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REVIEW ARTICLE

Saving the Planet with Appropriate Biotechnology: 5. An Action Plan

Salvando el planeta con biotecnología apropiada: 5. Un plan de acción

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ABSTRACT

We evaluate suggestions to harness the ability of calcifying organisms (molluscs, crustacea, corals and coccolithophore algae) to remove permanently CO_2 from the atmosphere into solid (crystalline) $CaCO_3$ for atmosphere remediation. Here, we compare this blue carbon with artificial/industrial Carbon dioxide Capture & Storage (CCS) solutions. An industrial CCS facility delivers, at some cost, captured CO_2, nothing more. But aquaculture enterprises cultivating shell to capture and store atmospheric CO_2 also produce nutritious food and perform many ecosystem services like water filtration, biodeposition, denitrification, reef building, enhanced biodiversity, shoreline stabilisation and wave management. We estimate that a mussel farm sequesters three times as much carbon as terrestrial ecosystems retain. Blue carbon farming does not need irrigation or fertiliser, nor conflict with the use of scarce agricultural land. Blue carbon farming can be combined with restoration and conservation of overfished fisheries and usually involves so little intervention that there is no inevitable conflict with other activities. We calculate that this paradigm shift (from 'shellfish as food' to 'shellfish for carbon sequestration') makes bivalve mollusc farming and microalgal farming enterprises, viable, profitable, and sustainable, ***alternatives to all*** CCUS industrial technologies and terrestrial biotechnologies in use today.

Key Words: aquaculture; atmosphere remediation; CCS; carbon sinks; blue carbon; habitat restoration.

RESUMEN

Evaluamos sugerencias para aprovechar la capacidad de los organismos calcificantes (moluscos, crustáceos, corales y algas cocolitóforos) para eliminar permanentemente el CO_2 de la atmósfera en forma de $CaCO_3$ sólido (cristalino) para la remediación de la atmósfera. Aquí, comparamos este carbono azul con soluciones artificiales/industriales de captura y almacenamiento de CO_2 atmosférico (CCS). Una instalación industrial de CCS libera, a algún costo, CO_2 capturado, nada más. Pero las empresas acuícolas que cultivan conchas para capturar y almacenar CO_2 atmosférico también producen alimentos nutritivos y realizan muchos servicios ecosistémicos como filtración de agua, biodeposición, desnitrificación, construcción de arrecifes, biodiversidad mejorada, estabilización costera y manejo de ondas. Estimamos que una granja de mejillón secuestra tres veces más carbono que los ecosistemas terrestres. La producción de carbono azul no necesita riego ni fertilizante, ni genera conflicto con el uso de tierras agrícolas escasas. El cultivo de carbono azul se puede combinar con la restauración y conservación de la sobrepesca y por lo general implica poca intervención con otras actividades. Calculamos que este cambio de paradigma (de "marisco como alimento" a "mariscos para el secuestro de carbono") hace que el cultivo de moluscos bivalvos y las empresas agrícolas microalgales, sean viables, rentables y sostenibles, ***alternativas a todas las*** tecnologías industriales de CCUS y biotecnologías terrestres que se usan en la actualidad.

Palabras clave: acuicultura; remediación de la atmósfera; CCS; sumideros de carbono; carbono azul; restauración del hábitat.

1. Introduction

In a recent paper Moore *et al*. (2021a) gave a plain language guide to the Earth's carbon cycle by briefly summarising the observations and origins of increased levels of greenhouse gases in our atmosphere, mainly CO_2 but including CH_4 and N_2O. They concluded, following many other writers, that the only tenable explanation for our atmosphere's present state is that it is the consequence of mankind's 'dangerous anthropogenic interference' in making excessive use of fossil fuels onwards since the start of the Industrial Revolution. Arguments that deny the truth of this are not tenable. The Earth's global carbon cycle was almost exactly in equilibrium for several thousand years while humans were evolving, before industrial humans intervened. Moore *et al*. (2021a) describe how the excess greenhouse gas emissions of our recent industrial history are projected to change the future global climate over this century and beyond and discuss 'reasons for concern' (RFCs) and climate tipping points. Finally, the review gives a short account of the various improved management, engineering and natural climate solutions advocated to increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, agricultural lands, and industry.

Unfortunately, the most recent research indicates that massive tree planting is not the panacea that many believe. Carbon capture by trees and other photosynthetic organisms is widely thought to be our most effective strategy to limit the rise of CO_2

concentrations in the atmosphere by pulling carbon from the atmosphere into the sinks represented by the organism's biomass and the soil. However, practical experience indicates that putting such plans into effect could do more harm than good to our environment. Planting trees can release more carbon from the soil sink than the plants sequester into their biomass. And, in all cases, the photosynthetically-produced biomass carbon sink is only ever a temporary sequestration because when the organism dies its biomass rots, and its sequestered carbon is returned to the atmosphere. Moore *et al.* (2021a) suggest that forests should be planted for the intrinsic values of forests; for clean, oxygenated air, natural biodiversity, and restorative conservation of terrestrial ecosystems, rather than tree planting as a means to sequester atmospheric CO_2.

The review of Moore *et al*. (2021a) concludes with the basic message that cultivation of ***aquatic calcifiers*** (coccolithophore algae, corals, crustacea and molluscs) offers the only effective and **permanent** carbon sequestration strategy, because they enable the return of the excess CO_2 to where it belongs; back into the distant future's fossil record. In a subsequent review, Moore *et al*. (2021b) claim that shellfish cultivation, in particular, is the only industry on the planet that (a) feeds us, (b) permanently removes CO_2 from our atmosphere, and, with care, could (c) engineer our marine habitats to maintain the health and biodiversity of those ecosystems into the future.

About 30-50% of shellfish biomass is represented by the animals' shells, and shellfish shell is made by converting atmospheric CO_2 into crystalline calcium carbonate which is stable for geological periods of time. The human tradition of eating shellfish is recorded in the ancient middens of shellfish shells that track migrations of early humans around the world. Recent history shows increasing exploitation of marine resources by an ever-growing human population. By the end of the 19th century oysters had become a cheap staple food on both sides of the Atlantic, but the dredging that supplied this fishery destroyed 85% of the world's oyster beds. In the tropics, Giant Clams have also been fished to extinction in many Indian Ocean and Pacific waters. In the 21st century, these animals deserve to have the same vigour applied to their restoration and conservation as we applied to dredging them from the seabed. In return they will cleanse our atmosphere by permanently sequestering its excess CO_2 into limestone. And we must start now, before *Homo sapiens* is added to the lengthening list of organisms driven to extinction by humanity's follies.

Heilweck & Moore (2021) make the case is for greater use of the High Seas to replace forage fish with mussel meat in the diet of farmed fish as well as producing, in the oceans, the increasing amounts of nutritious food that will be required by the ever growing human population, whilst at the same time pulling down carbon from the atmosphere with bivalve cultivation. The vision is to preserve the oceans as a healthy and sustainable food source for mankind by emphasising conservation and ecosystem balance beyond coastal waters.

The plans are for huge (centralised) bivalve mollusc farming facilities on the high seas, using factory ships and offshore factory rigs (re-purposed disused oil rigs?) located on seamounts outside Exclusive Economic Zones and employing Perpetual Salt Fountains on the flanks of the seamount to bring nutrients to the farms. If properly designed (and the design and building capabilities exist throughout the offshore industries around the world), this will immediately provide (i) feed for animals and food for humans, (ii) sustainable marine ecosystems, and (iii) permanent atmospheric carbon sequestration in the form of reefs of bivalve shells (Heilweck & Moore, 2021).

Cultivating coccolithophore algae for carbon sequestration is another proposal discussed by Moore (2021). Coccolithophores have been major calcium carbonate producers in the world's oceans for about 250 million years. Today, they account for about a third of the total marine $CaCO_3$ production by coating their single cells externally with plates of microcrystalline $CaCO_3$. The possibility that these algae could be used to trap atmospheric CO_2 on a very large scale with existing technology has not been widely considered.

There is scope for both high technology cultivation in bioreactors and low technology cultivation in terraced raceway ponds or lagoons on tropical coastal sites. The latter could produce a sludge of pure $CaCO_3$ as a feedstock for cement production in place of the fossilised limestone currently used (cement production accounts for around 8% of industrial fossil CO_2 emissions). On the high seas coccolithophores naturally produce extensive blooms, which emit the volatile gas dimethyl sulfide to the atmosphere, where it promotes formation of clouds that block solar radiation. The vision is for aquaculture nurseries onboard factory ships, cultivating both coccolithophores and bivalve molluscs, creating and maintaining blooms of coccolithophores in the oceanic high seas to sequester carbon from the atmosphere and provide the additional ecosystem service of generating cloud cover to cool the immediate environment (Heilweck & Moore, 2021; Moore, 2021).

The key objective we wish to achieve is to enable the world's oceans to produce the increasing amounts of food that will be required by the growing human population. With calcifiers this can be done in a sustainable manner, whilst permanently removing carbon from the atmosphere. To ecologically-friendly bivalve cultivation, we couple the determined use of coccolithophore algae cultivation, in the High Seas and in raceway lagoons on land. Together these could extract permanently more carbon from the atmosphere and make further contributions to the amelioration of the dangerous anthropogenic interference that our industrial society has inflicted on the atmosphere.

In order to carry out our recommendations we need:

- planetary-scale funding, and
- central management with global political authority to initiate, fund and maintain projects over several decades as necessary.

Most important of all, though, is that we (meaning humanity as a whole) must develop the determination to make the changes in human activity and human behaviour that are essential if we are to meet the challenge of climate change. Importantly, this means not only all the widely discussed matters involved in reducing fossil fuel usage but serious changes in the ***attitudes*** and ***motives*** of the world's scientific communities in respect of the solutions they promote.

Most of today's scientists would recommend Negative Emissions Technologies, or **NETs**, which are technologies that remove and sequester CO_2 from the atmosphere with the intention of mitigating climate change. NETs that are currently most widely ***expected*** (or hoped) to be of value are:

- biological processes to increase carbon stocks in soils, forests, and wetlands,
- generate energy from biomass, and capture and store the resulting CO_2 emissions,
- capture CO_2 directly from the air with chemical processes and sequester it in geological reservoirs.

Formal consideration has only been given to near-shore coastal ***Blue Carbon***, namely, mangroves, tidal marshlands, and other tidal or salt-water wetlands, seagrass beds, and kelp forests. However, these Blue Carbon options are, like terrestrial forests, reversible if the carbon sequestering practices are not maintained, because they depend on sequestering carbon in the biomass of ***living*** organisms; when the organisms die, they are digested by microorganisms and their carbon is returned to the atmosphere as respiratory CO_2.

Focussing exclusively on ***near-shore coastal*** NETs wilfully ignores the **oceanic options for CO_2 removal and sequestration** that are offered by the 70% of the Earth's surface covered by the high seas.

We wish to remedy this exclusion. The central thrust of our argument being that the physiological chemistry of a few types of aquatic creatures, the ***calcifiers of the coasts and open seas***, (coccolithophore algae, corals, crustacea and molluscs) enables them to extract CO_2 from the atmosphere and sequester it **permanently** as crystalline $CaCO_3$, returning it **permanently** to the fossilised state.

2. Comparing industrial and biotechnological solutions for carbon capture and storage

The main purpose of this review is to assess the current artificial/industrial Carbon Dioxide Capture, Utilisation & Storage (CCUS) solutions and show their power and potential in curtailing greenhouse gas (GHG) emissions, ***and*** their main disadvantages. Key evaluation models of sustainability for current carbon capture and storage (CCS) infrastructure are used to explain what problems could arise and potential ways to avoid the likely risks through drastic changes in fundamental attitudes. The shortfalls of each industrial solution are also presented in the context that all activities should be carried out with due regard for ***long term human and environmental well-being***, rather than economic growth alone.

Overall, we discuss below: solutions for atmospheric carbon reduction; the carbon market; industrial/artificial carbon dioxide capture, utilisation and storage systems; carbon emissions reduction targets. We make comparisons between 'soft' nature based biotechnological solutions, including coastal blue carbon and the ultimate blue carbon, which is the ocean's calcifiers and 'hard' industrial or artificial solutions which require significant amounts of energy to operate and maintain and resource-heavy infrastructure to implement. From sustainability assessment of CCUS methods we conclude that changing the paradigm of shellfish farming from '***shellfish as food***' to '***shellfish for carbon sequestration***' places the value of the exercise of shellfish cultivation onto the production of shell. This takes the food value of the animal protein as one of the ***several*** ecosystem services that bivalve molluscs and calcifying microalgae (specifically, coccolithophores) supply. ***We calculate that this paradigm shift makes mussel farming, and by default other bivalve molluscs and microalgal farming enterprises, viable alternatives to* all *the CCUS industrial technologies in use today.***

3. Solutions for atmospheric carbon reduction

There is a current global industrial trend towards adoption of carbon capture and storage (CCS) technologies, such as flue gas CCS injection facilities in fossil fuel and other heavy industry plants (others include steel, concrete and fertiliser production). Current climate policies and industry trends are directing and incentivising the increase of industrial CCS as central technology for reaching climate change targets. Whilst CCS is essential in meeting the emissions targets, as already stated by the IPCC in 2005, complications have arisen in putting all our eggs in that basket. To date, the developed carbon emissions mark*et al*ong with major heavy industry players have integrated and adopted a major CCS solution that allows for a 'business as usual' approach.

> "… Talking up carbon capture is good for fossil fuel companies — it makes the next few decades look profitable for them. Companies from ExxonMobil to Shell to Occidental Petroleum have all boasted about investments in carbon capture while continuing to double down on their core business model of finding and digging up as much oil and gas as possible." (Aronoff, 2020).

What is lacking in this approach, namely environmental ecosystem services and bio-circular economic value, is in fact guaranteed by certain ***biotechnological*** CCS solutions available to us. To ensure our humanity's future, these biotechnological solutions are vital. They offer sustainable engineering solutions, environmental ecosystem services, guaranteed life cycle extension and bio-circular economic value economy in addition to carbon sequestration potential.

4. The Carbon Market

The importance of carbon sequestration will be increasingly significant as we proceed further into the 21st century. Not only is carbon sequestration an environmental and atmospheric issue, but it is also now considered an economic market, whereby carbon credits are offered by legislators and a carbon market continues to be expanded and refined. Nations currently have a monetary value assigned to the quantity of carbon directly emitted into the atmosphere. By doing so, we have created the greenhouse gas (GHG) emissions market or emission trading systems (ETSs). As such, we have "put a price on carbon" and from this point on will call it simply '**the carbon market**'.

Described as a unique environmental commodity, the carbon market was created out of the Kyoto Protocol. This international treaty extends the 1992 United Nations Framework Convention on Climate Change (UNFCCC), committing nations to reduce greenhouse gas emissions, based on the scientific consensus that global warming is occurring and is most likely caused by human-made CO_2 emissions. The Kyoto Protocol, completed in December 1997, required industrialized countries to reduce their total greenhouse gas emissions to 5.2% below 1990 levels (Jacobson, 2001). As listed in Annex A of the Protocol, developed countries must limit all GHG emissions, which are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons [HFCs], perfluorocarbons [PFCs], and sulfur hexafluoride (SF6) (Fig. 1).

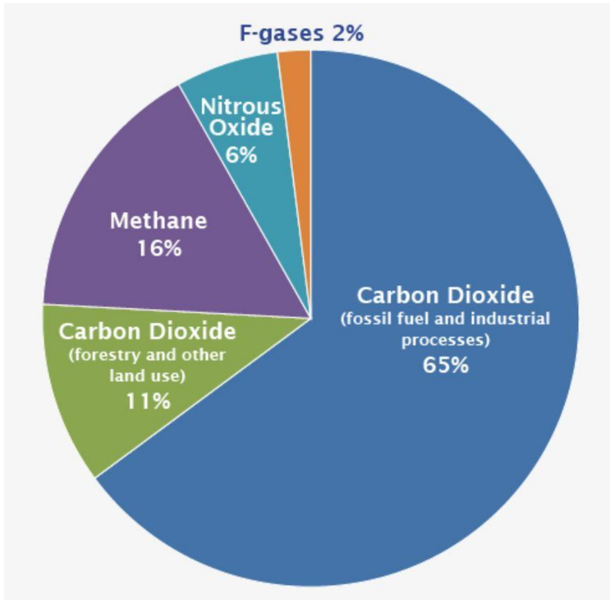

Fig. 1. Global greenhouse gas emissions by type of gas. 65% of carbon dioxide emissions derives from fossil fuel use and industrial processes and 11% of carbon dioxide is emitted by deforestation, decay of biomass, etc. Methane represents 16% of the total and nitrous oxide 6%. 2% of the total is from fluorinated gases (hydrofluorocarbons [HFCs], perfluorocarbons [PFCs], and sulfur hexafluoride [SF6]). Image from the United States Environmental Protection Agency website (https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Gas), data from the Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014).

