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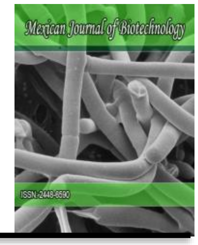

REVIEW ARTICLE

Saving the planet with appropriate biotechnology: 1. Diagnosing the problems

Salvando el planeta con biotecnología apropiada: 1. Diagnóstico de los problemas

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ABSTRACT

We give a plain language guide to the Earth's carbon cycle by briefly summarising the observations and origins of increased levels of greenhouse gases, mainly CO_2 but including CH_4 and N_2O, in our atmosphere. The only tenable explanation for our atmosphere's present state is that it is the consequence of mankind's excessive use of fossil fuels since the Industrial Revolution onwards. We deal with the arguments that deny the truth of this, then illustrate the Earth's global carbon cycle, which was almost exactly in equilibrium for several thousand years while humans were evolving, before industrial humans intervened. We describe how the excess greenhouse gas emissions are projected to change the global climate over this century and beyond and discuss 'dangerous anthropogenic interference' (DAI), 'reasons for concern' (RFCs) and climate tipping points. Finally, we give 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. This review concludes with our basic message, which is that cultivation of aquatic calcifiers (coccolithophore algae, corals, crustacea and molluscs) offers ***the only effective and permanent carbon sequestration strategy***.

Keywords: aquaculture, atmosphere remediation, bivalve farm, carbon dioxide, global warming, habitat restoration.

RESUMEN

En este documento describimos con lenguaje sencillo el ciclo del carbono de la Tierra resumiendo brevemente las observaciones y el origen del aumento de los niveles de gases de efecto invernadero, principalmente CO_2 pero incluyendo CH_4 y N_2O, en nuestra atmósfera. La única explicación sostenible para el estado actual de nuestra atmósfera es que esto es debido al uso excesivo de combustibles fósiles por parte de la humanidad a partir de la Revolución Industrial y hasta hoy día. Nos ocupamos sobre los argumentos que niegan la verdad sobre esta situación, luego ilustramos el ciclo global del carbono de la Tierra, que estuvo casi exactamente en equilibrio durante varios miles de años mientras los humanos evolucionaban, antes del desarrollo industrial. Describimos cómo el exceso de emisiones de gases de efecto invernadero cambiará el clima mundial a lo largo de este siglo y en el futuro y discutimos la "interferencia antropogénica peligrosa" (DAI), las "razones de preocupación" (RFC) y los puntos de inflexión climático. Por último, describimos de manera breve las diversas soluciones mejoradas de gestión, ingeniería y clima natural que plantean aumentar el almacenamiento de carbono y/o evitar las emisiones de gases de efecto invernadero en bosques, humedales, pastizales, tierras agrícolas e industria. Esta revisión concluye con nuestro mensaje básico, que es que el cultivo de calcificadores acuáticos (algas cocolitóforos, corales, crustáceos y moluscos) ofrece ***la única estrategia de secuestro de carbono eficaz y permanente.***

Palabras clave: acuicultura, remediación de la atmósfera, cultivo de bivalvo, dióxido de carbono, calentamiento global, restauración del hábitat.

1. A plain language guide to the Earth's carbon cycle

The birth of the Industrial Revolution is marked by the invention of the first practical coal fired steam engine by Thomas Newcomen in 1712; his 'Atmospheric Steam Pump Engine', was installed at a coalmine at Dudley Castle in Staffordshire, England; working day and night the Engine raised 120 gallons of water every minute from a depth of 156 feet.

Newcomen engines were expensive, rugged and reliable but were extremely inefficient. Nevertheless, by the time Newcomen died on 5 August 1729 there were at least 100 of his engines in Britain and across Europe.

In 1764, James Watt was commissioned to repair a Newcomen steam engine and found ways to make it much more efficient. Five years later, Watt was granted his first British patent for the unique design of his new steam engine; this was the design that set the world in motion with steam powered railway locomotives, steam ships and power for the textile mills that brought the Industrial Revolution into full activity in the 1760s. By the turn of the century in 1800, about 10 million tons of coal had already been mined, and burned, in Britain (see Table 1).

In the 19th century, and for many years subsequently, coal was king, steam power its agent and the iron foundry the maker of industry in Britain and, increasingly, around the world.

This is when appreciable amounts of carbon dioxide (CO_2) began to be added to the atmosphere through the combustion of ***fossil*** fuels (coal, oil and natural gas). The rate of combustion has continually increased with the passing of time, so that, by 2019, global carbon emissions from fossil fuels (and including cement production) reached an estimated mass of CO_2 of 36.8 Gt (= gigatonne, see Table 1).

