundreds of GtC already in excess in the atmosphere).

The dominant carbon sequestration strategies

- The dominant strategies are **afforestation** and industrial **carbon capture and storage** (CCS).
- Afforestation (including blue carbon) has to be promoted to support resilient biotopes which are the basis of all life, including us.
- But as a carbon sink, afforestation is not a viable strategy. Not enough land available and not safe enough for the long term.
- CCS has a too disabling energy penalty due to capture, filtration, compression, transport and injection operations. Depending on the technique, 60% to 180% more energy is required! Even a low average of 100% would mean having to double the extraction of fossil fuels or use renewable energies to achieve this. We might as well use these renewable energies directly and leave fossil fuels to their natural reserves. This technology seems to be nothing more than an artefact used by the concerned industry to continue to exist.
- If neither afforestation, nor CCS are reliable strategies, what about **marine calcifiers**? To make their shells, they need calcium (the 5th most important element in the earth's crust) and bicarbonate = hydrogencarbonate (which makes up 90% of the 38,000 GtC dissolved in the oceans). There will be no shortage of raw material.

Calcifiers’ evolution as ecosystem engineers

- From the origin of life, cells employ calcium ions (Ca^{2+}) to carry signals in internal biological processes.
- The seas have often become calcium rich during Earth history, putting the cell's calcium ion control mechanisms (homeostasis) at risk of over-stretching.
- The evolution of calcifiers has led them to detoxify excess calcium by **reacting it with CO_2** to make $CaCO_3$ shells. The protection offered by the shell was a bonus.
- The vast fossil calcium carbonate deposits, show calcifiers' abilities as ecosystem engineers, even (especially?) during geological periods of acidified oceans and great excesses of atmospheric CO_2 caused by massive volcanic events.
- Now the same primitive calcification process appears to be effective at **sequestering atmospheric carbon in excess**. If they've done it before, we can make them do it again!

Shellfish shell is mineralised atmospheric CO_2

- Shellfish shell is a biomineral composed of 95% crystalline **calcium carbonate** ($CaCO_3$) with a small amount of matrix proteins included. It's quite a mineral.
- The animals make this by reacting **calcium ions** (Ca^{2+}) with **hydrogencarbonate ions** (HCO_3^-) present by dissociation of CO_2 in water.
- Carbon dioxide levels in the atmosphere and in the upper layers of the sea are in equilibrium.
- Metabolic carbon of living organisms, used to produce proteins, lipids, carbohydrates or nucleic acids, is derived from photosynthetic fixation of atmospheric CO_2. There is no other significant source.
- As shellfish feed on phytoplankton, the CO_2 used for the shell comes ultimately from the atmosphere.

Shells sequester carbon for geological times

- Calcium carbonate ($CaCO_3$) is crystalline, **undigestible and chemically stable**.
- It only dissociates at very high temperatures or below the Carbonate Compensation Depth (CCD) at sea, a phenomenon due, among others, to high pressures.
- Such high temperatures are given by volcanic eruptions after subduction of the calcium carbonate sedimentary layer (millions of years turnover) or burning in cement plant kilns and waste incinerators (immediate).
- Below the CCD the dissociated calcium and hydrogencarbonate ions are carried by the global thermohaline circulation (1000 years turnover) and are likely to recrystallize for an other millennium when swept in lesser depths.
- Except in the case of burning $CaCO_3$ by man, the **CO_2 is (almost) permanently removed** from the atmosphere.