The carbon market deals with a specific ***Environmental Commodity***. These Environmental Commodities are commodities that take the form of non-tangible energy credits, the value of which derives from the need for cleaner forms of energy. The market formed as a result of governmental efforts to deal with GHG emissions by tax reductions or other financial incentives and was first implemented by regulatory policies from government bodies. Many industries produce GHGs in the manufacturing of their products and as governments across the world place strict limits on the rights of individuals or institutions to pollute by generating GHGs, those rights become scarce, valuable and tradeable (Pines, 2020). Without such limitation by governmental regulation the right to pollute would have no economic value as production and supply could be unlimited theoretically.

This is a point worth remembering: ultimately, regulatory policy has the power to assign value and create economic markets, no matter what the value-assigned object might be (a service, a chemical, object or organism, an environment or a pollutant). The markets or ETSs that trade Environmental Commodities emerged as a way to buy and sell ***the right to pollute***. The question that needs to be asked is whether the future of humanity on this planet would be better served by markets based on **Global Health** rather than **Global Pollution**?

Many would agree that after more than two decades since adoption of the Kyoto Protocol, ETSs and the 16 compliance carbon markets in operation across the world have failed in their primary objective of ensuring significant reductions in GHG emissions to curtail anthropogenic-inputs and mitigate rising atmospheric GHG input. Indeed, Pearse & Böhm (2014) argue that:

> "…carbon markets do not have a role to play in a policy scenario that requires radical emissions reductions in order to avoid dangerous greenhouse gas concentrations … carbon markets should not be the preferred climate policy choice…" (Pearse & Böhm, 2014).

More clearly as of late, has been the misguided allocation of carbon credits and carbon offsets in the name of business, rather than in the name of climate change; meaning, in short, that the rich and powerful nations win more than poorer nations. This, however, is a political narrative we do not wish to develop here. In summary, the current rules and regulations built by policy-makers have created ***a flawed carbon market*** in order to solve the climate change crisis, albeit with good initial intentions. So, what is the alternative?

Well, in short, **redefining market value** is the key. An ideal, possibly utopian, scenario might be one where the market focuses primarily on ***improving and sustaining global environmental health*** and secondly on GHG emissions reductions(although the latter is a significantly-weighted factor).

Global health fundamentally relies on:

- raising environmental awareness,
- continuous educated decision-making,
- sympathetic planning protocols,
- timely action,
- full implementation,
- extensive monitoring,
- conservation of environmental systems.

Whereas GHG emissions and carbon trading, by definition, can be produced, reduced, moved around, traded and sequestered, global health cannot and should not be passed around. The policies would ideally settle on any management body or agency holding responsibility for their local environment and the global environmental impact of their businesses. If value ***is*** assigned to global health, then global markets must be regulated with rules that uphold the natural capital values that the Earth's natural ecosystems offer as services (also known as ***ecosystem services***). Such a move would fundamentally shift us towards planning and implementing true ***circular economy*** with our planet and a healthy and harmonious relationship from market to industrial and commercial ventures to communities. We will return to this theme towards the end of this review.

5. Industrial Carbon Dioxide Capture, Utilisation & Storage (CCUS)

Industrial, or artificial, carbon capture and storage is usually considered essential to meeting climate goals. However, what are not discussed very often are the ***potential negative implications*** of widespread adoption of certain artificial **carbon capture and utilisation** (CCU) and **carbon capture and storage** (CCS) solutions (under the overall acronym **CCUS**). Technology being developed now, which is likely to be constructed over the next few years, with the expectation of operating for at least 10 years to become economically viable, will place enormous unforeseen burdens on all aspects of the activities into the short-term. This is particularly worrisome given the very short (decadal) timeframes which are implicit in the climate models describing future GHG emissions to the atmosphere and consequential climate change used by the IPCC and other expert bodies that describe the climatic paths we may already be heading into due to historic rates of GHG emissions.

The implications emerge more clearly when we understand how the carbon market works and who are the current big players. It is also important to remember that money is the key hurdle for change and in this case, **where** the money is channelled and **what** it is directed towards. Carbon dioxide capture, utilisation and storage is, in many ways, a 21st century technological marvel as a climate solution. A major reason for CCUS being so readily embraced is its mitigation potential of ***significantly large amounts*** of CO_2 from point sources.

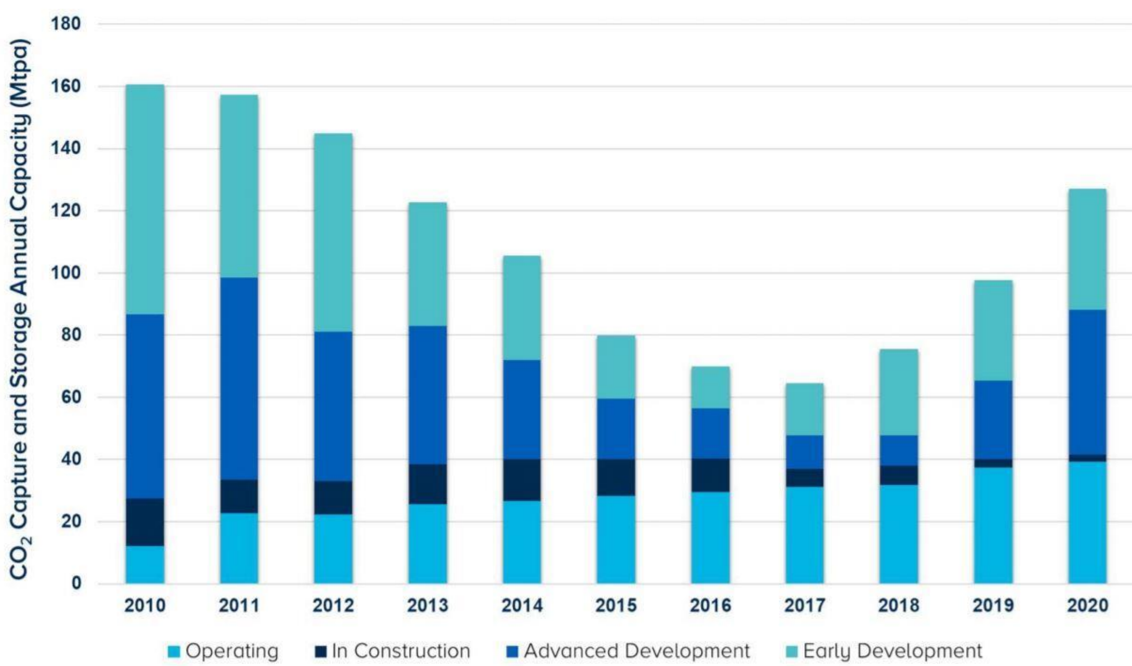

Fig. 2. Progress of carbon capture and storage (CCS) programmes in terms of annual capacities for carbon sequestration around the world from 2010 to 2020. Source: Marshall *et al*., 2020.

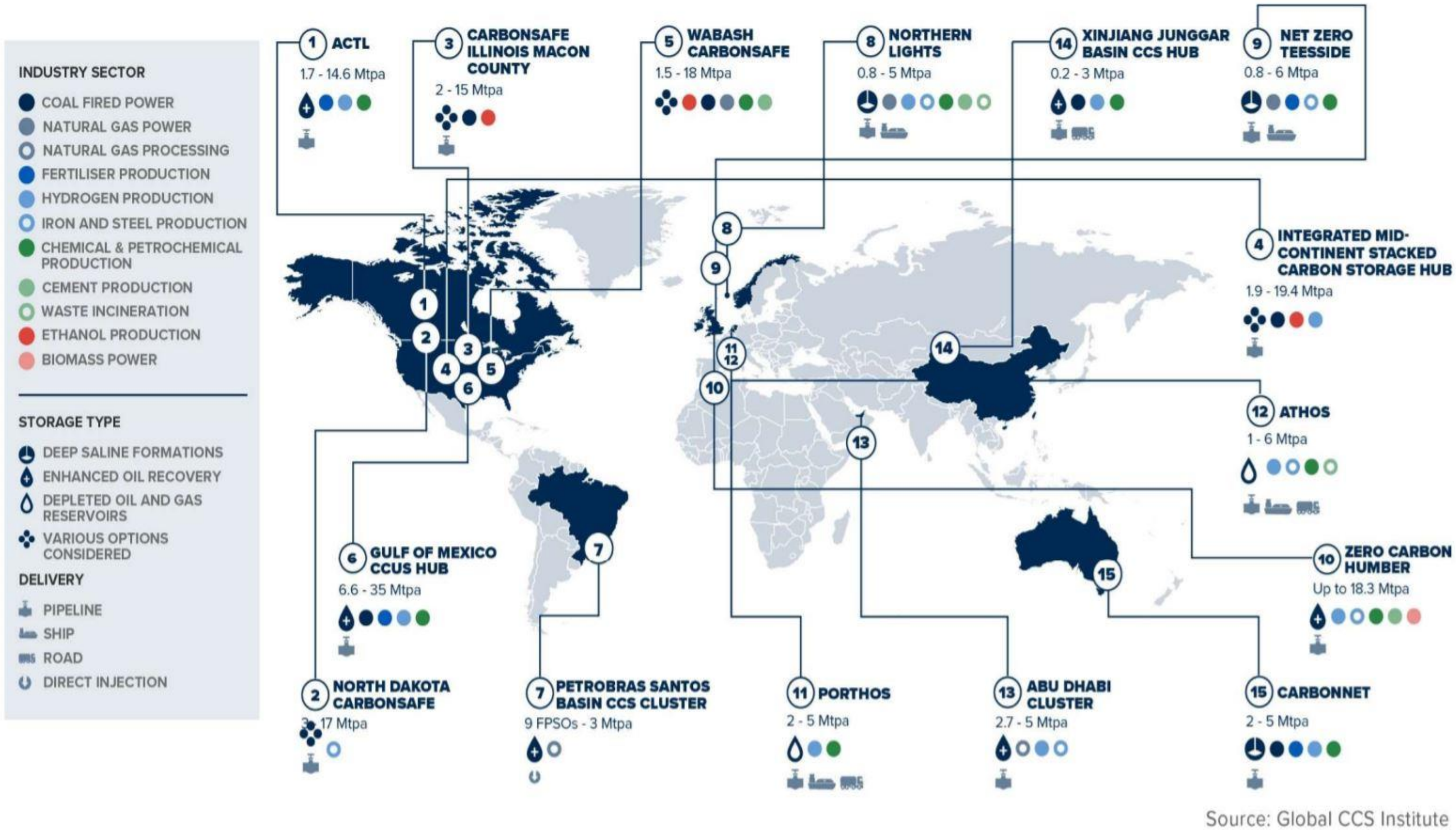

Fig. 3. Global distribution of key CCS projects in 2019. Source: Marshall *et al*., 2020.

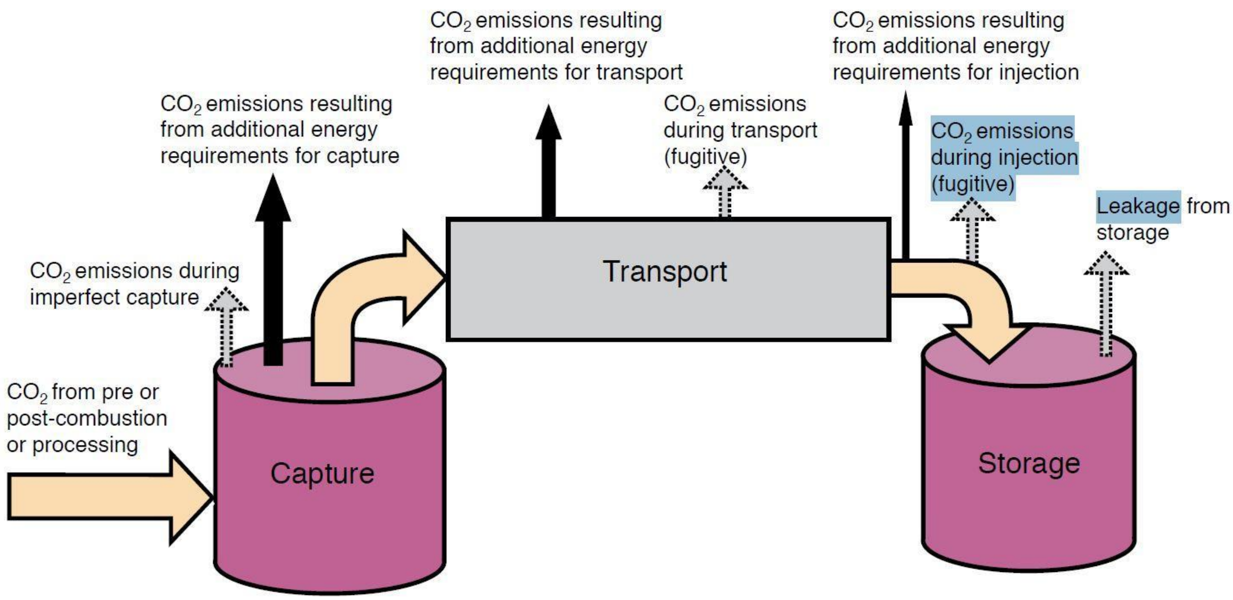

Fig. 4. Simplified flow diagram of possible CO_2 emission sources during carbon capture and storage. From the Special Report prepared by Working Group III of the Intergovernmental Panel on Climate Change (IPCC, 2005).

As a brief background of its inception, the IPCC 2005 meeting on climate change first brought CCS into global attention in a weighty expert reviewed special report on *Carbon Dioxide Capture and Storage* (IPCC, 2005), which outlined the technology, the costs, the benefits, the complications, and the potential for playing a significant role in climate change mitigation. In 2011, six years after CCS was first presented in that IPCC special report, the UN Framework Convention on Climate Change agreed upon CCS as a ***Clean Development Mechanism*** (CDM), which under Article 12 of the Kyoto Protocol, allows such projects to "… earn saleable certified emission reduction (CER) credits, each equivalent to one tonne of CO_2, which can be counted towards meeting Kyoto targets".

Generally speaking, CCUS has a key role in achieving the goals of the Paris Climate Agreement targets and are deemed as ***vital emissions reduction technologies*** by both the IPCC and International Energy Agency (IEA). The global CCS programme, between 2010 and 2020, expressed in terms of annual capacities for carbon sequestration from 2010 to 2020 is illustrated in Fig. 2 and the global distribution of key CCS projects in 2019 is shown in Fig. 3. An important question that is raised as the cost of CCUS roll-outs increases is simply this: ***is it really worth it?*** The answers given to that question are certainly not a unanimous 'yes' because recent innovations in ***bio***technological solutions could provide better alternatives, such as improved energy efficiency, renewable energy, or ***bio***technological innovations.

Before we go further with that proposition, we should establish exactly what CCS is. According to the IPCC 2005 Special report on Carbon Capture and Storage (IPCC, 2005), CCS is a process consisting of the separation of CO_2 from industrial and energy-related sources, transportation to a specified storage location and long-term storage and isolation from the atmosphere (Fig. 4).

CCS is currently considered to be the primary tool for mitigation and stabilisation of atmospheric greenhouse gas concentrations. The utilisation aspect of GHG emissions, or CCU, has more recently been developed as a ***better practice*** as compared to CCS due to the utilisation of the emissions as a secondary resource rather than solely storing them. CCUS is therefore more closely suited to a circular economy, but more on that later.

The capture of CO_2 and other GHG emissions via CCUS can be applied to large point sources, where the emissions can be compressed and transported for storage in geological formations, in the ocean, in bedrock as mineral carbonates or for use in further industrial processes (IPCC, 2005). According to Zevenhoven & Fagerlund (2010), CCS involves injecting CO_2 into host rocks or employing an *ex situ* application step, reacting huge volumes of CO_2 as carbonate minerals, and storing these in geological formations. The initial steps involve ***capturing the CO_2 emissions***, followed by ***transportation*** and ***injection***. Each step can involve variations in physical and chemical processes, each major CCS project utilising different solutions of varying efficiencies. The end results are nonetheless similar; CO_2 either in liquified or mineralised form which is now available for either utilisation or direct storage in geological underground pockets. A more recent review (Hills *et al*., 2020) discusses mineralisation in geologically derived minerals and industrial wastes, emphasising the manufacture of products with value. The authors suggest that this sort of CCUS technology can manage significant quantities of CO_2.

Leakage and escape of injected CO_2 (as with other historically mass-stored chemical pollutants) has been a topic of major concern over the last two decades and many of these concerns have been allayed by pilot experimental studies by expert geologist teams. Possible escape routes for geologically injected sequestered CO_2 are shown in Fig. 5.

Larkin *et al*. (2019) listed **29** potential hazards in a risk assessment of CCS injection and storage activities, suggesting that for 0-50 year, 51-499 year and >500 year time periods, the likelihood of the occurrence of ***major leakage*** from CCS storage resulting in "… measurable negative effects on human health or the environment …" is approximately 1 in 10^3. Ho & Tsai (2020) note the enormously wide uncertainties involved with CCS leakage potential, such as uncertainties in saline aquifer storage capacity (0.1 to 76,000 Gt), uncertainties of CO_2 sequestration capacity in solution (0.2 to 76%), and uncertainties in the distances affected by salt precipitation (1 to 175 m) inhibiting the well's pores and reducing holding capacity.