Table 1. Explanation of some units used in atmosphere science

Terminology. Is a mass weighing a **ton**, or is it a **tonne**, or a **long ton**, or even a **short ton**?	
The British **Imperial ton**, also known as the Long Ton or Displacement Ton, is the name for the unit called 'the ton' in the avoirdupois system of weight measurements, as standardised in the thirteenth century to be equal to 2,240 pounds. The UK adopted the metric system in 1985 and most Commonwealth countries followed British practice.	= 1,016.0469088 kg
The **short ton** is commonly used in the United States and was formalised in 1832 to be equivalent to 2,000 pounds. In the US it is known simply as a common ton.	= 907.18474 kg
In the metric system the mass of one cubic metre of pure water at 4°C is specified as being 1,000 kg, and is called the **tonne** (referred to as metric ton in the US). A tonne is equivalent to 2,204.6 pounds.	= 1,000 kg
The International Bureau of Weights and Measures adopted the symbol 't' for the tonne (it is a **symbol**, not an abbreviation). You will encounter several ways of defining the very large masses dealt with in atmospheric and geophysical sciences; a few equivalencies are shown below.	
1,000 t (1 × 10^3 t) = 1 kt (kilotonne)	= 1 Gg (gigagram) or 10^9 g
1 million t (1 × 10^6 t) = 1 Mt (megatonne)	= 1 Tg (teragram) or 10^{12} g
1 billion t (1 × 10^9 t) = 1 Gt (gigatonne)	= 1 Pg (petagram) or 10^{15} g
You will also encounter very low concentrations of materials, in the atmosphere and elsewhere, expressed in the units 'ppm' (parts per million) and 'ppb' (parts per billion). These are ratios that describe how much of substance X is present in mixture M by expressing it in the form '10 parts of X in one million parts of M' (which would be written simply as '10 ppm'). This saves writing strings of zeros because 10 ppm = 0.001%, or 0.00001 as a fraction of one. Obviously, 10 ppb = 0.01 ppm = 0.000001% = 0.00000001%. These ratios may refer to the relative **volumes** of gases or liquids (usually written as 'ppmv', meaning 'parts per million by volume'); or **weights** (masses) of components of a dry mix (usually written as 'ppmw', meaning 'parts per million by weight'); or **both**, as for example, when a solid material is added to a solution (usually written as 'ppm w/v', meaning 'parts per million, weight into volume'). This last one is particularly convenient for making up dilute chemical solutions because 'one milligram of dry substance per litre of solution' (1 mg l^{-1}) = 1 ppm.	

The last ice age ended about 12,000 years ago and the period since then (called the **Holocene**) has featured relative stability in both climate and atmospheric gas concentrations over most of that time. The compositions of ancient atmospheres are obtained from ice and still frozen bubbles of gas in ice cores removed from the polar ice sheets of the Arctic and Antarctic or high mountain glaciers. Glacial ice is formed from the gradual accumulation of annual layers of snow, so the upper layers are the most recent and layers are successively older the deeper you go. A really deep-drilled ice core can contain layers of ice formed thousands of years ago that has remained frozen and undisturbed until the core was cut. Core drilling at Vostok station in East Antarctica extended the ice record of atmospheric composition and climate over the past four glacial–interglacial cycles and revealed that atmospheric levels of the two important greenhouse gases, CO_2 and methane, of the present-day have not been experienced by the atmosphere at any time during the past 420,000 years (Petit *et al*., 1999).

Other ice core data have revealed that levels of CO_2 (at about 280 ppm by volume) and CH_4 (at about 650 ppb by volume) in the atmosphere, as well as another greenhouse gas, nitrous oxide (N_2O), have been relatively constant for the past two thousand years (Fig. 1). As Fig. 1 shows, levels of all three gases started to increase rapidly about 200 years ago, and the increases in these three greenhouse gases are the primary cause of the warming of the Earth's averaged temperature by more than 1°C over the past century. Importantly, the ***rate*** of increase of atmospheric CO_2 over the past 70 years is nearly 100 times greater than that at the end of the last ice age. ***Such abrupt changes in the atmospheric levels of*** CO_2 ***have never before been seen*** (Fig. 2) and must be caused by human activities (that is, they are **anthropogenic**).

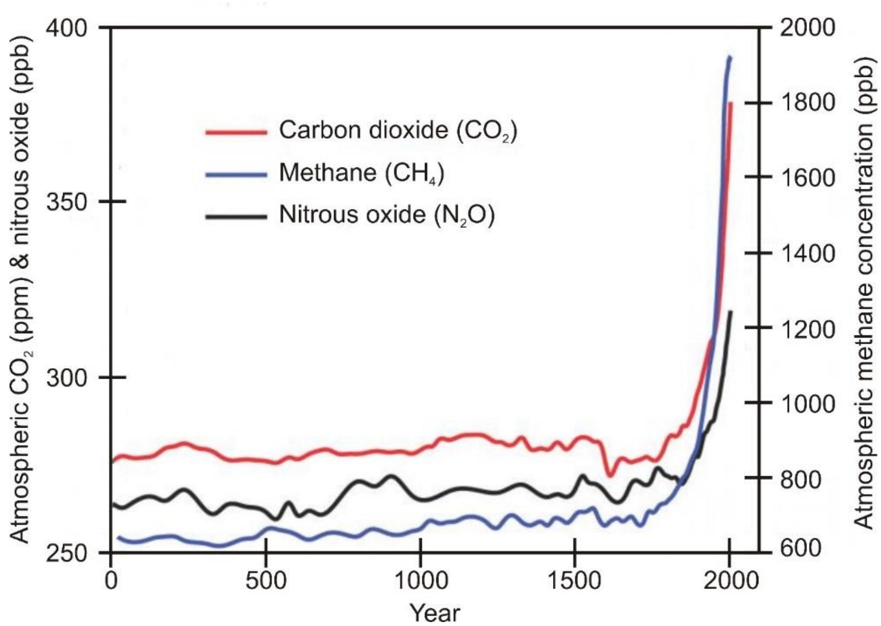

Fig. 1. Atmospheric concentrations of carbon dioxide, methane, and nitrous oxide between the years zero AD and 2000 AD. Data derived from the *IPCC Report AR4* (2007); Forster *et al*., 2007. Figure redrawn after a graphic from PennState College of Earth and Mineral Sciences, METEO 300 *Fundamentals of Atmospheric Science* by William H. Brune (2020) [https://www.e-education.psu.edu/meteo300/node/606].