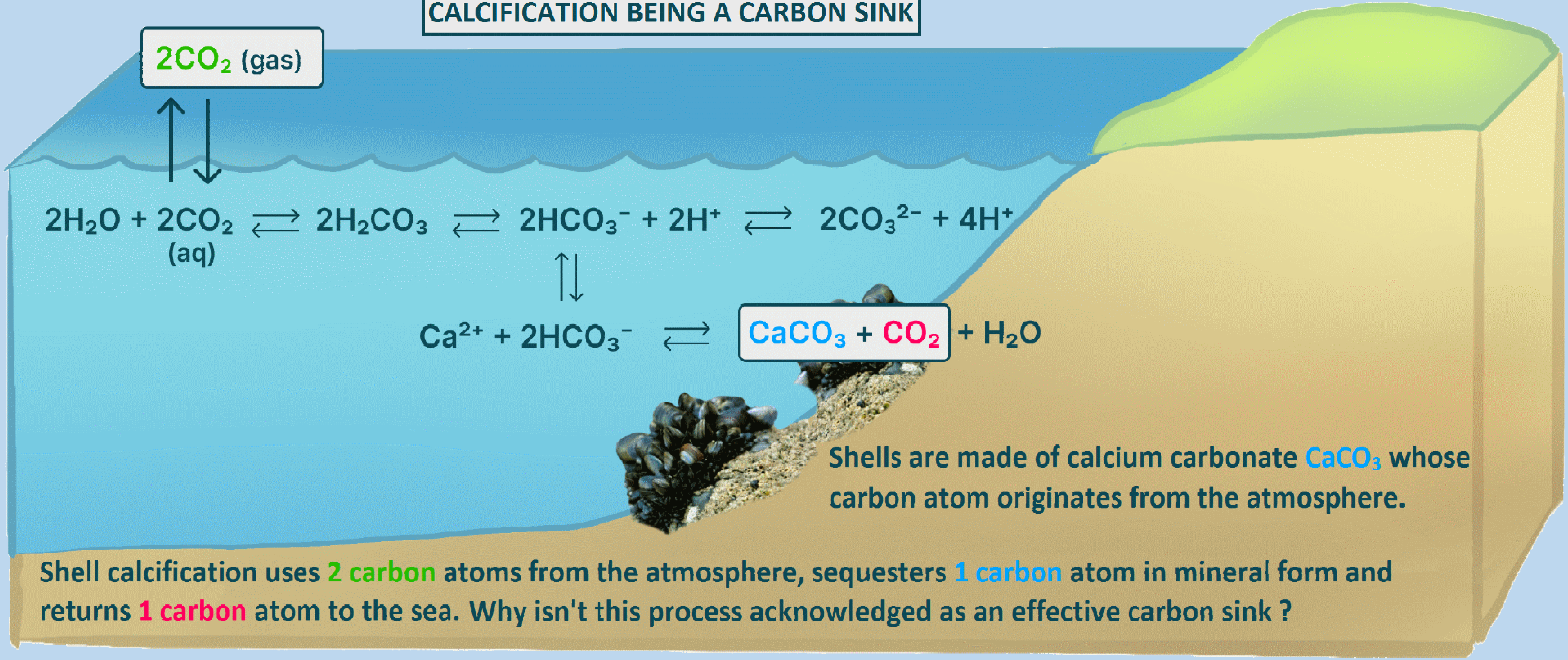
Shells are not in the carbon trading system!

- There is controversy about the relative importance of the different carbon fluxes during formation of shells.
- For one side it is a carbon sink due to the evident carbon sequestration by the shells. There is 95% $CaCO_3$ in the shells and 12% C in $CaCO_3$, giving 11.4% carbon in the shells. It's a fact.
- The other side claims the biomineralisation process is a net producer of atmospheric CO_2, because the calcification reaction releases CO_2.
- Between these two, stoichiometric analysts are trying to get a clearer view, by assessing the quantities of CO_2 released by the calcification reaction, the animal's respiration and its entire metabolism and comparing them with the quantity of carbon sequestered by the shell. As a carbon sink, their overall results are rather poor.

Biomineralisation releases CO_2: this is not true

- **Because we need to consider the process as a whole, as it occurs in nature.**
- The biomineralisation **reaction** releases **one** carbone dioxide molecule CO_2 for each calcium carbonate molecule $CaCO_3$ produced. That's correct. The chemical equation is formal.
- But **two** hydrogencarbonate ions HCO_3^- originating from **two** carbon dioxide molecules CO_2 are used to make **one** calcium carbonate molecule $CaCO_3$.
- That means that one of the two CO_2 used for one $CaCO_3$ simply remains in the environment and the other one is **really sequestered**.
- The following diagram illustrates the phenomenon. The equation above illustrates the dissolution of CO_2 in water, each element of which has been doubled so that the HCO_3^- element corresponds in number to the requirements of the equation below, which is the equation of the formation of calcium carbonate.

CONCEPTUAL DIAGRAM OF SHELLFISH CALCIFICATION BEING A CARBON SINK



Stoichiometric values are irrelevant

- **Because we need to consider the process as a whole, as it occurs in nature.**
- The carbon released by the animal's respiration nearly outweighs the carbon sequestered in its shell. That's correct. If we stop the reflection there, the carbon sink is real, albeit very small.
- But it's hardly possible to isolate an organism from a dynamic network of interacting flows and hope to draw relevant conclusions.
- Every organism releases all its carbon in the cycling of his **short life**.
- It makes **no long term difference** whether this carbon is released directly by phytoplankton or by an animal that has ingested it.
- It makes **no long term difference** whether available nutrients and luminosity are used by a not ingested phytoplankton or by one born thanks to the living space offered by an ingested one. Phytoplankton growth dynamics are not taken into account in these stoichiometric studies.
- The long term difference is made by having mineralized CO_2 to insoluble, crystalline **$CaCO_3$ that has left the biosphere, permanently**.

Does biomineralisation acidify sea water?