Most CCS projects that have been successful to date are site-specific, either pilot or small-to-medium-scale and have yet to reach annual expected injection capacities. Put simply, there is not enough historical data on long-term, wide-ranging, and large-scale CCS to really gauge the impact of potential hazards to be comfortable about global-scale CCS implementation.

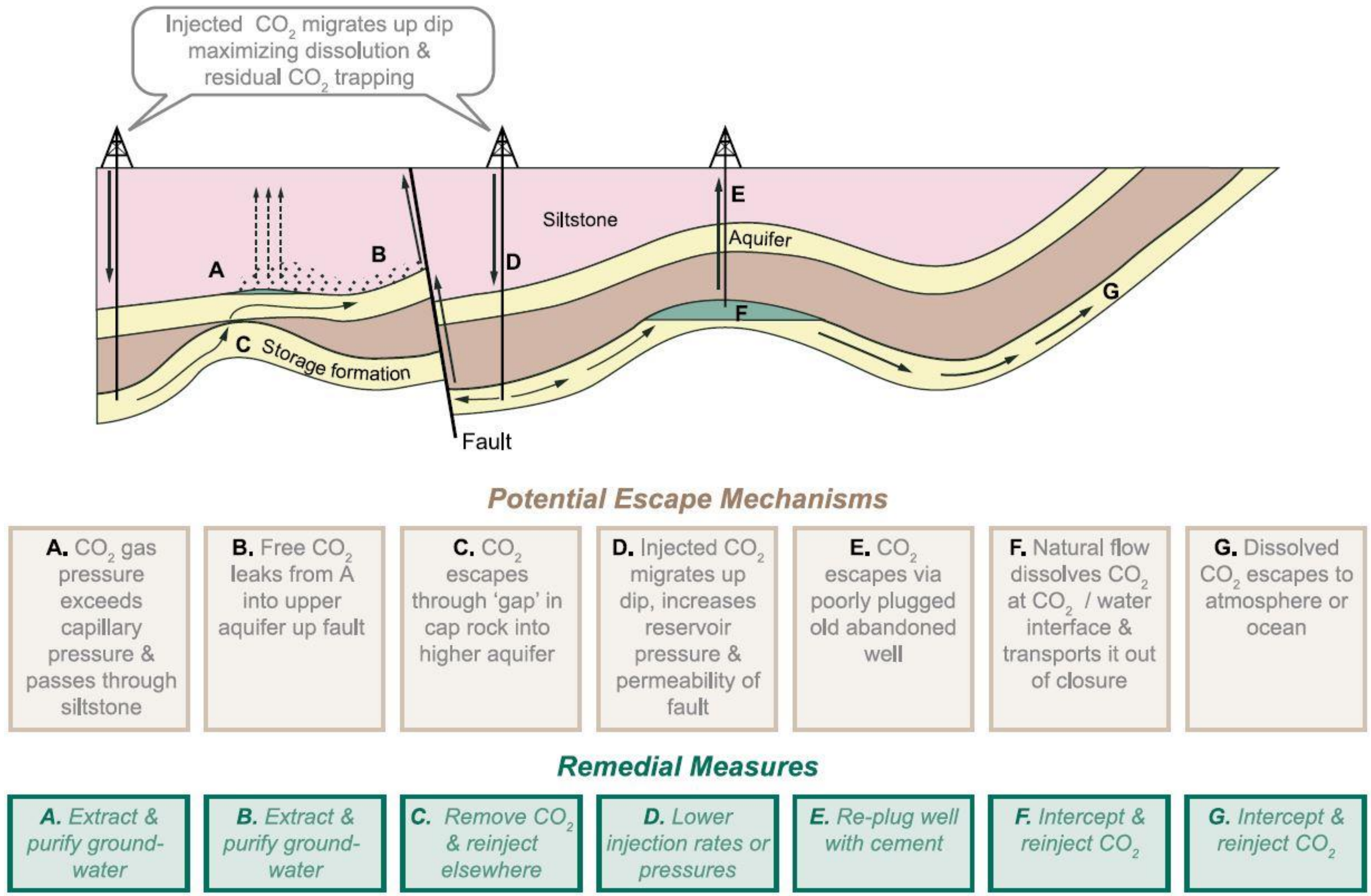

Fig. 5. Potential leakage routes and remediation techniques for CO_2 injected into saline formations. The remediation technique used would depend on the leakage route identified in a reservoir as shown in the bottom set of panels. From the Special Report prepared by Working Group III of the Intergovernmental Panel on Climate Change (IPCC, 2005).

Confidence in the technology continues to be expressed, however. Miocic *et al*. (2019) calculated leakage rates from a 420,000 year old naturally occurring, but faulted, CO_2 reservoir in Arizona, USA. Surface travertine ($CaCO_3$) deposits provide evidence of vertical CO_2 leakage which can be dated by uranium-thorium decay.

The data show that leakage varies along faults and that individual seeps have lifespans of up to 200,000 years. Time-averaged leakage equated to a linear rate of less than 0.01% y^{-1}. Friedmann *et al*. (2020) estimate that 85 Gt of CO_2 must be captured and stored from coal-fired power generation alone between 2030 and 2050:

> "… Most gas power plants operate for about 30 years, while coal-fired generation plants operate for 40–50 years, and this newly installed capacity will remain in operation through to 2060 without premature closure - CO_2 emissions from the global coal fleet are expected to approach 10 Gt CO_2 in 2030 and exceed 7 Gt CO_2 in 2050 (Cui *et al*., 2019). If they operate, around 90 percent of those emissions must be captured and stored in 2030, and effectively all emissions must be captured and stored in 2050 to achieve net-zero. If power production from the global coal fleet is only half what has been assumed in this simple illustrative analysis, approximately 85 Gt of CO_2 must be captured and stored from coal-fired power generation alone between 2030 and 2050 to be consistent with a 1.5°C climate outcome." (Friedmann *et al*., 2020).

If that 85 Gt reservoir leaks back into the atmosphere at a rate of about 0.01% y^{-1}, the reservoir's total content of sequestered CO_2 will be returned to the atmosphere in 10,000 years. In comparison with the human lifetime, 10,000 years is an unimaginable length of time, but it is totally insignificant compared with the length of time that atmospheric CO_2 has remained sequestered in, for example, coccolithophore limestone layers laid down in the Triassic Period.

Due to the sheer size and capacities anticipated for CCS storage sinks, assuming the current global trend for fossil fuel use with CCS continues, even tiny error margins could result in thousands of tonnes of CO_2 leaking back into terrestrial and coastal ecosystems. This has the potential for environmental damage along the same lines as contaminating leachates from historic landfills or mines implemented by our engineering forefathers.

Whilst the economic and energy-system risks due to potential CCS leakage are arguably modelled with confidence (Liu *et al*., 2016; Deng *et al*. 2017), it is our environmental ecosystems that are calling for more attention. Industrial CCS has small risks, but huge consequences for our environment. The key question is 'what if?'

Once the gas is in storage, there is no going back, and the environmental risks can only be managed after complications arise. CCS technology is arguably the most significant and powerful carbon sequestration tool we have that can serve as a point-source, 'brute-force' carbon sink solution. Although relatively few sites, globally, are suitable for CCS (because the geological characteristics must be perfect), several sites have been found and classified as having the giga tonnage (Gt) CO_2-storage potential required to meet Paris Agreement climate goals (Fig 3, above).

The *Global CCS Institute* (https://www.globalccsinstitute.com/) is the leading organisation and knowledge-base on CCS projects for industry as well as research and development. According to this Institute's website, current CCS projects either in operation or under procurement or construction (Fig. 3) have been estimated to sequester CO_2 at rates from 100,000 to 30 million tonnes per annum, per CCS project site.

Operational lifetimes are expected to be at least 25 years. As an example, the *CarbonNet Project* located in South Gippsland, Victoria, Australia is working towards establishing a commercial scale CCS network with storage at the project's Pelican site in Bass Strait, off the South East coast of Australia's 'Ninety Mile Beach'.

The site is projected to sequester up to 5 million t of CO_2 annually (it is site 15 in Fig. 3). This is a significant quantity of CO_2 gas. On a molar mass basis, carbon represents 27.29% of the mass of CO_2. Consequently, that 5 million t of CO_2 corresponds to **1,364,500 t of carbon** removed from the atmosphere ***annually*** by the individual **Pelican Site CCS facility**.

The key consideration here is that these large point-source quantities of CO_2 are, for the most part, found in heavy industrial plant sites. Artificial CCUS solutions include but are not limited to CO_2 injection or subsurface mineralisation, CO_2 flooding and enhanced oil recovery (EOR), deep sea storage (such as deep water pressurised storage conveyed by pipe), which are the major solutions.

Less impactful, but equally innovative are: Direct Air capture and storage (DAC, e.g., Climeworks™), Dry Ice Emissions capture (e.g., DecarbonIce™) or capturing CO_2 from hydrogen production (e.g., CryoCap™).

Although sceptics have raised significant concern for the environmental risks involved with CCS projects, the science has (so far) proved its safety and efficacy, albeit, at very small scales beyond pilot field trials alone. As a result of stricter government policies towards fossil fuel use and of heavy GHG emissions in general, the major CO_2 emitters (namely fossil fuel companies) have sought to invest into CCS as a **business solution** to become carbon neutral.

In turn, the highest quantifiable CCU/CCS technologies are capitalising on a new market demand created by government policy, where major heavy industries and GHG emitters are needing to protect themselves ***and their banks*** against possible future sanctions.

As discussed by Moore *et al*. (2021a), the 2019 report of the US National Academies of Sciences, Engineering, and Medicine entitled *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (NASEM, 2019) describes negative emissions technologies, or NETs as optimal carbon sequestration solutions. NETs are technologies that remove and sequester CO_2 from the atmosphere with the intention of mitigating climate change, with a biotechnological component.

NETs have previously received less attention than industrial technologies aimed at reducing the level of future CO_2 emissions by reducing fossil fuel consumption, though this requires massive deployment of low-carbon technologies and agricultural land-use change between now and the target date of 2050. One key point here is that CCUS is more useful for achieving zero or carbon neutral operations, not negative, especially when the CCUS-facilitated plant is not processing biological or waste resources (also known as 'BECCS', Bioenergy with CCS).

According to the Global Carbon Project, about 37 billion tonnes of CO_2 gas was emitted globally by heavy industries in 2019 [https://www.globalcarbonproject.org/]. The number of heavy emitting plants is rising, particularly in Asia as mentioned earlier. To date there are more than 5,000 large industrial plants globally that produce CO_2 emissions above 1 million tonnes per year. Again, due to recent industrial development in Asia and lacking regulatory action or initiative, this number continues to grow at significant capacity. Interestingly, the number of CCS plants under development between 2010 and 2017 reduced significantly, followed by a recent resurgence in development of the technology (Fig. 2). To date, close to 40 CO_2 injection facilities have been brought into operation (mostly in the USA) and many more are in development (Fig. 3, above). This activity is monitored by the Center for Climate and Energy Solutions (https://www.c2es.org/), an independent, nonpartisan, nonprofit organisation which is

> "… working to forge practical solutions to climate change …" (and view https://www.c2es.org/content/carbon-capture/).

Facilities already in operation are implemented as an add-on or retrofit to heavy industrial plants; particularly in the oil and gas industries and fossil fuel energy generators, but also cement, steel, and fertiliser producers, though the technologies are generally applicable to any CO_2 emitting facility. The CCS system captures CO_2 produced directly from the industrial plant's output flue gases and pumps it underground into deep saline pockets under cap rock.

Although injection into sedimentary basins has been commonly conducted for enhancing oil recovery from certain wells (Enhanced Oil Recovery is one of the business goals of CSS; Fig. 6), it has been proved that basaltic cap rock pockets provide much more safety and encapsulation for mineralised CCS storage into stone (with pioneer work laid out via pilot studies in Iceland; see https://www.carbfix.com/).

Figure 3 (above) displays the main CCS projects as of 2019, as listed by the *Center for Climate and Energy Solutions* (URL: https://www.c2es.org/content/carbon-capture/). Many of the projects shown in this figure are pioneering new approaches and/or new technologies, a few examples will illustrate the range of these technological innovations:

The Northern Lights project is part of the Norwegian full-scale CCS project, which includes capture of CO_2 from industrial capture sources in the Oslo-fjord region (cement and waste-to-energy industries). The process uses CO_2 mixtures with amine-gases and cryogenic separation and distillation to separate and liquify CO_2 gas. Amine gas treatment, also known as amine scrubbing, is widely used to remove hydrogen sulfide

(H_2S) and carbon dioxide (CO_2) from gases in refineries, petrochemical plants, natural gas processing plants and other chemical industries.

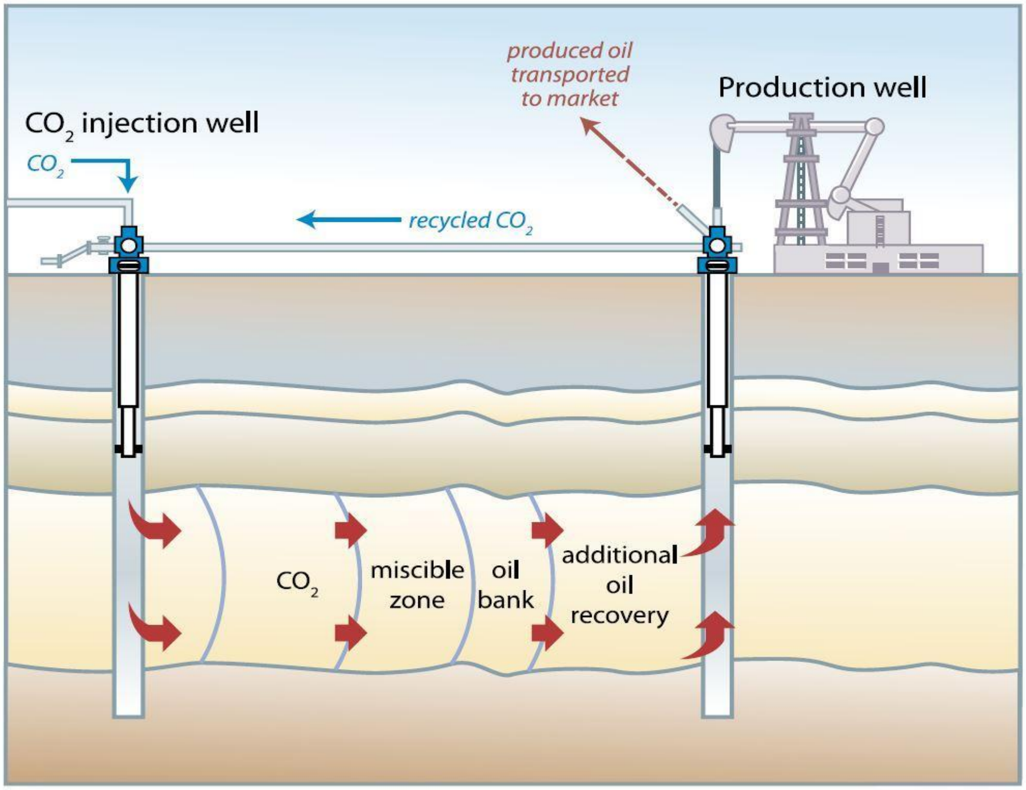

Fig. 6. Enhanced Oil Recovery (EOR) by CO_2 injection with some storage of retained CO_2. The CO_2 that is produced with the oil is separated and reinjected back into the formation; recycling CO_2 this way decreases the amount of CO_2 that must be purchased and avoids emissions to the atmosphere. From the Special Report prepared by Working Group III of the Intergovernmental Panel on Climate Change (IPCC, 2005).

The process uses aqueous solutions of various alkylamines, most commonly diethanolamine (DEA), monoethanolamine (MEA) and methyldiethanolamine (MDEA). The gas mixtures have advantageous physical properties under pressure that permit gas liquefaction and cryogenic distillation to purify and liquify the CO_2 (Mandal *et al*., 2001; Xu *et al*., 2014). Liquid CO_2 is shipped from the capture sites to an onshore terminal on the Norwegian west coast. From there, the liquified CO_2 will be transported by pipeline to an offshore permanent storage location 2700 m below the seabed of the North Sea. The facility is capable of sequestering 5 Mt y^{-1}.

The CarbonNet Project/CO2CRC in Australia is capable of up to 5 million ton/year and utilises metal organic framework (MOF) material to capture CO_2. Metal organic frameworks resemble a sponge, filled with magnetic nanoparticles that adsorb carbon dioxide gas. Otherwise known as magnetic induction swing adsorption (MISA), the advantage of the process is that it requires one-third of the energy input (used mainly to regenerate the capture media) compared to any other reported CO_2 capture method (Sadiq *et al*., 2020).

CarbFix in Iceland is a project that commenced in 2006 and has since developed innovative geological carbon storage by capturing and rapidly storing CO_2 as a mineral formed in reactive, porous, basaltic subsurface. The project has also explored mineral fluid interactions to predict the fate and impact of CO_2 injected into the subsurface. The process involves first dissolving the CO_2 gas into water and then injecting it into the subsurface.