Ice core data reveal other significant changes in the atmosphere during the last 200 years or so, particularly in the Northern Hemisphere. For example, the ice itself reveals increases in the amounts of nitrate and sulfate, which, like the greenhouse gases, are also produced ultimately from the combustion of fossil fuels. These constituents are the key components of acid rain and, indeed, data from the same ice cores also reveal an increase in acidity (Geng *et al*., 2014).

William H. Brune (Distinguished Professor of Meteorology, PennState College of Earth and Mineral Sciences), in his 2020 online course METEO 300: *Fundamentals of Atmospheric Science* website [https://www.e-education.psu.edu/meteo300/node/606] describes the situation this way: "… As fossil fuel emissions have increased over recent decades, so has the growth rate of atmospheric CO_2, as indicated by the concave-upward curvature in Fig. 1. The growth rate has approximately doubled from about 1 ppmv per year in the 1960s to about 2 ppmv per year in the 2000s (Fig. 2; Table 2). According to the Global Carbon Project [https://www.globalcarbonproject.org/], 86% of the anthropogenic CO_2 emissions during 2009–2018 were from fossil fuel burning and 14% were from land-use change (e.g., deforestation).

However, CO_2 injected to the atmosphere from human activity does not stay there. 44% of the emissions from human activity during 2009–2018 accumulated in the atmosphere, 29% were absorbed by terrestrial ecosystems, 23% were absorbed by the ocean, and 4% is unaccounted for. Superimposed on the accelerating trend over the past few decades is an annual cycle in which CO_2 declines during Northern Hemisphere summer and rises during most of the rest of the year. This cycle reflects photosynthesis (an atmospheric CO_2 sink) and respiration (an atmospheric CO_2 source) of terrestrial ecosystems in the Northern Hemisphere, where most land is present. Note that the current increase to above 400 ppm now extends well above any other time in, at least, the past 800,000 years when CO_2 varied only between about 180 and 280 ppm by volume …" (W.H. Brune, 2020; https://www.e-education.psu.edu/).

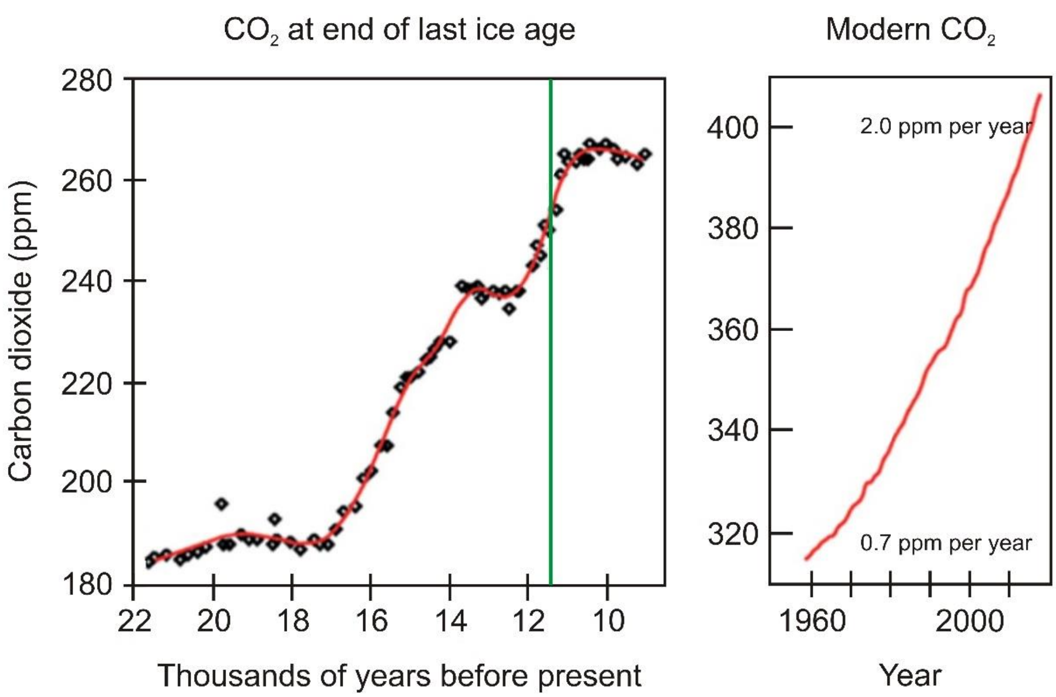

Fig. 2. Atmospheric content of CO_2 since the end of the last ice age. The figure on the left shows the CO_2 atmospheric concentration (in ppm) from the end of the last ice age to the present day. The figure on the right shows the atmospheric CO_2 content over the most recent 60 years. The vertical green line on the lefthand figure corresponds, as closely as can be achieved at this scale, to a period of 60 years similar to that depicted in the righthand figure for modern times. This serves to show that the tremendously rapid rise in atmospheric CO_2 concentration we are experiencing in our lifetimes is totally unprecedented in the last 22,000-year-history of planet Earth. Redrawn after a figure in the World Meteorological Organization's *WMO Greenhouse Gas Bulletin,* issue No. 13 (2017) [https://ane4bf-datap1.s3-eu-west-1.amazonaws.com/wmocms/s3fs-public/ckeditor/files/GHG_Bulletin_13_EN_final_1_1.pdf].

No natural cause for these concentration increases has been found, instead these unnaturally rapid changes in the composition of the atmosphere over the past several decades primarily reflect changes in human activity. These include enhanced deforestation and agriculture, but the changing atmosphere is mainly caused by the burning of fossil fuels; the so-called 'fossil fuel emissions' resulting from using coal, oil and natural gas to release their energy content for our transport, industrial and domestic activities (Table 2 lists some reliable information sources).