- **Open water** calcification releases a proton (H^+) that does acidify the seawater which becomes therefore less able to absorb CO_2. That's correct. It thus becomes an induced source of CO_2.
- But **biological systems** perform their processes within phospholipid membrane boundaries, evolved specially to protect the life processes from the open water environment.
- **Biological calcification** takes place on the surfaces of enzymatic polypeptides, within organelles that have phospholipid membranes, contained in a cell enclosed within another phospholipid bilayer membrane. In other words, biomineralisation takes place inside the animal's mantle cells **without acidifying the open water environment**.
- Protons generated during **biomineralisation** are strictly controlled by the mantle cells and used for cellular metabolism, such as synthesis of ATP. **That's life**!

Does sea acidification affect calcifiers?

- Since the industrial era, the ocean’s pH has fallen from 8.2 to 8.1. This may not seem much, but it is significant for a cologarithmic value.
- Laboratory experiments claiming ocean acidification disturbs calcifier mineralisation have used **next century projected pH** levels or even worse.
- To date, natural coccolith deposits (external plates of coccolithophores, phytoplankton practising photosynthesis AND biomineralisation) have increased and shellfish produce **more calcium carbonate** (though less crystalline and more amorphous).
- However, it seams that acidification, combined with higher temperatures, contributes to the rejection of symbiotic algae (zooxanthellae) from corals and giant clams.
- So, the answer is nuanced, but we **still have time,** before the next century, to use most calcifiers to sequester atmospheric carbon in excess.

Time to recognise shellfish as carbon sinks?

- After the Kyoto Protocol, without scientific consensus and as shellfish farming was economically self-sufficient, it has been **empirically** decided not to recognize shellfish as carbon sinks.
- But the most harmful effect of climate change is the undermining of the ecological basis of food production and **calcifiers can provide carbon sinks AND food** while contributing to biodiversity through their many ecosystem services.
- Shellfish farming is at the confluence of the aspirations of the Intergovernmental Panel on Climate Change (IPCC), the World Food Programme (WFP) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).
- The current paradigm of settled science must evolve! Politically, and even without reaching a scientific consensus, the benefit of the doubt must this time be given to shellfish.

This could change the face of the world!

- Carbon dioxide removal with shellfish is **massively scalable**. The potential of biomineralisation far exceeds that of any other carbon capture solution envisaged to date.
- With investment from carbon credits, **thousands of entrepreneurs** over the world (families, communities, associations and other private or public entities) could start tomorrow to produce food and calcium carbonate while preserving their environment.
- Shellfish don't need land, fresh water, fertilizers or feed to grow (all elements that will become rare). Their cultivation is the **most efficient** animal protein production system.
- Shellfish offer many **ecosystem services** for marine habitat and its biodiversity.
- Carbon credits could also fund shellfish cultivation only to **clean up waters** from ports, bays and other threatened coasts.
- Entering the carbon offset market is **the key** to this overall scalability.
- And why not look further ahead and open our horizon towards the **High Seas**?

The limits to carbon credits from shellfish, a small downer for shellfish farmers.

- Only **collected shells** that can be verified by a certification authority could qualify for carbon credits.
- Shells that are incinerated with household waste will, of course, not be eligible, nor those used for agriculture as soil or feed supplements.
- Carbon credits for shells used for road building (potentially a long-lasting reservoir) or cement industry (in place of fossiliferous limestone) might be discussed.
- The best use of shells would be to build/restore **underwater reefs**, enhancing biodiversity and the carbon reservoir of the biosphere while protecting /regenerating coastal areas.
  See **https://rocsinternational.com**

The High Seas to scale up calcifiers' carbon sink while providing healthier aquafeed

- **Forage fish** are crucial for marine biotopes, food security in developing countries AND for the booming fish farming industry.
- As a result, all three lack this ressource and modern aquafeed for farmed fish are mostly composed from **terrestrial ingredients**, with all the know-how of the "modern" food industry.
- The resulting ultra-processed aquafeed is more likely to cause hormonal dysfunctions to the end-consumer than to fulfil the historical benefits of **marine proteins**. Yes, that's a rather violent comment. It's a concentrate of my website.
- The idea is to take over from forage fish with **mussel meat**, produced on huge High Seas farms located above seamounts outside EEZ and using Perpetual Salt Fountains to provide the needed primary nutrients for phytoplankton growth.
- Apart from the amount of shells thus produced, the induced carbon sink could still be massively up scaled in a stylish way. But there's no more room here to develop.
  See **https://commonseagood.com**

Open access and peer-reviewed publications

- **Saving the Planet with Appropriate Biotechnology: 1. Diagnosing the Problems**
  Moore D., Heilweck M. & Petros, P. (2021).
  Mexican Journal of Biotechnology, 6 (1): 1-30.
  DOI: https://doi.org/10.29267/mxjb.2021.6.1.1.

- **Saving the Planet with Appropriate Biotechnology: 2. Cultivate Shellfish to Remediate the Atmosphere**
  Moore D., Heilweck M. & Petros, P. (2021).
  Mexican Journal of Biotechnology, 6 (1): 31-91.
  DOI: https://doi.org/10.29267/mxjb.2021.6.1.31.