> "… This had two advantages: firstly, CO_2-charged water is denser than pure water, so it tends to sink. Secondly, the acidic CO_2-charged water promotes reactions in the subsurface, specifically the dissolution of basalt, which in turn leads to the fixation of carbon as stable mineral phases … Once it is made into a mineral the carbon is immobile over geologic time frames, representing a safe, long time solution for CO_2 storage…" (source: Carbfix.com website).

The process was field-tested at the CarbFix pilot site in Hellisheidi, Iceland, where the original injection was shown to fix over 90% of the injected 170 tons of pure CO_2 as stable carbonate minerals in less than 18 months. Economic studies show costs in the order of "… 30-40 US$ per tonne, which is no more expensive than other less safe alternatives…" (quotations above taken from the ***Carbfix.com*** website at https://www.carbfix.com/co2-react-2013-2017). Hellisheidi has achieved costs less than $US25 t^{-1} and as of January 2020 "… over 50,000 tonnes have been injected into reactive basalts … for permanent storage". Here, the CO_2 is captured in a scrubbing tower with annual capacity of about 12,000 tonnes of CO_2 and 6,000 tonnes of H_2S, about 30% and 75% of the plant's emissions respectively." (https://www.carbfix.com/faq).

The costs of CCS adoption were discussed in the Special Report *Carbon Dioxide Capture and Storage* prepared by Working Group III of the Intergovernmental Panel on Climate Change (IPCC, 2005). According to Kheshgi *et al*. (2012) the publication of this report:

> "… raised the profile of CCS, particularly among the expert community dealing with international climate policy (Meadowcroft & Langhelle, 2011).
>
> The expert community now commonly sees CCS as a major option for reducing global emissions of CO_2. The technology plays a major role in long-term scenarios where there is significant reduction in greenhouse gas emissions (Clarke *et al*. 2009; IEA, 2010). For CCS to play such a major role, the separation, transport and storage would have to handle large volumes of CO_2 and involve huge investments in facilities and infrastructure …".

We illustrate costs of CCS adoption in Table 1, below, for which we have recalculated the cost ranges given in the original 2005 publication using the Consumer Price Index inflation calculator of the US Bureau of Labor Statistics as featured on ***Ian Webster*'s** website (https://www.in2013dollars.com/us/inflation/).

Table 1. Cost ranges for the components of a CCS system as applied to a given type of power plant or industrial source

CCS system components	Cost range	Remarks
Capture from a coal or gas-fired power plant	21-104 US$ per t CO_2 net captured	Net costs of captured CO_2, compared to the same plant without capture.
Capture from hydrogen and ammonia production or gas processing	7-76 US$ per t CO_2 net captured	Applies to high-purity sources requiring simple drying and compression.
Capture from other industrial sources	35-159 US$ per t CO_2 net captured	Range reflects use of a number of different technologies and fuels
Transportation	1.4-11 US$ per t CO_2 transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) Mt CO_2 yr^{-1}.
Geological storage[a]	0.7-11 US$ per t CO_2 net injected	Excluding potential revenues from EOR or ECBM.
Geological storage: monitoring and verification	0.14-0.4 US$ per t CO_2 injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements.
Ocean storage	7-41 US$ per t CO_2 net injected	Including offshore transportation of 100-500 km, excluding monitoring and verification.
Mineral carbonation	69-138 US$ per t CO_2 net mineralised	Range for the best case studied. Includes additional energy use for carbonation.

All numbers are representative of the costs for large-scale, new installations, with natural gas prices assumed to be 3.9-6 US$ GJ^{-1} and coal prices 1.4-2 US$ GJ^{-1}. Monitoring costs are also reflected. [a]Over the long term there may be additional costs for remediation and liabilities. Data Source: The Special Report prepared by Working Group III of the Intergovernmental Panel on Climate Change (IPCC, 2005); all costs recalculated for inflation using the factor $1 in 2004 is equivalent in purchasing power to about $1.38 in 2021.

Table 2. The costs of CO_2 capture, transport and geological storage for new power plants using bituminous coal or natural gas			
Power plant performance and cost parameters[a]	Pulverised coal power plant	Natural gas combined cycle power plant	Integrated coal gasification combined cycle power plant
Reference plant without CCS			
Cost of electricity (US$ per kWh)	0.062-0.075	0.045-0.073	0.060-0.089
Power plant with capture			
Increased fuel requirement (%)	24-40	11-22	14-25
CO_2 captured (kg per kWh)	0.82-0.97	0.36-0.41	0.67-0.94
CO_2 avoided (kg per kWh)	0.62-0.70	0.30-0.32	0.59-0.73
% CO_2 avoided	81-88	83-88	81-91
Power plant with capture and geological storage[b]			
% increase in cost of electricity	43-91	37-85	21-78
Power plant with capture and enhanced oil recovery[c]			
% increase in cost of electricity	12-57	19-63	(-10)-46
All changes are relative to a similar (reference) plant without CCS. Data sourced from Table TS.10 in IPCC (2005); see Table TS.3 in that report for the assumptions underlying quoted cost ranges. Costs recalculated for inflation using the factor $1 in 2002 is equivalent in purchasing power to about $1.45 in 2021.			

Despite the economic advantages of CCUS apparent from Table 1, the technologies face a number of practical and economic barriers that must be overcome before they can be deployed on a sufficiently large scale, and over a sufficiently long time interval, to make serious inroads into the atmosphere's accumulated fossil-CO_2 burden. The main economic and environmental hurdles in sight are:

- the significantly large capital investment and hard infrastructure required for implementation, operation and maintenance; and
- the extremely energy-intensive process required for carbon utilisation (CU) or sequestration (CS).

The most important disincentive to CSS implementation is its cost. This was foreshadowed in IPCC's special report on CCS, which stated that fossil fuel-based power plants equipped with CCS for mineralised subsurface injection, will require 60–180% ***more energy*** (= more cost) than a power plant without CCS (IPCC 2005).

Table 2 shows the total costs of CCS and electricity generation for three power systems with pipeline transport and two geological storage options. Again, the data is sourced from the Special Report *Carbon Dioxide Capture and Storage* prepared by Working Group III of the Intergovernmental Panel on Climate Change (IPCC, 2005), with costs adjusted for inflation as in Table 1. Overall, the situation is well summarised by this quotation from the Wikipedia article on *Carbon Capture and Storage [CSS]*:

> "The increased energy required for the carbon capturing process is also called an energy penalty. It has been estimated that about 60% of the energy penalty originates from the capture process itself, 30% comes from compression of CO_2, while the remaining 10% comes from electricity requirements for necessary pumps and fans. CCS technology is expected to use between 10% and 40% of the energy produced by a power station. CCS would increase the fuel requirement of a plant with CCS by about 15% for a gas-fired plant. The cost of this extra fuel, as well as storage and other system costs, are estimated to increase the costs of energy from a power plant with CCS by 30%–60%, depending on the specific circumstances." (source: https://en.wikipedia.org/)(Rochon *et al*., 2008; Rubin *et al*., 2012; Thorbjörnsson *et al*., 2015).

The early recognition of this energy penalty may well be the reason for the relatively late uptake of CSS technology by the power generation industries, as compared with gas-processing industries (Fig. 7). Though, of course, the scale of the infrastructure required by power generation facilities and the long lead times required for its design and implementation must also have contributed to the marked difference evident in Fig. 7 between the operation of CCS applications in these two types of industry. We have assembled a summary of cost estimates of CCUS technologies and their CO_2 removal rates in Table 3.

The UN Sustainable Development Goals (SDGs) are shown in the final column of Table 3 because in pursuance of the Paris Climate targets through climate change mitigation technologies (artificial or bio-based), we must consider both the opportunities and risks associated with such solutions that remove GHGs from the atmosphere. Such an approach is helpful in determining the true sustainability of solutions because value factors such as land and water use, cultural and land heritage as well as biodiversity and nutrient stocks are given ***significant*** weighting. Smith *et al*. (2019), also explored this for land-based solutions, by "… looking through the lens of the functions …" provided by each solution and "… their impact on ecosystem services [classified according to the new Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) classification known as Nature's Contributions to People (NCPs) …" (Smith *et al*., 2019). Especially for solutions that help conserve or improve natural ecosystem services, the valued benefits usually go far beyond what project engineering or financial models would normally include. Meaning, ***we should be placing even higher-than-usual value on natural capital and global environmental health improvement indicators on current and future decision-making***.

Table 3. Summary of CCUS solutions including cost estimates, CO_2 removal rate estimates and UN Sustainable Development Goals (UN SDGs) addressed

Solution	Estimated Global Potential Removal Rate of CO_2 (current) ($Gt\ y^{-1}\ CO_2$)	Estimated Cost of Implementation at Scale (US$ t^{-1} CO_2)	Number of UN SDGs Addressed (/17)
Terrestrial afforestation	2.5-9 (higher values directly impact food security)[x]	15-50[x]	10[a]-13[b,h]
Blue carbon afforestation	0.13-0.84 (only based on post-1980 coastal wetland recovery)[x, h]	10[x]	12[e,f,h]
Enhanced Weathering (TEW)	2[g]	75-250[g]	9[h]
Ocean Fertilisation (Macronutrient only)	3.7[i]	≥20[i]	2[j]
Agricultural & Other Soil Management (e.g., biochar)	0-3[x,h]	0-50[x]	12[h]
Bioenergy with carbon capture and sequestration (BECCS)	3.5-5.2 (assumes only waste biomass as feedstock)[x] 10-15 (assumes waste biomass ***and*** dedicated energy crop feedstocks)[x]	Electricity: 70[x] Fuels: 37-132[x]	7-9[h]
Direct Air Capture	<0.01[k]	90-600 (current demonstrated cost of DAC)[x]	<8[l]
CCUS	15[m]	25-210[n]	CCUS: 4[o]-6[c]

Sources: [x] NASEM, (2019), [a] The State of the World's Forests 2018 (FAO, 2018), [b] De Jong *et al.,* (2019), [c] Aker Carbon Capture Presentation 2020, [d] CCM Technologies 2020, [e] Kuwae & Hori (2019), [f] United Nations Development Programme - Thailand (UNDP Thailand, 2019), [g] Beerling *et al*. (2020), [h] Smith *et al*. (2019), [i] Jones (2014), [j] Secretariat of the Convention on Biological Diversity (2009), [k] Budinis (2020), [l] Beuttler *et al* (2019) [note that all authors are employed by Climeworks AG, which is one of the main proponents of direct air capture], [m] IOGP (2019), [n] Irlam (2017), [o] Zapantis (2017).

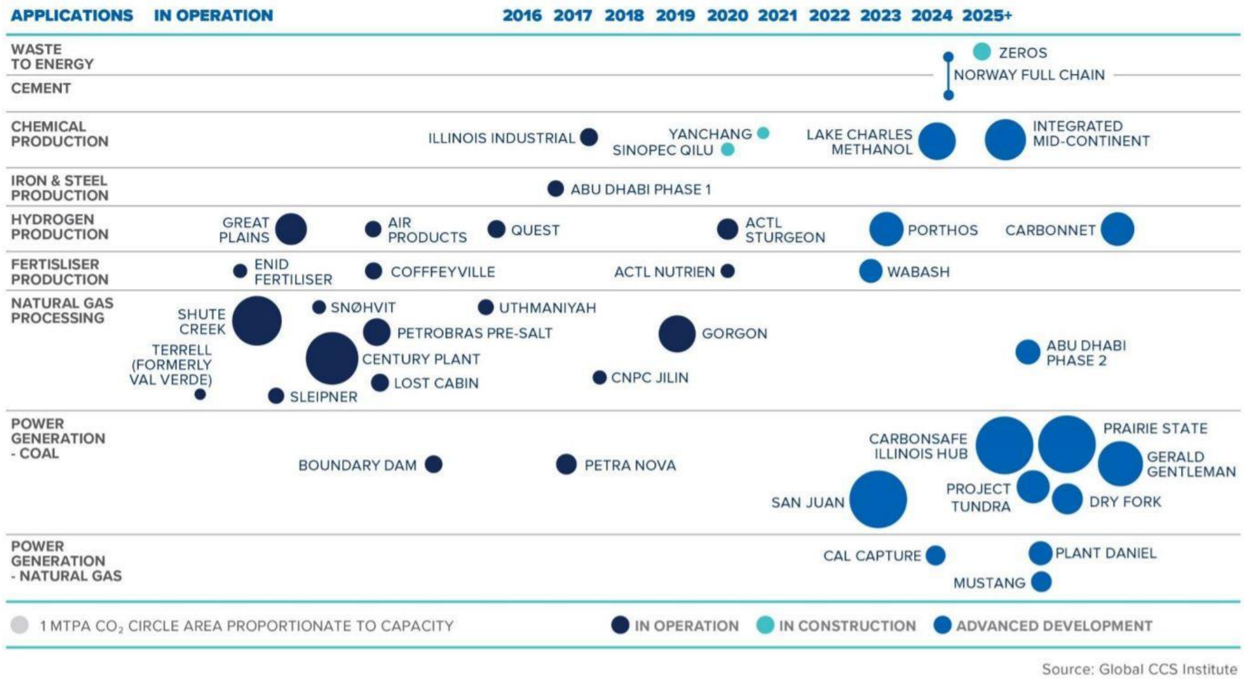

Fig. 7. CCS projects around the world since the 2005 IPCC Special Report *Carbon Dioxide Capture and Storage.* Source: Marshall *et al.*, 2020.

There are some other issues that seem to be held in the background of the CCS arena, though common in the business world. These result in some ambiguity in regard to ***how*** climate is to be managed, raising the questions: where does the controlling influence and interest lie, and who are the major stakeholders? These are robust questions that need to be asked, especially in a situation where CCUS is most wholeheartedly backed by the major fossil fuel-based enterprises themselves. A quick analysis of the **Global CCS Institute**'s current (December 2020) 88 members (https://www.globalccsinstitute.com/membership/our-members/), at least 48 out of 88 members rely on or have direct business interests in fossil fuel use. A further 17 members currently rely on fossil fuel industries either indirectly or partially, leaving ***only 22 of the 88 members with no immediate evidence of business reliance or connection to fossil fuel use***. However, it is important to keep in mind that these members might also have significant shareholders or be subsidiaries of upper tier companies who do have vested interests in continued fossil fuel use. Here, we looked only as far as each company's web page or Wikipedia descriptions where available.

The ***Global CCS Institute*** recognises the IPCC's latest targets in a September 2020 report (Friedmann *et al*., 2020) these certain actions are:

- A 50% reduction of CO_2 emissions is needed to achieve net-zero climate goals by 2030.
- A rapid implementation of climate mitigating infrastructure is needed urgently, including the expansion of CO_2 pipelines from the current 8,000 km to 43,000 km by 2030.

- Urgent development and implementation of clear climate policies to optimise financial and regulatory risk mitigation for CCS infrastructure.

The report also offers the following advice:

> "Due to the urgency of the climate crisis, time is of the essence. There are no important technical barriers to scale-up. The costs are well within the conventional boundaries of global energy investments and the policy options well understood. The next ten years will prove decisive – if the governments of the world are to meet their climate goals, these key policies must enter into force with deliberate speed" (Friedmann et al., 2020).

Indeed, 43,000 km of CO_2 pipeline is a lot of hard infrastructure. So, let us assume that by 2030 we achieve a reduction in fossil fuel usage and then ask ourselves: will that not make some of these pipelines redundant? We must not ignore the fact that retrofitting conventional fossil-fuel plants with CCS serves not only to assist in climate change mitigation, but also to create redundant hard infrastructure for future generations, not to mention the enormous continual efforts required to monitor and manage the thousands of highly concentrated CO_2 sinks that come with this direction.

Of course, some facilities *may* be able to convert to biomass-use instead of total decommissioning, but the costs of conversion will usually outweigh the construction of a whole new plant, particularly given the likelihood of more cost-effective and optimised designs, construction and manufacturing materials and technological services that will be available decades from now. The scenario can be seen as similar to mine tailings ponds; we are now seeing more and more closed mining sites requiring increasing levels of risk management, primarily environmental.

On another important note, Krüger (2017) published an interesting piece on the conflicts over CCS in international climate governance, namely postulating two theses:

- That the future of climate governance is contingent on decisions about the **continued use of fossil fuels**.
- That CCS-conflicts have an unpredictable influence that could lead to implications and cracks within the paradigm of ecological modernisation and thus could **politicise international climate policy**.

Krüger (2017) discusses the consequences of allowing private business interests to determine the direction of humanity's future. The problem, however, is one of necessity. On the one hand, CCUS is a power-house technology that could play a central role in deciding where humanity ends up by the end of the 21st century. On the other hand, because it is desired most by fossil fuel-reliant enterprises to safeguard their own business, CCUS is tainted with contention. It may be the magical release from our worst nightmares; or it could be the Poisoned Apple which will send us into the Sleeping Death of our times.

Artificial CCS solutions are researched, developed, and engineered to address specifically the question of 'how can we prevent GHG emissions entering our atmosphere?' However, if these artificial CCS solutions are continuously implemented, unchecked rapidly and widely, they could result in serious implications and even more problems for our future generations of scientists and engineers.