Although 'an atmospheric hypothesis' of the Earth's glacial periods possibly being due to the concentration of CO_2 in the atmosphere was framed by Chamberlin (1899), it was the first Swedish Nobel laureate, the physical chemist, Svante August Arrhenius, who made the earliest quantified estimate of the contribution of CO_2 to the greenhouse effect by deduction from observational data. He was also the first to speculate about whether variations in atmospheric concentration of CO_2 might contribute to long-term variations in climate (Arrhenius, 1896). This notion had a chequered history for a while because the role of water vapour in absorption of infrared radiation in the lower atmosphere was given more prominence.

Table 2. URLs and hyperlinks to other reliable sources of information

The Carbon Cycle at NASA's Earth Observatory at this URL: [http://earthobservatory.nasa.gov/Features/CarbonCycle/?src=eoa-features].	CLICK HERE
Download the US DOE Report of 2008, *Carbon Cycling and Biosequestration*: *Report from the March 2008 Workshop*, DOE/SC-108, U.S. Department of Energy Office of Science; free download from [https://genomicscience.energy.gov/carboncycle/report/]	CLICK HERE
Earth System Research Laboratories' Global Monitoring Laboratory (U.S. Department of Commerce, National Oceanic & Atmospheric Administration) [https://www.esrl.noaa.gov/gmd/outreach/behind_the_scenes/gases.html]	CLICK HERE
RealClimate is a commentary site on climate science by working climate scientists for the interested public and journalists [http://www.realclimate.org/index.php/archives/2018/01/the-global-co2-rise-the-facts-exxon-and-the-favorite-denial-tricks/]	CLICK HERE
The Global Carbon Project (GCP) integrates knowledge of greenhouse gases for human activities and the Earth system [https://www.globalcarbonproject.org/]	CLICK HERE
World Meteorological Organization WMO Greenhouse Gas Bulletin. See issue No. 13 of 30 October 2017 [https://ane4bf-datap1.s3-eu-west-1.amazonaws.com/wmocms/s3fs-public/ckeditor/files/GHG_Bulletin_13_EN_final_1_1.pdf]	CLICK HERE
Carbon Dioxide Measurements of the Scripps Institution of Oceanography CO_2 Program [https://scrippsco2.ucsd.edu/]	CLICK HERE
Geenpeace: Nine ways humans have altered Earth's Holocene climate [https://www.greenpeace.org/international/story/22792/]	CLICK HERE
PennState College of Earth and Mineral Sciences, METEO 300 Fundamentals of Atmospheric Science, by William H. Brune (2020) [https://www.e-education.psu.edu/meteo300/node/606]	CLICK HERE

Improvements in measurement of the absorption spectra of gases, though, enabled Callendar (1949) to restate the theory of the contribution of CO_2 to the greenhouse effect in these terms: "… this theory depends on the fact that, whereas carbon dioxide is almost completely transparent to solar radiation, it is particularly opaque to the heat [infrared radiation] which is radiated back to space from the earth. In this way it [the CO_2] acts as a heat trap, allowing the temperature near the earth's surface to rise above the level it would attain if there were no carbon dioxide in the air …" Callendar (1949). That quotation states the fundamental essence of the meaning of 'greenhouse gas'.

Subsequently, Revelle & Suess (1957) stated the consequential impact of that greenhouse gas in very direct terms by describing a ***planetary-scale experiment*** in which mankind is "… returning to the atmosphere and oceans the concentrated organic carbon [previously] stored in sedimentary rocks over hundreds of millions of years …" (Revelle & Suess, 1957).

Revelle & Suess (1957) also demonstrated, by comparing $^{14}C/^{12}C$ and $^{13}C/^{12}C$ carbon isotope ratios in wood and in marine material that the average lifetime of a CO_2 molecule in the atmosphere before it dissolves into the sea is of the order of 10 years. It follows that most of the CO_2 released by fossil fuel combustion since the beginning of the industrial revolution must have been absorbed by the oceans. They concluded (in 1957) that "… the increase of atmospheric CO_2 from this cause is at present small but may become significant during future decades if industrial fuel combustion continues to rise exponentially …" Unfortunately, fossil fuel combustion has further intensified since then and the CO_2 concentration in the atmosphere has risen steadily, and it is still rising. Except for a one-year reduction in 2008/2009, every year of the 21st century has seen a year-on-year increase in anthropogenic CO_2 emissions (MacDowell *et al*., 2017). The latest data we can find are CO_2 measurements by the Scripps Institution of Oceanography and the National Oceanic and Atmospheric Administration (NOAA) which show that the amount of CO_2 in the air in May 2020 reached the alarming monthly average value of ***417 ppm***. This value is the highest atmospheric concentration observed in human history and is probably the highest reached at any time in the last 3 million years [source: https://www.washingtonpost.com/].