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- **Saving the Planet with Appropriate Biotechnology: 3. The High Seas Solution**
  Heilweck M. & Moore D. (2021).
  Mexican Journal of Biotechnology, 6 (1): 92-128.
  DOI: https://doi.org/10.29267/mxjb.2021.6.1.92.

- **Saving the Planet with Appropriate Biotechnology: 4. Coccolithophore cultivation and deployment**
  Moore D. (2021).
  Mexican Journal of Biotechnology, 6 (1): 129-155.
  DOI: https://doi.org/10.29267/mxjb.2021.6.1.129.

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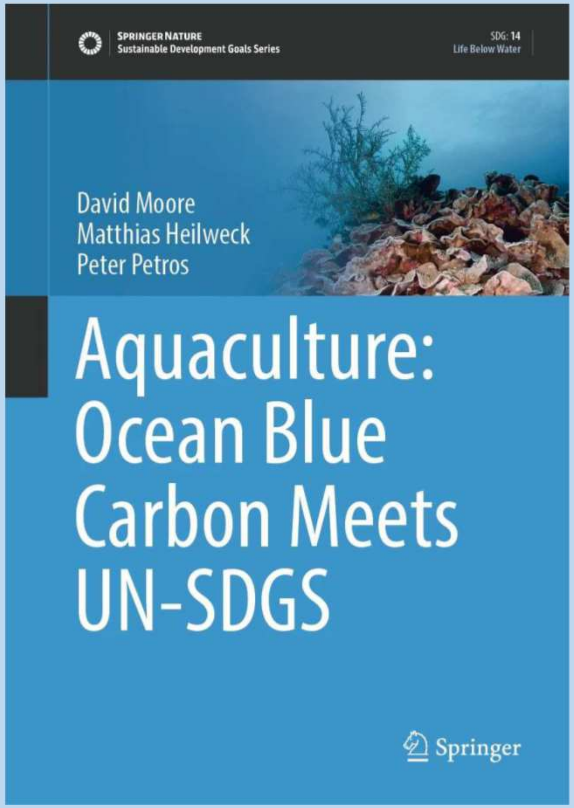
- **Saving the planet with appropriate biotechnology: 5. An action plan**.
  Petros, P., Heilweck, M. & Moore, D. (2021).
  Mexican Journal of Biotechnology, 6 (2): 1-60.
  DOI: https://doi.org/10.29267/mxjb.2021.6.2.1.

- **Planetary bioengineering on Earth to return and maintain the atmospheric carbon dioxide to pre-industrial levels: Assessing potential mechanisms**.
  Moore, D., Heilweck, M. & Petros, P. (2022).
  Frontiers of Astronomy and Space Sciences, 9: article number 797146.
  DOI: https://doi.org/10.3389/fspas.2022.797146.

Open access and peer-reviewed publications

- **Potential of ocean calcifiers to sequester atmospheric carbon in quantity and even reverse climate change.**
  Moore, D., Heilweck, M., Fears, W.B., Petros, P., Squires, S.J., Tamburini, E. & Waldron Jr., R.P. (2023).
  Journal of Fisheries Research, 7(1): article 132***.*** Publisher's URL: https://www.alliedacademies.org/articles/potential-of-ocean-calcifiers-to-sequester-atmospheric-carbon-in-quantity-and-even-reverse-climate-change-23764.html

Book



Aquaculture: Ocean Blue Carbon Meets UN-SDGS

Springer Nature 2022, ISBN: 978-3-030-94845-0.

Sustainable Development Goals Series.

SDG – 14, Life below water.

https://link.springer.com/book/10.1007/978-3-030-94846-7

Web sites

- **Commonseagood**
  Edited by Matthias Heilweck.
  About investing the High Seas and producing significant amounts of mussel meat for healthy aquafeed and mussel shells for carbon sinks.
  https://commonseagood.com/
- **Rocsinternational**
  Edited by William Fears.
  About restoring oyster reefs to provide marine habitat, ecosystem service and carbon sinks.
  https://rocsinternational.com/

Online press articles

- **Shellfish motivation: the climate crisis could be solved with seas, not trees.**
  Dr David Moore
  The Fish Site, on 13 February 2020
  https://thefishsite.com/articles/shellfish-motivation-the-climate-crisis-could-be-solved-with-seas-not-trees
- **Can bivalve aquaculture prevent the “widespread institutional failure” of our attempts to tackle climate change?**
  Dr David Moore, Matthias Heilweck and Peter Petros
  The Fish Site, on 13 February 2021
  https://thefishsite.com/articles/can-bivalve-aquaculture-prevent-the-widespread-institutional-failure-of-our-attempts-to-tackle-climate-change