As we see it, the problem is that CCUS has attracted market-trading, but without the optimal regulatory framework and market rules that would alleviate mistrust, misguidance, and corruption. The carbon trading schemes that have been opened in many nations to date have yielded both positive and negative results in relation to the problem posed by climate change. As the initial goal of carbon sequestration is to reduce atmospheric CO_2 levels, the primary goal of a carbon market or carbon trading scheme is to sequester the most carbon. As a result, industries and corporations have started to look at technologies that will sequester the most carbon, and that aligns with their future business plans. These are the methods of carbon sequestration best supported by fossil fuel companies and are therefore ***not the ideal solutions for our environment and its ecosystems***. It is the technology that secures the industry's business plan and market position heading forward into the future, rather than the technology that is best for planet Earth.

As we all know, increasing carbon emissions, atmospheric GHG levels and global warming result from a complex system of biogeochemical processes affected by many anthropogenic practices. Because of this, rather than a ***carbon trading market***, it would make more sense to introduce a **global environmental health market** that offers traders and participating industries and businesses, alongside the carbon credits, trading credits that could be equally important contributors to our attempts to avert global warming. For example, **biodiversity credits**, **ecosystem service credits**, and **biomimicry-of-technology credits**.

That is not what we have. Instead of introducing an ***environmental-with-carbon market***, we only have a carbon market. What is concerning about current practices is that removal of carbon from the atmosphere is the ***only*** environmental concern and those other global environmental health indicators are not at the forefront of any aspect of the carbon trading market. The value is placed on removal of carbon from the atmosphere at almost any cost. Consequently, the money (what little is left of it after successive traders have taken their top slice) therefore, goes to carbon credits, not environmental credits.

We would rather see a market, that consists of rules and regulations based on a global ***environmental health market*** which is focused on altering the root anthropogenic causes of our current ills. These are not only global warming, but include active destruction of ecosystems by over-exploitation, global loss of biodiversity, and anthropogenic species extinctions at rates not seen since the darkest days of the planet's geological history.

The carbon market is already established, with the ebb and flow of supply and demand circulating, but we should not concentrate solely on the symptomatic results of unsustainable anthropogenically-raised GHG emissions. As we make more serious attempts to ameliorate the damage our industrial activities have already done to the atmosphere, we must not ignore those broader anthropogenic mistakes. These should be change-incentivised towards restoring and maintaining the natural circular economies of healthy environmental ecosystems. Between the additional energy required for industrial CCS, the CO_2 emissions during the process and the leakage during storage (which certainly increases with the years), it seems that twice as much oil and gas would have to be extracted to store the CO_2 emitted simply by the current use of these fossil fuels. Widespread use of CSS would be like being blindfolded on the edge of a precipice and taking a big step forward!

6. Carbon emissions reduction targets

Key climate-focused actions are required in order to avoid climate catastrophe. As we progress into the third decade of the 21st century, climate records proved that 2011-2020 was the warmest decade on record, with the warmest six years all being since 2015 (WMO, 2020), while the ***Copernicus Climate Change Service*** satellite data showed that 2020 was statistically at dead heat with 2016 as the world's warmest year on record. Copernicus data comes from a constellation of Sentinel satellites that monitor the Earth from orbit, as well as measurements taken at ground level. Temperature data from the system shows that 2020 was 1.25°C warmer globally than the average from 1850-1900, a time often described as the 'pre-industrial' period. (https://climate.copernicus.eu/).

7. Comparing 'hard' and 'soft' (nature-based) carbon sequestration

The 'hard' carbon sequestration solutions available to us include the following processes.

CCUS & mineralisation; in the latter part of this combined process, CO_2 from the atmosphere forms a chemical bond with reactive rocks, like mantle peridotite and basaltic lava, both at the surface (*ex situ*) where CO_2 in ambient air is mineralised on exposed rock, and in the subsurface (*in situ*) where concentrated CO_2 streams are injected into bedrock to mineralise in the pores.

Direct air capture (DAC) uses chemical processes that capture CO_2 from ambient air and concentrate it, so that it can be injected into a storage reservoir or utilised in the value-chain of secondary industries.

Bioenergy with carbon capture and sequestration (BECCS). BECCS is a 'green' version of CCS, using plant biomass as an energy source, primarily to produce electricity by one of two methods: ***combustion*** or ***conversion***. ***Combustion*** uses the biomass directly as a furnace fuel for conventional electricity generation or for other furnace-based industrial applications (cement, paper pulping, waste incineration, petrochemicals and steel and iron production). Emitted CO_2 is captured from the flue gas stream resulting from combustion. ***Conversion*** of biomass involves digestion or fermentation to produce gaseous or liquid fuels, respectively; the main one being bioethanol, which produces almost pure CO_2 during fermentation. The subsequent combustion of the biofuel or gas (methane is generated by ***anaerobic*** digestion of biomass, including household food and garden wastes) also produces CO_2 which, ***if stored*** by the end user, results in overall lower emissions reduction by BECCS (if not stored the CO_2 is returned to the atmosphere by the end user). In 2019 there were five

BECCS facilities around the world, collectively capturing approximately 1.5 million tonnes of CO_2 per year (Mt y^{-1}). BECCS is a way to avoid use of fossil fuels, in addition to its capture and storage aspects. This energy production method recycles today's CO_2, which was extracted from the atmosphere by the biomass as it grew, back to the atmosphere; in contrast to fossil fuels, which make a net increase of ancient CO_2 to today's atmosphere. The biomass feedstock can be derived from a waste material (e.g., sugarcane wastes which are widely used for bioethanol) or dedicated energy crops (e.g., fast-growing tree species) planted purely as an energy-production feedstock. At the present time, biomass feedstock supply for energy generation by burning is dominated by forest management schemes (Consoli, 2019).

When combined with capture and sequestration of CO_2 the overall BECCS process can provide a ***net reduction of CO_2 in the atmosphere***. Industry opinion of BECCS is essentially that it is the best solution to decarbonise emission-intensive industries. However, public perceptions of this technology are variable and seem to be linked to the regulatory policies by which its use is incentivised (Bellamy *et al*., 2019). Payments based on the amount of CO_2 removed from the atmosphere were approved but guarantees of higher prices for producers selling energy derived from BECCS were strongly opposed.

Enhanced weathering. Enhanced weathering ***or accelerated weathering*** refers to geoengineering approaches intended to remove CO_2 from the atmosphere by using specific natural or artificially created minerals which absorb CO_2 and transform it into other substances via chemical reactions occurring in water (https://en.wikipedia.org/wiki/Enhanced_weathering).

Ocean fertilisation has also been suggested as a CO_2 removal technique involving dumping iron filings or other nutrients (e.g., urea) into seawater to ***stimulate phytoplankton growth*** in areas that have low photosynthetic production. The idea is that the new phytoplankton will absorb atmospheric CO_2 and, when the phytoplankton die, the carbon is expected to be sequestered 'as they sink to the ocean floor'.

Over the last 30 years there have been at least 13 ocean iron fertilisation experiments. However, scientific studies have shown that the amount of carbon exported to the deep sea is either very low or undetectable because ***much of the carbon is released again via the food chain*** (https://www.geoengineeringmonitor.org/2018/05/ocean-fertilization/).

The section below briefly outlines the nature-based (or 'soft') ***alternative solutions***. We will look at each solution holistically and from a sustainable infrastructure point of view, including consideration of all capital value offered by each solution to society. Following the outlining of each solution, a comparison of the value capital offered by each will be presented.

8. 'Soft' Carbon Sequestration Solutions (Nature Based)

Soft carbon sequestration solutions include all the nature-based negative emissions technologies (NB-NETs). NB-NETs differ from 'hard' solutions mainly in terms of natural capital. The 'hard' solutions (CCUS and direct air capture in particular) lack natural capital, primarily biomimicry-of-technology functionality, and ecosystem services. These aspects are provided by the 'soft' NB-NETs. As described elsewhere (Moore *et al*., 2021a), these NB-NETs have low to medium costs (US\$100 t^{-1} CO_2 or less) and offer substantial potential for safe scale-up from current deployment.

Griscom *et al*. (2017) provide a succinct overview of ***natural climate solutions*** (NCSs), which encompass 'soft' carbon sequestration potential. According to the study, NCSs can provide over one-third of the cost-effective climate mitigation needed between now and 2030 to satisfy the IPCC's 'below 2°C model'. However, this can only be achieved via aggressive fossil fuel emissions reductions, which if achieved can allow NCSs to offer a powerful set of solutions for Paris Climate Agreement nations.

As an added natural capital benefit, 'soft' solutions help improve soil health and productivity, clean air and water and help restore and maintain biodiversity and healthy nutrient flow. They showed that most NCSs, when implemented effectively, offer additional benefits such as water filtration, flood risk reduction, improved soil health, improved habitat biodiversity, and enhanced climate resilience, and they concluded:

> "… existing knowledge … provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change…" (Griscom *et al*., 2017).

Another valuable source of detailed information is the 2019 report of the US National Academies of Sciences, Engineering, and Medicine entitled ***Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*** (NASEM, 2019). The *Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration*, which produced this report, was created to recommend a detailed research development plan for what are known as **negative emissions technologies** (NETs), which are technologies that remove and sequester CO_2 from the atmosphere with the intention of mitigating climate change. NETs have received much less attention than the 'hard' technologies, but this report concludes that:

> "… If the goals for climate and economic growth are to be achieved, negative emissions technologies will likely need to play a large role in mitigating climate change by removing ~10 Gt y^{-1} CO_2 globally by mid-century and ~20 Gt y^{-1} CO_2 globally by the end of this century."

Deploying NETs may be less expensive and less disruptive than reducing some emissions, such as a substantial portion of agricultural and land-use emissions and some transportation emissions. NETs are envisaged by this Committee to:

- use biological processes to increase carbon stocks in soils, forests, and wetlands,
- produce energy from biomass, while capturing and storing the resulting CO_2 emissions,
- use chemical processes to capture CO_2 directly from the air and then sequester it in geologic reservoirs,

- enhance geologic processes that capture CO_2 from the atmosphere and permanently bind it with rocks (quoted from NASEM, 2019).

The summary of this report lists several conclusions that outline the main thrust of the research agenda it goes on to develop. Their Conclusion 2 lists some negative emissions technologies described as ready for large-scale deployment:

- afforestation/reforestation,
- changes in forest management,
- uptake and storage by agricultural soils.

All of these involve land use and management practices such as planting trees, changes in management of existing forests, or changes in agricultural practices that enhance carbon storage in agricultural soils. This is possibly the most conventional aspect because photosynthetic carbon capture by trees and other photosynthetic organisms is widely considered to be an effective strategy to limit the rise of CO_2 concentrations in the atmosphere by sequestering carbon in the plant body. The Intergovernmental Panel on Climate Change Special Report of 2018 (Masson-Delmotte *et al*., 2019) suggested that an increase of 1 billion hectares of forest will be necessary to limit global warming to 1.5°C by 2050.

The authors of this review like trees (and other plants) and we are in favour of planting more of them, ***but they should be planted for their intrinsic ecosystem value***. There are too many negative aspects of relying on them so heavily as a way to sequester carbon from the atmosphere on the long term basis required for full and lasting benefit (Moore *et al*., 2021a).

The ***Trillion Tree Initiative*** is a World Economic Forum initiative, designed to support the UN Decade on Ecosystem Restoration 2021-2030, led by the United Nations Environment Programme (UNEP) and the Food and Agriculture Organization of the United Nations (FAO) (https://www.1t.org/). This, and the parallel programme ***Trillion Trees***, which is a joint venture between BirdLife International, Wildlife Conservation Society (WCS) and the World Wide Fund for Nature (WWF) (https://trilliontrees.org/), sometimes seem to be the only nature-centric solutions catching the attention of mainstream media.

Such reforestation practices incorporating large-scale tree-planting could reduce the atmospheric carbon pool by about 25% by capturing more than 200 Gt of carbon (Bastin *et al*., 2019). Thus, aligning with IPCC 2018 climate targets to limit global warming to 1.5 degrees above pre-industrial levels before 2050 (Masson-Delmotte *et al*., 2018). However, while tree planting in general is usually considered by the mainstream public as one of the only natural solutions to counter climate change, such large-scale restoration efforts should be carefully considered to avoid negative impacts. Large-scale forest restoration projects in China (Hua *et al*., 2018) have revealed that while monoculture tree-planting can assist in carbon sequestration goals, they do not provide the same ecosystem services as native forests do, which are more valuable and should be further protected by policy. Indeed, similar concerns about adverse impacts on carbon sequestration being caused by ‘the wrong trees in the wrong places’ have been expressed by studies of ecosystems as far apart as Chile (Heilmayr *et al*., 2020) and China (Hong *et al*., 2020).

For decades, trees have been an inspiration and a powerful symbol of change, a symbol of sustainability, representing healthy growth both within us as individuals and all around us in our environment. Trees represent life. The phrase “just plant trees” has the power of the local hippy, the nature-lover, the “greeny”, nested within its meaning. At times it is a symbol of rebellion and a simple response when faced with our greatest challenge in the present modern day, which must surely be climate change. “Just plant trees” contains within it a love for mother nature and a respect for our planet and our humanity, but unfortunately, it funnels our knowledge and action and conveys it through just that: “trees”.

Unfortunately, recent research suggests the conclusion that mass tree planting will ***harm the environment*** if not planned properly. Importantly, forests are only effective CO_2 sinks while they remain alive. Seasonally shed leaves, petals, ripe fruit, and dead wood are digested and respired to CO_2 ***in the same year*** the CO_2 was fixed from the atmosphere. And when the tree dies there are legions of animals, bacteria and, especially, fungi just waiting for the chance to digest the forest’s biomass and convert it back to atmospheric CO_2 as quickly as possible. To quote Moore *et al*. (2021a):

> “… ‘That’s life’. Of course, sustainably managed forests can be harvested to provide wood fuels as environmentally benign alternative to fossil fuels (but still returning their CO_2 to the atmosphere), or timber for buildings and furniture. There are about 60 or so indoor wood decay fungi from which you need to protect your timber buildings and furniture, including dry rot, wet rot, cellar rot, and oak rot. The longevity of the carbon pools represented by wood products derived from harvested timber depends upon their use: lifetimes may range from less than one year for fuelwood, to several decades or centuries for lumber; but still, timber is only ever ***a temporary remedy*** for the atmosphere.”

Brandão *et al*. (2013) indicate that even if the carbon storage is temporary, any carbon removal and storage from the atmosphere has the potential to mitigate climate change. However, there is firm evidence that current projections of global forest carbon sink persistence are too optimistic because the ***increased growth rates*** of trees caused by increased levels of CO_2 in the atmosphere ***may shorten the lifespan of forest trees*** (Brienen *et al*., 2020):

> “… Faster growth has a direct and negative effect on tree lifespan, independent of the environmental mechanisms driving growth rate variation. Growth increases, as recently documented across high latitude and tropical forests, are thus expected to reduce tree lifespans…” and that “… recent increases in forest carbon stocks may be **transient** due to lagged increases in mortality …” (quoted from Brienen *et al*., 2020).

So, current plans for tree planting on a massive scale are not the panaceas that many believe. Putting such plans into effect could do more harm than good (Friggens *et al*., 2020; Heilmayr *et al*., 2020; Hong *et al*., 2020; Natural Capital Committee, 2020). In addition, our current forests are suffering from the effects of the climate changes that have already occurred: forested areas are dying due to newly emerged, virulent and invasive, pests and diseases as well as drought, often amplified by more devastating wildfires (Demeude & Gadault, 2020). These threats to forest ecosystems are worldwide. We cannot rely on forests to mitigate the effects of climate change while they are dying because of it!

Despite all these negatives there remains some hope that better management of forests and their carbon stocks can help improve overall terrestrial carbon cycle management providing knowledge of the role of fungi and soil microbes in carbon cycling is implemented into ***sustainable forest management*** practices (Soudzilovskaia *et al*., 2019; Domeignoz-Horta *et al*., 2020). There is more to terrestrial plant cover than just trees, of course, but the limitation that plants only store carbon while they are alive applies to all photosynthetic organisms (including aquatic ones); wherever the plant dies, its stored carbon is returned to the atmosphere through the respiration of the animals, fungi and bacteria that digest its biomass.

In addition, there is a large amount of carbon stored in soils, and that includes peatlands and permafrost. Peatlands cover an area of about 3.7 million km^2 in the northern hemisphere, about half this being permanently frozen permafrost. These northern peatlands are estimated to store around 415 billion metric tons of carbon, which is equivalent to over 45 years of current global CO_2 emissions. Unfortunately, this is not a permanent sequestration. Global warming will cause the northern ***peatlands to become a major source of greenhouse gas emissions*** into the atmosphere (methane, carbon dioxide and nitrous oxide) (Hugelius *et al*., 2020).

Therefore, do not expect planting trees on peatland to help. Friggens *et al*. (2020) recorded a 58% reduction in soil organic carbon stocks 12 years after birch trees (*Betula pubescens*) had been planted in heather (*Calluna vulgaris*) moorland. This decline was not compensated by the gains in carbon represented in the growing trees. This was a continuation of a long term study of the effects of planting two native tree species which showed that 39 years after planting, the carbon sequestered into tree biomass did offset the carbon lost from the soil but, crucially, there was ***no overall increase*** in carbon sequestered by the ecosystem.