McKinley *et al*. (2020) state that "… The ocean has absorbed the equivalent of 39% of fossil carbon emissions since 1750, significantly modulating the growth of atmospheric CO_2 and the associated climate change …. If emissions continue to accelerate, this sink is expected to grow …" (McKinley *et al*., 2020, and references therein). These authors show that two processes external to the ocean are sufficient to explain major variability of the ocean carbon sink in recent decades. First, the global-scale reduction in the ocean carbon sink in the 1990s can be attributed to slowed growth rate of atmospheric CO_2 level, followed by recovery of the sink after 2001 due to acceleration of atmospheric CO_2 growth. Second, the timing of global sink variability in the 1990s is explained as a global response to the 1991 eruption of Mount Pinatubo in the Philippines, on June 15, 1991, which was the second-largest volcanic eruption of the 20th century. They conclude that the most important control on the average magnitude of the ocean carbon sink is the variability in the growth rate of atmospheric CO_2 levels. This implies that if future fossil fuel emissions can be cut sufficiently to reduce growth of atmospheric CO_2, the ocean sink will act as a buffer, be reduced immediately "… and substantially mitigate atmospheric carbon accumulation for the next several centuries …" (McKinley *et al*., 2020).

Rapidly increasing atmospheric levels of CO_2 and other greenhouse gases are the atmospheric drivers of climate change because they can generate unpredictable changes in the climate system leading to severe ecological and economic disruptions. And so, our diagnosis of the fundamental problem is that human activities in the recent past have released into the atmosphere such quantities of greenhouse gases that were previously locked into fossilised rock strata such that the resultant climate change will inevitably cause damaging disruption to future human activities.

All the facts that lead to our diagnosis are well known and easy to understand. But this general scientific interpretation of those facts is often challenged by those wishing to play down the role of human activities in causing dangerous CO_2-increases.

2. The denial of anthropogenic CO_2-driven climate change

The fact is that the carbon dioxide greenhouse gas that we blame for climate warming represents only 0.04% of the total gases in our atmosphere. And another fact that weighs heavily with those wishing to deny that human activities cause climate change is that most of the CO_2 that is emitted, day by day, into the atmosphere comes from natural geological and biological sources, such as volcanoes or decomposition processes in nature or the aerobic respiration of all the living things on the planet. The anthropogenic contribution of CO_2 is (still) not much more than 5% of the atmosphere's total CO_2 burden; so, the anthropogenic CO_2 content in the air that we breathe is only about 0.002%.

Written like this, these undeniable facts do seem to provide reason for those who deny the validity of the claims of the world's scientists that ***human activities*** are causing dangerous CO_2-increases, arguing instead that the human contribution to the emissions of CO_2 in the air we breathe is too small to cause the dramatic changes the scientists are warning us all about; it's all down to Nature's natural carbon cycle they say. This, though, is pure mischief. Because, written like this, there is another undeniable and crucial fact that this denial does not consider, which is that the anthropogenic release of previously fossilised carbon from coal, petroleum and natural gas is a net ***addition*** to the natural carbon cycling of the present day global atmosphere. To explain what we mean, we must examine *the normal scheme of things* by finding out about the global carbon cycle.

3. The global carbon cycle

The chemistry of carbon is the chemistry of life on Earth. Carbon compounds make up the bodies of all the Earth's living organisms, provide the nutrients and energy that sustains them, and deliver the energy that fuels our global economy. And the carbon compounds that are emitted into the atmosphere regulate the temperature of the Earth through their activity as greenhouse gasses.

Most of the carbon on Earth is stored in rocks and sediments; with the rest being in the ocean, the atmosphere, and in all those living organisms. These are the reservoirs through which carbon atoms are continually recycled. Living organisms have a high turnover of carbon, but do not make any net addition of CO_2 to the atmosphere. Non-photosynthetic organisms use the carbon compounds of their food to make their own biomass and although the digestion of food releases CO_2 back to the atmosphere, through respiration, the growth of their biomass in life represents a net removal of carbon from the atmosphere, but when they die, the decomposition of their bodies releases all their carbon back to the atmosphere. On the other hand, photosynthetic organisms use the CO_2 directly from the air to make the nutrient sugars needed for their own biomass. It is a much greater net removal of carbon from the atmosphere of course, but only if the sun shines and they remain alive. At night, these organisms also respire, thus returning some carbon to the atmosphere, and when they die their biomass also rots, eventually returning all their carbon to the atmosphere. These are all part of the same regular biological cycle: remove carbon from the atmosphere to build live biomass and then return that carbon to the atmosphere after death.

The Earth's global carbon cycle was almost exactly in equilibrium before industrial humans intervened, which is evident from the constancy of the CO_2 concentration in the air for several thousand years while humans were evolving (Fig. 2). There are various reservoirs or sinks, some of which have short lifetimes (like the human lifetime), others have long lifetimes (like the hundred million-year-old geological limestone strata, or the equally old coal measures and deep reserves of petroleum and natural gas). Carbon flows between the reservoirs, shifting carbon out of one reservoir by putting more carbon into another reservoir. It is this exchange that is called **The Global Carbon Cycle** (Fig. 3).

In the long term, the carbon cycle maintains a natural balance that avoids all of Earth's carbon being dumped into the atmosphere or being stockpiled entirely in rocks. Because CO_2 is a greenhouse gas, which does not allow escape of re-radiated infrared, this balance acts like a thermostat, helping to keep Earth's temperature relatively stable over long periods of time. Any changes that put greenhouse gases into the atmosphere (Fig. 1) result in warmer temperatures on Earth. This thermostat works over a timescale of at least a few hundred thousand years, so it's a slow part of the overall carbon cycle. But over shorter time periods, say ten thousand to a hundred thousand years, the CO_2 content of the atmosphere, and consequently the temperature of Earth, can vary quite naturally (Fig. 2), and this is thought to be a contributory cause for the Earth shifting between ice ages and warmer interglacial periods over these time scales. Parts of the carbon cycle may even vary over shorter time scales. For example, seasonal variation in the CO_2 concentration of the atmosphere is consistently measured by stations of the global CO_2 measurement network, such as the Mauna Loa Observatory of the Scripps Institution of Oceanography, in Hawaii (view the current year's data at https://www.esrl.noaa.gov/gmd/ccgg/trends/). Seasonal variation is mainly due to seasonal changes over the year in the forests of the land masses of the northern hemisphere; spring and summer drawdown of CO_2 for plant growth, followed by emission of CO_2 from autumn and winter decay and digestion of shed flowers, fruit, leaves and branches.