The UK's Office For National Statistics (ONS, 2016) estimated that in 2007 UK soils contained approximately 4 million tonnes of carbon, of which 57% was the carbon stored in peat soils, but as the majority of UK peatlands are degraded (Natural England, 2010), they are a highly significant ***source of greenhouse gas emissions***. The aim of peatland restoration must be to reduce the extent of these emissions as a contribution to the 'net zero future' (Natural Capital Committee, 2020): this report states:

> "The right tree in the right place for the right reason can bring a multitude of benefits…" but adds "the wrong trees in the wrong places can have adverse impacts on soil (including soil carbon), water flows, water quality, recreation, biodiversity and air quality."

In the UK, the Countryside Charity CPRE (originally the *Campaign to Protect Rural England*) has warned that emissions from UK peatland could cancel out all carbon reduction achieved through new and existing forests, in their August 2020 report entitled '*Net-zero virtually impossible without more ambition on peatlands*' (https://www.cpre.org.uk/).

It is also necessary to recognise that all soils incorporate carbon stocks that must be managed sensitively, especially when undertaking reforestation projects. Indeed, current carbon stocks are much larger in soils than in vegetation, particularly in non-forested ecosystems in middle and high latitudes (Table 4).

Note that the data of Table 4 are based on past routine soil surveys, estimating the ***soil organic carbon*** (SOC) pool which accounts for a soil depth of only about ***one metre***.

Table 4. Global carbon stocks in vegetation and soil carbon pools down to a depth of 1 m

Biome	Area	Global Carbon Stocks (Gt C)		
	(× 10^9 ha)	Vegetation	Soil	Total
Tropical forests	1.76	212	216	428
Temperate forests	1.04	59	100	159
Boreal forests	1.37	88	471	559
Tropical savannas	2.25	66	264	330
Temperate grasslands	1.25	9	295	304
Deserts and semi-deserts	4.55	8	191	199
Tundra	0.95	6	121	127
Wetlands	0.35	15	225	240
Croplands	1.60	3	128	131
Total	15.12	466	2011	2477

Note: There is considerable uncertainty in the numbers given, because of ambiguity of definitions of biomass, but the table still provides an overview of the magnitude of carbon stocks in terrestrial systems. Data from the 2000 IPCC Special Report: Land Use, Land-Use Change and Forestry (Watson, 2000).

Deeper soil horizons, however, may have a high capacity to sequester significant amounts of SOC because the turnover time and chemical recalcitrance of soil organic matter increases with depth. In particular, the soil organic carbon (SOC) pool is ***the only terrestrial pool storing some carbon (C) for millennia,*** and it can be deliberately enhanced by agroforestry practices. Soil disturbance, especially, must be minimised and tree species with a high root biomass to above-ground biomass ratio and/or trees that have symbiotic nitrogen-fixing root nodules (to minimise fungal-recovery of nitrogen from otherwise stabilised soil organic matter) should be planted when carbon sequestration is the objective for the agroforestry system being established.

The size of the Earth's soil organic carbon reservoir is estimated to be around 1,500 Gt C in the first metre, excluding permafrost areas (Hiederer & Köchy 2011). 58% of the chemically stabilised and 31% of the physically stabilised fractions of the soil organic carbon pool occurred in the subsoil horizons. The subsoil below the one m depth may have the potential to sequester between 760 and 1,520 Gt C (Lorenz *et al*., 2005, 2014; Lorenz *et al*., 2011).

Bossio *et al*. (2020) stated that mitigating climate change requires clean energy and the removal of atmospheric carbon, commenting that "… building soil carbon is an appealing way to increase carbon sinks and reduce emissions owing to the associated benefits to agriculture." They quantify the role of soil carbon in natural (land-based) climate solutions showing that soil carbon represents 25% of the potential for nature based solutions to the climate crisis with a total potential of 23.8 Gt of CO_2-equivalent ***per year***. 40% of which is protection of existing soil carbon and 60% is rebuilding depleted stocks. They point out that soil carbon comprises 9% of the mitigation potential of forests, 72% of that for wetlands and 47% for agriculture and grasslands. Finally, soil carbon is important to land-based efforts to prevent carbon emissions and remove atmospheric carbon dioxide and deliver ecosystem services ***in addition to*** climate mitigation.

Removing atmospheric carbon dioxide levels may be the primary objective, but to deliver additional ecosystem services in addition to this is a significant advantage of all natural biotechnological solutions. In particular, the potential role of biodiversity in helping society and nature face the linked challenges associated with biodiversity loss and climate change has received little attention but must be addressed if efforts to resolve our environmental crises are to be effective (Mori, 2020).

What this means overall is that plans for terrestrial carbon sequestration are less promising because carbon storage by plants (a) is only ever temporary; (b) because large-scale reforestation may cause more problems than it solves; and (c) because disturbing the soil, as for example, is necessary for tree planting, can release carbon back to the atmosphere from the stabilised soil organic carbon pool in deeper horizons. Plant-rich environments have much to offer for both physical and mental wellbeing of humans, and biodiverse tree planting supports general biodiversity of woodlands and forest ecosystems. But tree planting, even on a monumental scale, will not contribute to solving the crisis of global warming.

But there is one further negative impact of any of these would-be cures of the climate crisis that involve growing plants on land, and this is that such activities are in direct competition for cultivable land that might otherwise be used for growing food crops for human use. The situation we have ***today*** is that there is not enough land on Earth to support the diet recommended by authorities for the whole of the human population (Dockrill, 2018; Rizvi *et al*., 2018). Consequently, if we wish, for the sake of carbon sequestration, to implement expansive plans for restoration of peatlands and permafrost, and afforestation, and pasture rotation management, and wildlife biodiversity enhancement, we might have to set out parallel international plans to ***decide which members of the human population should be allowed to starve to death*** to make the necessary land available.

Or perhaps we should turn away from '**green carbon**' and look towards the 70% of the planet's surface that is covered in ocean for a cure for the climate crisis? '**Blue carbon**' to the rescue?

9. Coastal blue carbon

Coastal Blue Carbon, described as "… land use and management practices that increase the carbon stored in living plants or sediments…" in ***mangroves***, ***tidal marshlands***, ***seagrass beds***, and other ***tidal or salt-water wetlands*** are among the technologies considered by NASEM (2019). These approaches refer to coastal ecosystems instead of the open ocean and the report is at pains to point out that the committee's initial task statement (or 'job description') was to focus exclusively on ***near-shore coastal*** NETs despite the recognition that oceanic options for CO_2 removal and sequestration, which fall outside the scope of its task, could sequester an enormous amount of CO_2. Gattuso *et al*. (2021) conclude:

> "… Ocean-based NETs are uncertain but potentially highly effective. They have high priority for research and development …".

This is an attitude we wish to promote in this review. So much attention is given to afforestation in the conventional media that the potential of aquatic 'blue forests' and other prevalent marine biota to capture and sequester carbon in our coastal waters and the high seas is yet to be realised by the general public.

The blue carbon systems described by NASEM (2019) are usually categorised or labelled as ***shallow coastal ecosystems*** (SCEs). These include but are not limited to, mangrove forests, seagrasses, kelp and other aquatic biota that thrive in healthy blue carbon forests, including shellfish, algae and many other microbiota.

Out of all the biological carbon captured in the world, over half is captured by marine living organisms and this is why it is called ***blue carbon*** (Nellemann *et al*., 2009; Pendleton *et al*., 2012). Moreover, compared to the average decadal time-scale for terrestrial systems to hold carbon before the aforementioned release back into the atmosphere (after their death), some blue carbon ecosystems could store the carbon for timescales of hundreds of millennia (Heilweck & Moore, 2021; Moore, 2021; Moore *et al*., 2021b).

Blue carbon science is relatively young but has revealed the importance of aquatic ecosystems in the carbon balance and ecosystem services (specific examples are the monetary value of mangroves and seagrasses in ecosystem services and the monetary value of the seafood industry) but it deserves significantly increased attention (Macreadie *et al*., 2019).

These coastal vegetation ecosystems (marshes, mangroves, and seagrasses) have high rates of annual carbon sequestration as well as very large pools of previously-sequestered carbon, which is largely in their sediments, and is in danger of being released to the atmosphere if these ecosystems are degraded (Pendleton *et al*., 2012).

Table 5. Annual values of carbon deposition defined as sedimentary, carbonate, or sedimentary + carbonate per ecosystem

Ecosystem	Carbon store type	Carbon deposition per annum (g m^{-2})
Seagrass	Sedimentary	83
Saltmarsh	Sedimentary	210
Mangroves	Sedimentary	174
Maerl (coralline red algae)	Carbonate	74
Horse mussel (density 40 m^{-2})	Carbonate (+?sedimentary)	40 (+ about 360 organic matter deposition[a])
Oyster (density 75 m^{-2})	Sedimentary (+?carbonate)	50
Terrestrial forests[b]	Net sink	29

Notes: +? indicates data deficiency.

[a]Data are available on organic content of sediment deposits rather than carbon deposition.

[b]Net global sink/global forest cover.

Data from Lee *et al*. (2020)

Quite clearly, these systems deserve much more attention in the public eye, particularly because there seems to be solid experimental evidence that they are able to sequester more carbon than forest ecosystems (Table 5). Lee *et al*. (2020) tabulated annual carbon deposition estimates for a variety of ecosystems. They showed that European flat oyster beds (at a density of 75 oysters m^{-2}) in the Northern Hemisphere have the potential to deposit more carbon per square metre than terrestrial forests in the Northern Hemisphere, through biodeposition to the seabed alone. Also, oyster beds compare favourably with other shellfish habitats (Table 5).

Nellemann *et al*. (2009) state that while the "… contribution of forests in sequestering carbon is well known and is supported by relevant financial mechanisms. In contrast, the critical role of the oceans has been overlooked…" and go on to point out that oceans play a significant role in the global carbon cycle "… Not only do they represent the largest long-term sink for carbon, but they also store and redistribute CO_2. ***Some 93% of the Earth's CO_2 (40 Tt* [= 40 million Mt or 40 × 10^{12} t]*) is stored and cycled through the oceans…*" (the emphasis is ours).

Primavera *et al*. (2019) discuss the conservation and management of **mangroves**, the goods and services of these ecosystems, and factors causing mangrove loss and their restoration. Examples of large-scale mangrove reforestation can be seen in equatorial regions throughout the world and are monitored by the ***Mapping Ocean Wealth*** website (view https://oceanwealth.org/), from which we quote the following:

> "… Global statistics on mangrove extents, gains and losses developed by our partners show the global extent of mangroves in 1996 was some 142,795 km^2, but in 2016 was some 136,714 km^2.
>
> In a first ever review of mangrove degradation, we have mapped some 1389 km^2 of degraded mangrove within the latest (2016) mangrove cover map.
>
> … an expert-derived model for "restorability" has been developed based on key environmental components which influence the ease of restoration. Using this model, some 6,665 km^2 are considered highly restorable. Full restoration of the areas identified could enable:
>
> - Carbon sequestration in aboveground biomass amounting to 69 million tonnes of Carbon, equivalent of annual emissions from 25,000,000 US homes;
> - Soil carbon stocks of 296 million tonnes saved through a combination of avoided emissions and sequestration emissions equivalent to emissions from 117,000,000 US homes.
> - Addition of commercial fisheries species in mangrove waters totalling 23 trillion young-of-year finfish and 40 trillion crabs, shrimp and molluscs;
> - Coastal protection from annual flooding to hundreds of thousands of people…" (all quoted from https://oceanwealth.org/applications/mangrove-restoration/).

There are examples of blue carbon restoration projects all over the globe, even in the coldest climates such as the arctic (see ***Nordic Blue Carbon Project***'s very informative website at https://nordicbluecarbon.no/).

Seagrasses (or **eelgrasses**) are submerged vascular flowering plants, found mostly along the coastline. The ***Ocean Health Index*** website estimates that globally they cover an area of 300,000 to 600,000 km^2 (http://www.oceanhealthindex.org/). Seagrasses have declined in area by about 29% since the beginning of the twentieth century, at an annual rate of about 1.5% and faster in recent years, being replaced by mud and sandy marine 'soils' (Fourqurean *et al*. 2012).

Healthy seagrass meadows store significant amounts of carbon. Röhr *et al*. (2018) sampled *Zostera marina* eelgrass meadows, spread across eight ocean margins and 36° of latitude, measuring organic carbon stocks in their sediments; this averaged 2,721 g C m^{-2}, which they extrapolated over the top 1 m of sediment to range between 23.1 and 351.7 Mg C ha^{-1} (equivalent to 23.1 to 351.7 tonnes C ha^{-1}). Using the lowest estimate of the seagrass meadow area globally these sedimentary carbon stocks extrapolate to between 693 Mt and 10.6 Gt of carbon currently sequestered in the sediment of the world's seagrass meadows.

Kelp forests. Seaweed farming to create kelp forests is another fashionable suggestion as a means to mitigate climate change. The crop is used for biofuel production, as an agricultural fertiliser for improving soil quality and substituting for synthetic fertiliser and is included in cattle feed to lower methane emissions from cattle. Kelp are large **brown algae,** in the Order *Laminariales*, which form prominent populations of 'underwater forests' in cool seas worldwide. There are 27 genera that vary in size, morphology, life span, and habitat. Although they are large, multicellular, photosynthetic and eukaryotic organisms, they are ***not plants***; rather they are protists belonging to a group known as 'heterokonts' because when they produce motile cells (usually to reproduce) those cells have two flagella of different length and different morphology. This is a major group of eukaryotes ranging from the giant multicellular kelp to the unicellular diatoms, which are themselves a primary component of phytoplankton. Seaweed aquaculture has been described as the fastest-growing component of global food production.

Duarte *et al*. (2017) claim that the total global annual production of kelp was 27.3 million tons in 2014 and a growth rate of 8% y^{-1}, and seaweed aquaculture comprises 27% of total marine aquaculture production (although the value of the seaweed produced amounts to only 5% of the total value of aquaculture crops). The key features of seaweed farming that make it attractive include that the kelp forests provide habitat and several ecosystem services for very diverse coastal communities, which theoretically could range along 25% of the world's coastlines. Ecosystem services, apart from carbon sequestration, include climate change adaptation by damping wave energy and protecting shorelines, and by elevating pH and supplying oxygen to the waters, thereby locally reducing the effects of ocean acidification and de-oxygenation (Duarte *et al*., 2017).

Kelps exhibit a great diversity of growth forms and life strategies, with the largest fronds reaching lengths of more than 30 m with biomasses of 42 kg (Wernberg *et al*., 2019). There is controversy over the longevity of carbon sequestration by kelp forests (Hill *et al*., 2015; discussed in Duarte *et al*., 2017), and some are even described as 'perennial kelps' but this is a misnomer as the maximum life-span of **fronds** has been calculated to be one year; it is the **holdfast** that is perennial (Tussenbroek, 1989). Kelp forests face many threats and are quite dynamic and variable. As a result "… it seems almost certain that many kelp forests a few decades from now will differ substantially from what they are today…" (Wernberg *et al*., 2019). We wonder what happens to any sequestered carbon during this turnover.

Oceanic microalgae. Among the most important primary producers in our oceans are photosynthetic microalgae with chloroplasts similar to those derived from red algae in which chlorophyll is masked by the accessory carotenoid pigment fucoxanthin, giving them a brown or olive-green colour. These 'Haptophyte' algae account for about 40% of the total chlorophyll-a biomass in oceans, so they are a dominant marine primary producer in today's oceans. This has made them candidates for use in atmospheric carbon sequestration and there is a considerable literature dealing with biorefinery and other technologies applying to microalgae (Singh & Dhar, 2019).

It is assumed, as with the kelps, that carbon fixation into their biomass makes them a carbon sink. For most haptophytes this is no more realistic than it is for any other primary producer; because these organisms are at the base of all food chains, all their biomass is converted into the biomass of organisms at higher levels in the food chain.

And in that process the primary producer's biomass is metabolised and eventually respired as CO_2 that is returned to the atmosphere.

However, there is one group of haptophyte algae, called **coccolithophores**, that have played a central role in the global carbon cycle in the Earth's oceans for hundreds of millions of years. These organisms fix dissolved inorganic carbon, which all originates from the atmosphere, through both photosynthesis and **calcification**, because these single-celled algae surround themselves with microscopic plates, called **coccoliths**, made of limestone (calcite, $CaCO_3$). Coccolith $CaCO_3$ is indigestible and completely stable (until heated to over 1,000°C). "… A massive quantity of calcified cells has been sedimented throughout geological time, as seen in the White Cliffs of Dover; thus, coccolithophores contribute to sequester atmospheric CO_2 as limestone …" (Tsuji & Yoshida, 2017; and see references therein). Now, ***that's an*** **effective** ***atmospheric carbon sink*** (Moore, 2021)!