Detailed quantifications of carbon fluxes and reservoirs, such as those shown in Fig. 3, are the starting points for the myths of the climate change deniers and global warming sceptics. The myths that deny the facts that human activities are causing climate change are not just an argumentative mischief because when those sceptics are in government and responsible for environmental regulations that scale back or eliminate climate mitigation measures, our climate disaster which is on the horizon can be brought even closer (view the *Climate Deregulation Tracker* of the Sabin Center for Climate Change Law at Columbia Law School, New York, at this URL: https://climate.law.columbia.edu/climate-deregulation-tracker).

The first, and major, myth is based on the ***true*** observations that although the great majority of the CO_2 emitted every day into the atmosphere is the result of natural phenomena, specifically, respiration of live organisms and decomposition of dead ones; only a few percent of the total result from human activities like burning fossil fuels, making cement from fossilised limestone and forest clearing and forest burning for agricultural expansion. The myth is that this few percent of anthropogenic CO_2 emissions must therefore be irrelevant. This is the big, spurious, totally missing the point sceptic myth. The point that is being missed is that ***human activities like burning fossil fuels and making cement from fossilised limestone are making a net addition of CO_2 to the present day atmosphere*** by releasing today carbon that was removed from the atmosphere long, long ago. The majority emitters, respiration, and decomposition, are merely **recycling** atmospheric CO_2. By which we mean that the food that you respire today (releasing CO_2 in the process) was made by the organisms that became your food using CO_2 drawn down from the atmosphere earlier the same year; so, you are recycling it back to the atmosphere, you are not making a net addition to the atmosphere. Similarly, decomposition of the biomass of an organism that dies today will return to the atmosphere (as CO_2) the carbon of which it was made when alive using CO_2 drawn down from the atmosphere in its recent past. Again, there is no net addition to the atmosphere.

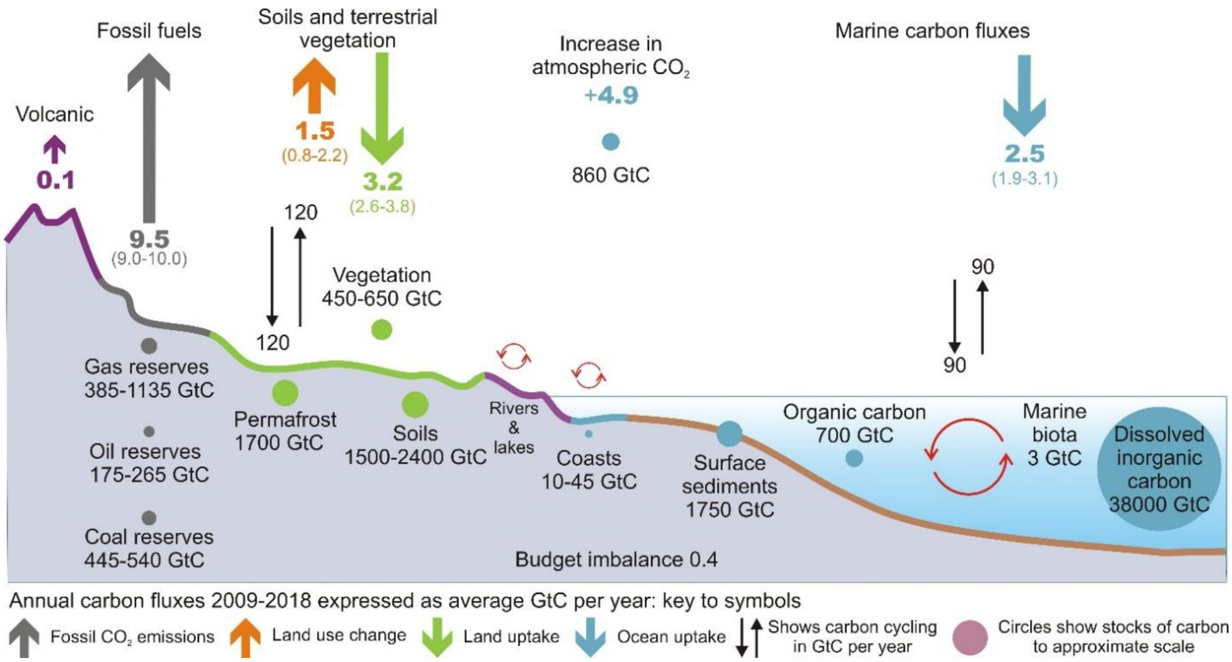

Fig. 3. The global carbon cycles. Schematic representation of the overall global carbon cycle emphasising those caused by anthropogenic activities. Data cover the decade 2009–2018. The key to symbols below the graphic shows the meaning of the arrows and units; large bold numerals indicate the mean annual total of carbon emitted or stocked in $GtC\,yr^{-1}$, with the statistical range of the estimates (±one standard deviation) shown below. Uncertainty in the atmospheric CO_2 growth rate is very small ($\pm 0.02\,GtC\,yr^{-1}$) and is neglected for the figure. An overall budget imbalance of $0.4\,GtC\,yr^{-1}$ is due to overestimated emissions and/or underestimated sinks. The anthropogenic perturbations ***are additional to*** the Earth's ***natural active carbon cycle***; with fluxes (vertical bidirectional arrows) and stocks (annotated circles) shown across the figure. Redrawn after a figure in Friedlingstein *et al*. (2019).

Another climate sceptic myth, is that the recent increase in concentration of CO_2 in the atmosphere is derived from volcanic emissions. This cannot be so because the total volcanic emissions can be measured to be about 0.1 Gt of carbon per year, compared to the anthropogenic emissions from fossil fuel burning alone of 9.5 Gt of carbon per year (Fig. 3). Total anthropogenic emissions (which include our damage to forest ecosystems) are now more than a hundred times greater than those from volcanoes. The volcanic emissions are important for long-term changes of atmospheric CO_2 levels over timescales of millions of years, but not over a few decades as we are experiencing (Fig. 2).

There is ***yet another denier myth***, that the oceans are the cause of the atmospheric CO_2 increase. This also ignores the rapid timescale of the rise in atmospheric CO_2 levels we are experiencing now because it depends on the variation in CO_2 levels during the Earth's glacial cycles. It is certainly true that during ice ages greater concentrations of CO_2 are dissolved into the oceans and there is correspondingly less in the atmosphere. It is also true that as the ice retreats and the world warms at the end of the glacial cycle that the CO_2 is returned to the atmosphere from the oceans. But this is a cycle that takes place over timescales of many thousands or millions of years; it is a fallacy to claim that the same natural phenomenon is happening today. Indeed, direct measurements completely dispose of this misconception. The upper ocean has been mapped and documented in detail by countless ship surveys that have demonstrated that ***today's oceans absorb CO_2 and do not release any***. The increase in CO_2 concentration in the upper ocean is itself a serious environmental problem because CO_2 dissolved in water forms carbonic acid. Consequently, rising CO_2 concentrations lead to acidification of the oceans, which has significant, and mostly adverse, ecological effects.

It is almost not even worth discussing the ***final climate sceptics myth***, which blames the world's forests for most of the increase in atmospheric CO_2 – it is too foolish to contemplate. But, for the sake of completion, this fallacy puts the blame on the world's forests because of their undeniable emission of CO_2 by the regular decay of their shed foliage and dead wood. By looking at this emission in isolation, these climate sceptics ignore the fact that the CO_2 emitted during the decay of leaves and dead wood is merely returning to the atmosphere the CO_2 that was removed from it to make those leaves and that wood in the first place. This natural activity of the forest (and other vegetation) is one of the carbon cycles that contribute to the Global Carbon Cycle (Fig. 3). To break that cycle and force the forests to really contribute to our accumulating atmospheric CO_2, you would have to clear-cut the trees and burn them, replacing the long-lived, carbon-sequestering, forest trees with transient pasture grasses or oil-producing monocultures. Now, who would be misguided enough to do that?

Ruling out the denial myths this way, we are left with the uncomfortable conclusion (already stated above) that the relentless rise in the concentration of the greenhouse gas CO_2 in **our** atmosphere that is being measured has just one cause, which is our profligate use of ***fossil*** fuels. We are motoring, flying, heating and cooking on gas towards our own extinction.

4. The likely effects of climate change

We are already experiencing the climatic effects of the increase in CO_2 concentration in the atmosphere, but the potential future effects of global climate change can be calculated from our understanding of the physical processes, and/or estimated from knowledge of the Earth's climate history. Both come to the conclusion that the average global warming due to the increase in CO_2 to date, is expected to be about +1°C. This corresponds exactly to the measured observations of global warming (Fig. 4). As we have shown above, there is no natural explanation for this, meaning that the best estimate for the anthropogenic share of global warming since 1950 is 100%.

This climate change has already had noticeable effects on our environment. Glaciers have dwindled, some have disappeared, winter ice on rivers, lakes and in polar waters is breaking up earlier, and continued melting of polar ice will only accelerate sea level rise, a gloomy prospect for coastal communities. And we mean coastal communities like Tokyo, New York, Shanghai, Kolkata, Dhaka, Osaka, Mumbai, Bangkok, Guangzhou, Shenzen and Miami; all of which appear among the Top 20 cities expected to be exposed to climate-change-induced coastal flooding by the 2070s (OECD, 2010; Nicholls *et al*., 2011; and view this 2019 UN News report at https://news.un.org/).

The previous paragraph suggests a bleak future caused by climate change, but ecologists around the world are ***already*** recording lengthening of summer seasons and drastic changes in the distribution ranges of fungi, plants and animals, including widening host ranges of disease and pest organisms. We are all aware of an increase in the number, duration and intensity of extreme weather events caused by the greater amounts of energy that are now being trapped in the atmosphere, and the great majority of the world's scientists agree on the hazards that will come if atmospheric CO_2 levels are allowed to rise even more (Randers, 2012).

For example, the Intergovernmental Panel on Climate Change (**IPCC**) includes over 1,300 scientists from around the world and forecast in their reports that global temperatures will continue to rise for decades to come, due to the greenhouse gases produced by human activities (IPCC 2007; Forster *et al*., 2007; IPCC, 2013; Stocker *et al*., 2013 [all available free online]). According to the IPCC, the extent of climate change effects on individual regions will vary between regions, and over time, and with the ability of different community and environmental structures to adapt to, or even mitigate the changes.