10. The ultimate Blue Carbon: the Oceans' Calcifiers

Except for the coccolithophores, all of the blue carbon atmosphere mitigators mentioned so far suffer from the same disadvantages as the plant-based terrestrial mitigation projects we have already mentioned. Namely:

- Yes, the photosynthetic organisms fix atmospheric CO_2 into their biomass; but this is only **temporary** and remains in the biomass only as long as the organism is alive.
- Photosynthetic organisms, the **primary producers**, are at the base of all food chains (photosynthetically-fixed carbon is, ultimately, the **only** metabolic carbon available on the planet).
- When the organism dies its biomass is digested and the carbon in the biomass starts its journey through metabolism until it is respired as CO_2 and returned to the atmosphere.
- Any of the biomass that escapes being respired as CO_2 has a chance to be sequestered in the ocean sediment or, on land, in the deep soil organic carbon sink. But only as long as that sink remains undisturbed.
- Organisms at the base of food chains tend to be eaten fairly rapidly. So, the biomass-CO_2 that is returned to the atmosphere today may have only been fixed from yesterday's atmosphere.
- Longer lived primary producers, from the 1-year-old fronds of ('perennial' kelp; it's the holdfast that's perennial, not the frond that makes the kelp forest) to the thousand-year-old oak tree in a terrestrial woodland, will all die eventually, and their residual biomass will be digested and returned to the atmosphere as respired CO_2.

Finally, the coccolithophores lead us to ***the limestone elephant in the room***, the one that so few people talk about except to dismiss it from consideration, but which is the central thrust of the case presented in the review you are reading now:

This is that the physiological chemistry of a few types of ocean creatures, the **calcifiers** of the coasts and open seas, (coccolithophore algae, corals, crustacea and molluscs) enables them to extract CO_2 from the atmosphere and sequester it permanently as crystalline $CaCO_3$.

Our ***case for the calcifiers*** is presented in our recent publications (Heilweck & Moore, 2021; Moore, 2020, 2021; Moore *et al*., 2021a & b) so we will not repeat it here. We ***will*** reiterate that it is the certainty and permanence of the removal of CO_2 from the atmosphere that would make a biotechnology using calcifying organisms so attractive. Even NASEM (2019) notes that ***terrestrial*** options and the few coastal blue carbon options they consider are reversible if the carbon sequestering practices are not maintained. "… Although temporary CO_2 storage will have some climatic benefit, scientific and ***economic requirements to ensure the permanence of storage within ecosystems are substantial*** …" (NASEM, 2019). Changes in policy could see afforested or reforested land cleared again and any return to intensive tillage would reverse any gains in soil carbon sequestration achieved by the afforestation. Restored coastal wetlands could be drained again for agricultural use, losing any advantage gained by the wetland restoration. Given the fact that there is insufficient agricultural land on Earth to grow food for the whole of the human population (Dockrill, 2018; Rizvi *et al*., 2018) it may become impossible in the future to avoid returning restored forests, peatland or coastal wetlands to intensive agriculture just to safeguard basic food supply. If that is done, all the benefits to the atmosphere achieved by the restorations will be lost.

We have been asked how we overcome the issue of calcification being said to be a CO_2 emitting process and not a sink. Our usual response to this question is as follows. The calcifying reaction scheme shows that two bicarbonate ions (which ultimately were derived from the atmosphere) react with Ca ions and **one** of them is precipitated as $CaCO_3$, and the other released as CO_2. So, while it is true that "precipitation of calcium carbonate is a source of carbon dioxide (CO_2)" it is illogical to claim that returning one out of two carbons to the environment is a "major way by which CO_2 is returned to the atmosphere" as some have put it to us.

To justify that claim we need to go one step further and add the consideration that there are a great many calcifying organisms in the oceans, which are all cycling through this reaction 24/7. Now, truly, this becomes a major way by which CO_2 can be returned to the atmosphere, but it must be remembered that the other one of those two carbons on the left of the reaction scheme is precipitated as $CaCO_3$. So, if calcification ***is*** said to be a major way by which CO_2 is **returned to the atmosphere** then it is ***also*** a major way by which carbon is **removed permanently from the atmosphere**.

It might be time to **start taking Blue Carbon more seriously**, and not just on coastal sites, but over the whole of the High Seas as well, changing our attitudes and policies to recognise the enormous value that marine restoration projects represent to humanity (Gordon *et al*., 2020). Remember that these authors conclude that "… [marine] restoration projects could help maintain species survival and ecosystem services, ultimately providing humanity with the breathing space to stabilize the climate …".

To achieve this, we need to rebuild marine life and Duarte *et al*. (2020) argue that this "… represents a doable Grand Challenge for humanity, an ethical obligation and a smart economic objective to achieve a sustainable future …" and in their opinion "… substantial recovery of the abundance, structure and function of marine life could be achieved by 2050, if major pressures - including climate change - are mitigated …".

The most influential report on climate change economics, policy and management is undoubtedly *The Stern Review* which was entitled *Economics of Climate Change*. Commissioned by the UK Government and released in October 2006, the report was published in January 2007 (Stern, 2007). The main findings of this report were that:

- Climate change could have very serious impacts on growth and development.
- There is still time to avoid the worst impacts of climate change, if we take strong action now.
- The costs of stabilising the climate are significant but manageable; delay would be dangerous and much more costly.
- Action on climate change is required across all countries, and it need not cap the aspirations for growth of rich or poor countries.
- A range of options exists to cut emissions; strong, deliberate policy action is required to motivate their take-up.
- Climate change demands an international response, based on a shared understanding of long-term goals and agreement on frameworks for action such as ethics and equity.

The case for avoiding the dangerous risks of climate change by emphasising low-carbon economic development and growth is even stronger now than when the Stern Review was published (and see Stern, 2015). Remember the climate records (not estimates or predictions, but ***records***) show that 2011-2020 is the warmest decade on record, with the warmest six years ever recorded all being since 2015 (WMO, 2020).The implication being that the impacts of climate change are happening ever more quickly than previously expected.

This makes action even more urgent, but action on climate change in any direction needs the application of insights from economic development and public policy and rigorous analysis of issues such as discounting, modelling the risks of unmanaged climate change, climate policy targets and estimates of the costs of mitigation. And significant obstacles remain in obtaining the international cooperation required.

The more recent Dasgupta Review (*The Economics of Biodiversity*; Dasgupta, 2021) goes even further, and to give just a flavour of the findings of this authoritative 600-page review we list here its main headlines (the stress is ours):

- Our economies, livelihoods and well-being all depend on our most precious asset: Nature.
- We have collectively failed to engage with Nature sustainably, to the extent that our demands far exceed its capacity to supply us with the goods and services we all rely on.

- Our unsustainable engagement with Nature is endangering the prosperity of current and future generations.
- At the heart of the problem lies deep-rooted, widespread institutional failure.
- The solution starts with understanding and accepting a simple truth: our economies are embedded within Nature, not external to it.
- We need to change how we think, act and measure success.
    - Ensure that our demands on Nature do not exceed its supply, and that we increase Nature's supply relative to its current level.
    - Change our measures of economic success to guide us on a more sustainable path.
    - Transform our institutions and systems – in particular our finance and education systems – to enable these changes and sustain them for future generations.
- ***Transformative change is possible – we and our descendants deserve nothing less***.

11. Sustainability Assessment of CCS Methods

Global warming is a symptom of root-cause problems in our societies, representing a significant complexity of challenges that can all be linked together as threats to humanity's life support systems. Our primary concern as a generation must be to determine how we can use our talents and techniques to engineer a future that lessens the burdens that we pass on to future generations.

A comprehensive review of 27 life cycle assessment studies of environmental impacts of carbon capture and storage (CCS) and carbon capture and utilisation (CCU) technologies was reported by Cuéllar-Franca & Azapagic (2015). They point out that an advantage of CCU over CCS is that utilisation of CO_2 is normally a profitable activity as products can be sold. Also, CO_2 has the advantage over conventional petrochemical feedstocks, of being a low cost and non-toxic renewable resource. However, current global demand for chemicals does not have the capacity to sequester enough CO_2 emissions to contribute significantly to meeting global carbon reduction targets. whilst using CO_2 for fuel production only delays its emission rather than eliminating it as needed for mitigating climate change. They go on to state:

> "… In addition, … there are other sustainability issues that must be considered before large-scale deployment of either CCS or CCU, notably environmental impacts. This is important to ensure that climate change is not mitigated at the expense of other environmental issues. It is also important that the impacts be assessed on a life cycle basis, to avoid shifting the environmental burdens from one life cycle stage to another. In an attempt to inform the debate in this field, this paper provides a comprehensive state-of-the-art review of different CCS and CCU technologies, analysing their life cycle environmental impacts based on the results of life cycle assessment (LCA) studies found in the literature" (Cuéllar-Franca & Azapagic, 2015).

Various assessment models exist to compare and evaluate the sustainability of infrastructure systems. ***Life cycle assessment*** is just that, an analysis over a complete generational life cycle (birth-to-birth) that assesses environmental impacts associated with all the stages in the life of any manufactured product (or other process) covering raw material extraction through materials processing, manufacture, distribution, and end use (with recycling/disposal where appropriate) (Wikipedia: https://en.wikipedia.org/wiki/Life-cycle_assessment).

The evaluation procedure is of significant importance in order to mitigate risks and manage uncertainties, whilst better adapting current infrastructure implementation with the future visions and plans for our societies. Proper ***sustainability*** evaluation is essential to enable better engineered futures, reducing waste of resources and reducing overburden for future societies. It is simply planning for a better future. Development and implementation of infrastructure systems that works towards the realisation of the United Nations' sustainable development goals is one way to map sustainability (UN, 2016; https://sdgs.un.org/goals).

Maack & Davidsdottir (2015) formulated an approach to project appraisal different from the conventional concentration on Cost–Benefit assessment that deals with financial flows and rate of return on investments. Their approach to evaluation is based on the theory that ***five capital value types*** support long term ***well-being***, rather than economic growth alone; as they describe it:

> "… The theory states that humans depend on the size of stocks and flows from natural, manufactured, human, social and financial capital. We describe the five capitals to illustrate the value categories and outline an approach to evaluate all these in the context of energy development …" (Maack & Davidsdottir, 2015).

They also comment that:

> "… There seems to be a disciplinary gap between the European and North American schools of thought in assessing such values. The American thought is more rooted in economic theory and stresses supply, demand and efficiency. The European one rather leans towards accounting effectively the cost of all components in human lifestyle patterns using inventories in the spirit of LCA … "
> "… Our review reveals that assessing aspects of sustainable development is highly complicated. The methods that are offered to measure each aspect are evolving.... Still, the theoretical discourse must lead to a practical implementation frame. Otherwise further economic changes will lead to changes without progress towards sustainable development … " (Maack & Davidsdottir, 2015).

More recently, Müller *et al*. (2020) published comprehensive guidelines for application of life cycle assessment (LCA) specifically to carbon capture and utilisation (CCU) technologies, with the aim of improving comparability of LCA studies through clear methodological guidance. Improved comparability is expected to help strengthen knowledge-based decision-making so that funds and time can be allocated more efficiently towards climate change mitigation and emissions control.

The sustainability of a project can be assessed by the ***four-capital model*** of sustainable development evaluation (Ekins *et al*., 2008). The concept of ***capital*** in this model derives from economics; capital stocks (or assets) provide a flow of goods and services, which contribute to human well-being. In its narrowest interpretation capital can be used to mean manufactured goods, but the concept applies also to 'intangible' forms of capital, which may affect (and even account for the bulk of) the value of an activity. Four types of capital have been defined:

- **Manufactured capital**, the traditional production assets like machines, tools, buildings, and infrastructure.
- **Natural capital** includes obvious natural resources, such as water, energy, mineral reserves; but also, assets like biodiversity, endangered species, and ecosystem services (generally, assets with a bearing on human welfare).
- **Human capital** refers to the health, well-being, and productive potential of individual people, encompassing mental and physical health, education, motivation, and work skills. Assets contributing to a happy, healthy, and productive society.
- **Social capital**, again, related to human well-being, but on a societal level, such as neighbourhood associations, civic organisations, and co-operatives. Social networks that support an efficient, cohesive society and the political and legal structures that promote stability, democracy, governmental efficiency, and social justice.

Application of the model to an activity uses **indicators of sustainability** for the assessment, and there are two main approaches to constructing indicators:

- **The framework approach**, which sets out a range of indicators intended to cover the main issues and concerns related to sustainable development.
- **The aggregation approach**, which seeks to express changes in a common unit (normally money), so that they can be aggregated.

An 'ideal' **indicator set** (aimed at evaluating the contribution of European Union structural funds to sustainable development) is listed in the appendix to Ekins *et al*. (2008).

A **three-pillar concept of sustainability**, the three pillars being social, economic, and environmental sustainability has been published by Purvis *et al*. (2019) who review and discuss historical sustainability literature, attempting to establish the origin of this three-pillar conception.

Assessing ***mariculture*** sustainability was formalised by Trujillo (2008) who developed a framework for evaluating sustainability of aquaculture production using a **Mariculture Sustainability Index** (MSI) with scores between 1 (poor) and 10 (very good). The MSI score is obtained as a combination of 13 indicators covering ecological, economic, and social aspects of the industry, and the original paper assessed sustainability in 64 countries over the 10 year period from 1994 to 2003 and involving 86 farmed species. Trujillo (2008) found the highest ranking countries for sustainable mariculture farm (a) native species, (b) of low trophic levels, (c) under non-intensive conditions, (d) for domestic consumption. The lowest ranking countries tend to farm (a) non-native species, (b) with high trophic levels, (c) under intensive conditions, (d) for export, often to countries ranking high for mariculture sustainability.

Mariculture assessment can be difficult because the required information is not always available about which species are cultivated, where they are cultivated, the methods used, local environmental impacts, sustainable yields expected for each species, location, method or a combination of these. However, Campbell *et al*. (2016) have made a global analysis of mariculture production and its sustainability over the years 1950–2030; and Neori & Nobre (2012) correlated trophic level and economics in aquaculture. They demonstrated the overall ecological efficiency, sustainability and economics of culturing carnivorous fish are improved by growing them in an ecological balance with species from low trophic levels in integrated multi-trophic aquaculture.

Studies referenced so far deal with finfish aquaculture, published studies of shellfish centre on considering only the sustainability of ***shellfish as food***. Filter-feeding bivalves (oysters, mussels, clams and scallops) are successfully farmed across the globe as a sustainable food source, and unlike all other aquaculture, and agriculture for that matter, commercially grown bivalves are the only sustainable form of human food that has ***no negative impact on the environment*** [https://www.eco-business.com/]. Indeed, bivalve molluscs offer several ecosystem services that add value to their environment beyond their food value. These additional bivalve ecosystem services in the habitat restoration context have been listed (National Research Council, 2010) as:

- Turbidity reduction by filtration.
- Biodeposition of organics containing plant nutrients.
- Induction of denitrification associated with organic deposition.
- Sequestration of carbon
- Provision of structural habitats (Reef structures) that promote diversity of fish, crustacea and other organisms.
- Habitat and shoreline stabilization.

Jacquet *et al*. (2017), with the title '*Seafood in the future: bivalves are better*' add these advantages of ***bivalve farming*** to the above list:

- Bivalves don't require feeding.
- Bivalves build food security.
- Bivalve welfare is not as serious a concern as it is for terrestrial farm animals.

They point out that as human population expanded rapidly, terrestrial farmers domesticated sheep, goats, cows, and pigs, and chickens and these animals became part of a highly industrialised food system that destroys habitat, pollutes the environment, and is unsustainable. And go on to claim:

> "… Aquaculture - the farming of aquatic animals and plants for food - is the fastest growing food production system in the world. But it is growing in the wrong way. We are farming carnivores, like salmon, that need us to catch additional fish to feed them, which is putting additional pressure on wild ecosystems. We are also completely ignoring welfare concerns.

If done correctly, aquaculture could provide sustenance for our growing planet as well as reduce overfishing. But if we want to avoid repeating the same mistakes, we need to make changes now, including changing our diets generally to include more plants and fewer animals, and [particularly] eating more bivalves - oysters, mussels, and clams - instead of fish, shrimps, and octopus …" (Jacquet *et al*., 2017).

In parallel to this study, Hilborn *et al*. (2018) examined the environmental cost of foods sourced from animals. They reviewed 148 assessments of food production from livestock, aquaculture, and capture fisheries, measuring four metrics of environmental impact (energy use, greenhouse-gas emissions, release of nutrients, and acidifying compounds), standardising these per unit of protein production. They found that the lowest impact forms of animal protein originated from species that feed naturally in the ocean and that can be harvested with low fuel requirements. Specifically, the ***lowest impact production methods*** were small pelagic fisheries and ***mollusc aquaculture***, whereas the highest impact production methods were beef production and catfish aquaculture (Hilborn *et al*., 2018).

If aquaculture is to meet the growing demands for food around the world, its future will hinge on sustainable and ethical practices being used by the industry and a more consistent regulatory regime (Dumbauld *et al*., 2009). In terms of potential, Costello *et al*. (2020) have examined the main food-producing sectors of the ocean, wild fisheries, finfish mariculture and bivalve mariculture, to estimate 'sustainable supply curves' that account for ecological, economic, regulatory and technological constraints for an overall estimate of future seafood production. Finding:

"… that under our estimated demand shifts and supply scenarios (which account for policy reform and technology improvements), edible food from the sea could increase by 21-44 million tonnes by 2050, a 36–74% increase compared to current yields. This represents 12-25% of the estimated increase in all meat needed to feed 9.8 billion people by 2050…" Costello *et al*. (2020).

12. Conclusions

There is no doubt that the concept, or paradigm, '***shellfish as food***' provides us with a food source that is widely accepted as a healthy and nutritious meat, and a production industry that is productive, sustainable, ethical and environmentally-friendly.

But that's not how ***we*** want this branch of aquaculture to be judged, because we want to **change the paradigm** to '***shellfish for carbon sequestration***'. Changing the paradigm means placing the **value** of the exercise of shellfish cultivation onto the **production of shell**, taking the food value of the animal protein as ***one of the several ecosystem services*** that bivalve molluscs supply (listed above).

Our claim is that cultivation of coccolithophores, corals, crustacea and molluscs on a massive scale would make a massive and continued ameliorative contribution to climate change on this planet; potentially achieving the UN's Sustainable Development Goal 14 (***to conserve and sustainably use the oceans, seas and marine resources for sustainable development***) (https://sdgs.un.org/goals).

That being the case the comparison that matters to us is not that between aquaculture and agriculture but ***the comparison between the aquaculture of calcifiers and industrial methods of carbon dioxide capture, utilisation and storage***. Unfortunately, there is a dearth of data bearing on 'shellfish for carbon sequestration'; too little for an easy attempt at a formal life cycle assessment/sustainability assessment, but we can bring a few pertinent points to attention. Firstly, Turolla *et al*. (2020) have carried out a life cycle assessment of Manila Clam (*Ruditapes philippinarum*) farming in a lagoon in the Po River Delta and shown it to be a fully sustainable aquaculture practice. Indeed, they found that annual production of one tonne of fresh ready-to-sell clams sequestered in their shells 444.55 kg of CO_2, 1.54 kg of nitrogen and 0.31 kg of phosphorus per year.

This study brings home the fact that if you create an ***industrial*** carbon dioxide capture, utilisation and storage facility, that's what you get. Captured CO_2; nothing else. But secondly, if you create a ***bivalve mollusc farming enterprise***, which is a nature-based negative emissions technology (NB-NET), then half the mass of the animals you cultivate is comprised of shell in which atmospheric CO_2 is captured and stored, permanently. But there's more. The other half of the animal's mass is meat that you can sell as a return on your initial investment. And while the animals were growing, they were performing all those other ecosystem services mentioned above (filtration, biodeposition, denitrification, reef building, enhanced biodiversity, shoreline stabilisation and wave management). How much value do you put on all that?

In terms of actual costs in monetary terms, Avdelas *et al*. (2020) provide a production cost (and farm gate sale price) for mussels produced by four different methods, averaged across eight EU countries and across the years 2010 to 2016 (tabulated in Moore *et al*., 2021b). These authors showed that the overall average production cost of mussels in the EU over those years was 0.87 € kg^{-1} (for a farm gate price of 1.08 € kg^{-1}). Other useful data from the same source are:

- The total number of enterprises reporting was 2,720.
- The grand average value of assets per enterprise = approximately €700,000.
- The grand average turnover per enterprise = approximately €384,000.
- From these data we can make these extrapolations:
- An average production cost of mussels of 0.87 € kg^{-1} is equivalent to 870 € t^{-1}.
- One tonne of fresh mussels has a farm gate value of 1,080 €.
- One tonne of fresh mussels is equivalent to 0.5 t of shell.
- The molar mass of CaCO3 = 100.0869 g; the molar mass of CO_2 = 44.01 g.
- Assuming the shell is made entirely of $CaCO_3$, 0.5 t of shell is equivalent to 0.5 t × 44/100 = 0.22 t CO_2.

This 0.22 t CO_2 cost 870 € to be converted to a permanent sink ***but*** was accompanied by highly nutritious mussel meat with a sales value of 1,080 €. And all this was achieved with a commercial cultivation process that has no negative impact on the environment but offers several highly beneficial ecosystem services. ***We believe that this makes mussel farming, and by default other bivalve mollusc farming enterprises, viable alternatives to all the CCUS industrial technologies*** illustrated in Tables 2 and 3, above.

13. The Action Plan

Our suggestions for a realistic action plan would fall into three levels of activity:

- Immediate activity.
- Infrastructural activity designed to change the paradigm.

Immediate activity (assuming global funding and programme management are both in place)

- As the shellfish cultivation industry is the only industry on the planet that can expand without damaging the atmosphere, we want shellfish producers to greatly expand their production specifically to generate more shell.
  - Central funding and management (a development foundation?) should be available to invest cash *immediately* in every existing aquaculture enterprise with the aim of doubling their production each season for the next five to ten seasons.
  - Central funding should guarantee farm-gate prices as the markets react and adapt to successively greater production volumes.
- From the project launch date, the ability of shellfish to sequester carbon permanently should be used in promotional and advertising materials at all levels of the shellfish food supply chain to encourage enhanced sales ['*Eat more shellfish. SAVE the atmosphere*'].
- Carbon offsetting programmes, those used by the general public to offset the carbon emissions of their transport and other domestic activities, should include projects to fund shellfish cultivation because of its ability to offer a permanent removal of atmospheric carbon. There is a wide variety of potential projects, ranging from support for developing/expanding local subsistence fisheries as a means to employ and feed communities in need, through to supplementing the funding of local aquaculture programmes to enable them to expand their activities continually for several to many years.
- Primary CO_2 emitter industries might be encouraged to ***sponsor*** a different kind of help to balance their carbon footprints by funding the larger scale infrastructural activities which are anticipated, which include industrial scale installations offshore and ocean-going factory ships. The high-energy industries that most need to compensate their heavy carbon footprints have all the necessary skills and experience to take such large-scale efforts forward.
- Central governments should be persuaded and encouraged to fund shellfish cultivation to sequester atmospheric carbon as a contribution to their carbon neutrality goals. As well as making significant financial input to the projects most appropriate to them, their responsibilities could include political, legal and administrative facilitation of the anticipated projects.

14. Waste shells?

If mollusc aquaculture is to play an increasingly significant role in the global provision of protein foods and feed, then it can be expected that there will be a diversification of mollusc products, with more sold in processed form, where shells are removed during processing. In such a scenario, ***shell waste valorisation*** will be of increasing concern. In areas of high shellfish production, such as China, Europe and the Americas, shell waste is already an issue, with shell dumps providing an unsightly and odorous nuisance. This is completely unjustified because far from being a nuisance waste product shellfish shells are an environmentally and economically valuable commodity. By far the best thing to do with waste shells is return them to the seabed where the scraps of flesh that remain can feed scavengers and detritus-feeders and the shells contribute to reef formation. On the other hand, uses for waste shells that have been published include:

- Calcium supplementation in poultry farming.
- Acidity regulation in hobbyist aquarium systems.
- Use of crushed mollusc shells as a replacement for more commonly used mined limestone for addition to agricultural land to adjust soil pH and/or drainage.
- For use in paper whitening.
- As an eco-friendly road de-icer.
- Calcination of waste shells produces quicklime (CaO) which also has many uses, most notably as far as release of fossil carbon to the atmosphere is concerned, in cement manufacture.

15. Infrastructural activity designed to change the paradigm

This phase assumes that (a) an administrative, legal and political secretariat is in place. This could be an authority formed under the United Nations Convention on the Law of the Sea (UNCLOS) which will fund, regulate, supervise and, where necessary, impose, activities aimed at sustainable atmosphere amelioration in both coastal and international waters. Let's call it ***The Ocean Decade Commission***; (b) Central government start-up funding and major energy-industry sponsorship-funds are secured. (c) All activities listed under 'Immediate activity', above, have been initiated.

We expect the ***Ocean Decade Commission*** to fund developmental research into high-technology programmes. Biotechnological research on aquaculture is well established around the world but we need to co-ordinate this varied activity towards the common goal of extracting CO_2 from the atmosphere and sequestering it permanently as crystalline $CaCO_3$.

- To provide the calcium carbonate for use as a feedstock for cement production, replacing the fossil limestone currently used to make quicklime, we need to exploit fully the potential for cultivation of coccolithophore algae on large scales:
    - in giant illuminated fermenters;
    - in 'rice-paddy-like' terraces flooded with flowing seawater.

- Coccolithophore cellular biomass will also provide lipids and biofuels to replace fossil fuel usage, as well as other bioactive substances with potential pharmaceutical uses.
- Genetically-manipulated coccolithophores could provide tailor-made coccoliths for devices in the nanotechnology industries.
- We need to fund research programmes specifically to develop shellfish cultivation aimed primarily at farming shells (taking any food extracted as a by-product at a guaranteed price):
- We need to adapt existing aquaculture farming methods to a wider range of sites and locations, for example: a mussel farm or other bivalve farm on every offshore wind turbine, every oil and gas rig, every pier, wharf and jetty, every breakwater or harbour wall. This to include standardising methods of creating clam gardens and bivalve shell-reefs as a contribution to shore protection and wave-calming measures. In fact, bivalve farming wherever possible, at low risk and low effort, taking any food extracted as a by-product at a guaranteed price.
- We need to develop new aquaculture farming methods to establish new organisms and new methods to enhance incorporation of atmospheric carbon into shells.

Specific Recommendations

16. Seamount Installations & Factory Ships

The **largest installations** we wish to build are factory rigs, either floating above 1000 metres deep anchorages (or with dynamic positioning) or fixed to the flat tops of seamounts (guyots or table mounts) that rise close to the surface. These are extinct volcanoes rising up from the seafloor, sometimes almost to the surface, perfectly suited to support an infrastructure on its top, with any necessary pipework along its slopes. For the first such international installation we have located a suitable guyot in the Vitória-Trindade Chain, which is called Davis Bank, which is located off the central coast of Brazil. Starting 175 km off the coast of Espírito Santo State and extending for 950 km eastward, the seamounts of this chain are disposed almost linearly at 20° and 21°S. There are many other seamounts in the world's oceans that we hope would be utilised once the value of the operation to the atmosphere has been demonstrated.

The **primary function** of these factory rigs will be to provide the infrastructure necessary for massive-scale cultivation of mussels on long lines. Current mussel farms based on this method are yielding 150 to 300 metric tonne of prime mussels, per hectare per year. To put these figures into perspective, beef production is only around 0.340 tonne per hectare per year, almost a thousand times less. We can reasonably expect production of between 3 to 6 million tonne of mussel flesh in a square of 90,000 ha, like the flat top of Davis Bank. The seamount installations will be equipped with:

- The manufacturing facilities to establish, maintain and harvest 90,000 ha of long line mussel farm.

- The mariculture facilities for mussel hatcheries/nurseries, macroalgae cultivation and distribution (for the kelp forests), zooplankton (copepod) nurseries, and coccolithophore cultivation.
- Pipe laying equipment for the illuminated perpetual salt fountains that will be created around the seamount.
- Industrial equipment for processing harvested mussels to make aquafeed from the mussel flesh.
- Equipment for the return of waste mussel shells to the seamount top and sides (some of this will be pre-attached with mussel spat to establish shell reefs around and across the seamount.
- Wind (and possibly water) turbines for renewable energy generation to supplement a geothermal energy power plant.

The **purpose of these massive mussel farming installations** is to provide mussel meat intended as an ***aquafeed***, for fish farms elsewhere, as a replacement for the fishmeal that is currently derived from capture fishing of forage fish.

As fish farming expands to feed the growing human population, increasing quantities of wild captured forage fish are necessary to feed the farmed fish but forage fish catches are already declining. Current attempts to feed farmed carnivorous marine fish with fishmeal substitutes from terrestrial agricultural resources are fundamentally flawed because it is illogical to use scarce agricultural land to feed a marine resource. A 'fishmeal' produced from mussel meat would be a natural and well balanced diet for farmed fish. The expected production capacity mentioned above (3 to 6 million tonne of mussel flesh in a square of 90,000 ha) can be compared to the world's largest capture fishery dedicated to the production of fishmeal which is currently the ±5.5 million tonne of anchovies caught in Peruvian waters. This kind of activity, occurring in all oceans, is environmentally destructive because these low trophic fish species are the subsistence food for around a billion people who live in coastal communities, not to mention food chains involving higher trophic animals, all of which depend on a healthy marine environment which is currently being jeopardised by overfishing.

Our concept is that as uncontrolled harvesting of forage fish as fish food is not sustainable, we need to establish extensive mussel farms as an alternative source of nutritious aquafeed for future generations of fish farms, especially in developing countries where the essential development of aquaculture is delayed by the lack of aquafeed. In addition, although the planned mussel production by seamount installation is centred on harvesting mussel meat, it also represents a sequestration programme for atmospheric carbon on a massive scale. If, say, the Davis Bank installation produces 200 tonne of mussels on long lines per hectare per year (a modest production average), about 50% of that harvest will be shell, representing 100 tonne of calcium carbonate. Calcium carbonate contains 12% by mass of carbon. Thus, 12 tonne of carbon per hectare per year, would be permanently removed from the atmosphere each year. This is equivalent to about **1.1 million** t y^{-1} across a fully-operational 90,000 ha seamount bivalve farm.

It is difficult to compare this performance with the highly varied terrestrial data "… due to the inconsistent use of terms, geographic scope, assumptions, programme definitions, and methods. For example, there are at least three distinct definitions for a 'ton of carbon'…" (Richards & Stokes, 2004). We calculate the range of estimates to be between 0.27 and 9.55 tonnes of carbon per hectare per year, with an estimate of about 4 t ha^{-1} y^{-1} being a fair average (Richards & Stokes, 2004; Toochi, 2018; Le Quéré *et al*., 2018; Pugh *et al*., 2019). Comparing with this 'fair average' the mussel farm sequesters three times as much carbon as terrestrial ecosystems retain. Though, of course, ***mussel shell sequestration is an immediate permanent removal from the atmosphere***, whereas ***terrestrial ecosystems retain their carbon sinks only transiently***, while the plants are alive and growing.

We also plan that the seamount installations will create small biodegradable floating devices, spawned with bivalve mollusc larvae, to be released from the facility into the passing Brazil current towards the South Atlantic gyre. There is no intention to harvest these, but to let them sink when the shells are heavy enough. This is a highly scalable simple technology to create a self-replicating carbon sink.

A final point is that the seamount installations are planned to be Integrated Multi-Trophic Aquaculture (IMTA) facilities, where the waste products of one species are recycled as feed for others. Mussel faeces cause pollution problems in most of today's monoculture farm locations. To avoid this, the soluble nutrients in faeces can be assimilated by macroalgae ('kelp forests'), and the solids can be assimilated by scavengers and detritus feeders on the sea bottom. IMTA establishes greatly improved biodiversity so that the 'mussel farm' becomes a self-sustaining ecological community or biotope/habitat.

17. Factory ships

More mobile versions of the seamount installations will be a fleet of factory ships intended only to enhance shell production. These will be equipped with bivalve hatcheries and production facilities for biodegradable floatation devices that will be released, already spawned with fixed juvenile bivalve molluscs, into ocean currents and ocean gyres. There is no intention to harvest these self-replicating carbon sinks. In addition, the factory ships will be equipped with bioreactors to cultivate coccolithophore algae (derived from waters local to their operating zones) that will be used to establish and maintain extensive coccolithophore blooms in the open ocean well away from shipping lanes and fishing areas.

- Coccolithophore blooms produce the volatile gas dimethyl sulfide (DMS), which promotes cloud formation above the bloom. So, here is potential to stimulate formation of clouds that reflect solar radiation, which cools the ocean by altering the radiative energy budget, consequently, reduces coccolithophore activity, thereby reducing levels of DMS in a classic, self-regulating feedback loop.

18. Coral reef restoration

For 40 years or more a wide range of academics and agencies have studied the decline of stocks of giant clams and their coral reef habitats due to commercial over-fishing, climate change and growth in demand for aquarium supplies and recreational (tourist) SCUBA fishing. Numerous well tested techniques and protocols exist that are able, within a reasonable time scale, to restore the biodiversity of coral reef systems in the wild to something close to normality. These include growth and reattachment of reef-building corals, coupled with distribution of captive bred, adult giant clam restorations, in which the giant clams share the role of ecosystem engineers with the corals, building the reef framework. Unfortunately, local efforts to implement these conservation schemes have in general been only partially successful for a mixture of reasons, among which are:

- Limited time and limited funding both contributing to limited scale of the operations.
- Conflicting demands between conservationists and local communities.
- Conflicting politics between local, regional, and even national and international administrations.
- The high costs and lengths of time required to produce "seed" clams have been problems for many operations.
- Lack of consistently committed involvement of local communities in the projects. In some cases, projects were not matched to what the local community needed or wanted.
- Poor survey and reporting protocols, together with poor funding for monitoring, have limited assessment of some reintroduction and restocking programmes even to the point of failing to report successful results.

We would expect the proposed ***Ocean Decade Commission*** to intervene in these fragmented activities to unify the operations, supply generous funding for their expansion, and, probably most important, provide an over-arching secretariat offering consistent transnational activity over several decades and across the Indian and Pacific Oceans and into the South China Sea.

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