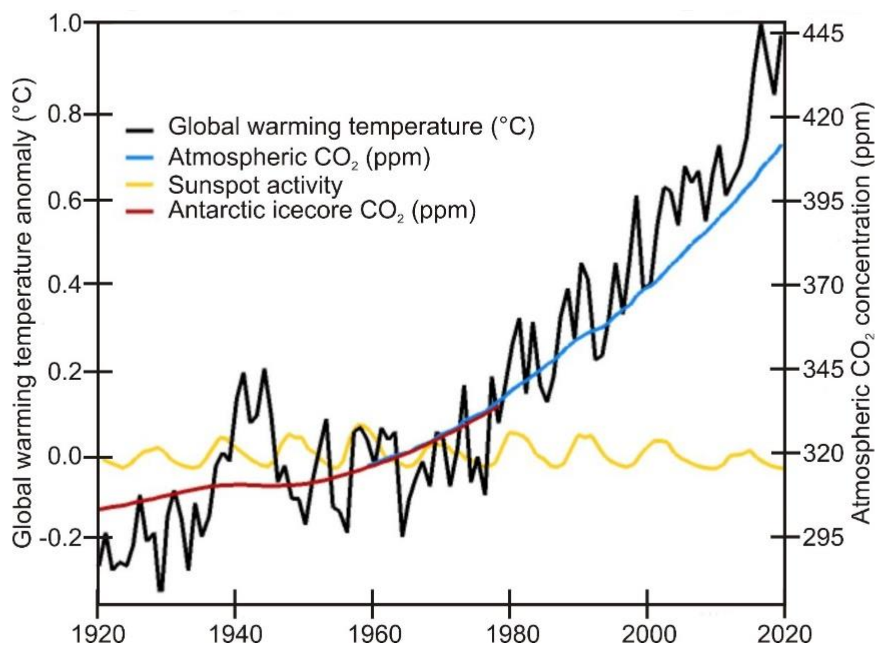

Fig. 4. Evolution of global temperature (black), atmospheric CO_2 concentration (blue), CO_2 concentration in air trapped in Antarctic icecores (magenta) and solar activity (yellow) over the 100 years from 1920 to 2020. Temperature and CO_2 are scaled relative to each other as the physically expected CO_2 effect on the climate predicts (that is, the best estimate of climate sensitivity). The sunspot activity curve shows average number of sun spots per year; its amplitude is scaled from the observed correlation of solar and temperature data. Data taken from the website *RealClimate: Climate Science From Climate Scientists* [http://www.realclimate.org/]. This graphic was produced using the the climate widget at this URL: [http://herdsoft.com/climate/widget/]. 1920 was chosen as the start date as it represents the start of the dominance of the internal combustion engine in transport on land, sea and air; at the start of the First World War, horse-drawn transport dominated, but by the end of that war motorised transport dominated. You can create a version of this graph for yourself, covering years of your own choice with the widget at [http://herdsoft.com/climate/widget/].

The IPCC reports further predict that increases in global mean temperature of 1 to 3 degrees Celsius above 1990 levels will produce beneficial impacts in some regions and harmful ones in others. Net annual costs will increase over time as global temperatures increase. The IPCC states that, "… Taken as a whole, the range of published evidence indicates that the net damage costs of climate change are likely to be significant and to increase over time …"

Table 3. Some ***YouTube videos*** that describe the climate and climate change
A Brief History of CO_2 Emissions, a video illustrating the history of CO_2 emissions by the Potsdam Institute for Climate Impact Research (PIK) and the Urban Complexity Lab: [https://youtu.be/EQ7S0D1iucY].
What is Climate Change? - Start Here. The hard facts about global warming from Al Jazeera English [https://youtu.be/dcBXmj1nMTQ].
Climate Change 101 with National Geographic's Bill Nye, explains what causes climate change, how it affects our planet, why we need to act promptly to mitigate its effects, and how each of us can contribute to a solution [https://youtu.be/EtW2rrLHs08].
A new high-resolution computer model created by NASA shows CO_2, the greenhouse gas driving global warming, in 2014, 'the warmest year ever recorded' [https://www.youtube.com/watch?v=fJ0o2E4d8Ts].
Carbon Brief is a UK-based website covering the latest developments in climate science, climate policy and energy policy. In this video Dr Glen Peters explains why global CO_2 emissions rose in 2019 https://youtu.be/_hE-gGauVDg.
Carbon dioxide emissions inventory for commercial aviation. Video of highlights from a September 2019 paper that details calendar year 2018, presented by one of the paper's co-authors, Brandon Graver. [https://youtu.be/oAkvaDwjsc0].
UN Secretary-General António Guterres warns of the threat posed by climate change, in a major address in 2018 [https://youtu.be/VNe-jBVij-g].
Word artist Prince Ea makes a powerful case for protecting the planet, and challenges the human race to create a sustainable future in this short film in the National Geographic Short Film Showcase. Winner of the Film4Climate competition organised by the Connect4Climate Program of the World Bank [https://youtu.be/B-nEYsyRlYo].
Climate science explained in 60 seconds by the Royal Society of London and the US National Academy of Sciences [https://youtu.be/n4e5UPu1co0].
How does the climate system work? An animation to explain how the climate system works by the UK Met Office [https://youtu.be/lrPS2HiYVp8].
The jet stream and how it affects the major climate patterns of the world. The effects of climate change on climate patterns and how the jet stream plays a major role in those changes by Oregon State University [https://youtu.be/ifkc_NNufT4].

And a lot of evidence ***has*** been published in the last decade or so, which we cannot review here, so, rather than repeat other summaries we will refer to just two more (Melillo *et al*., 2014;

Wuebbles *et al*., 2017 [both available free online]), which together amount to over 1,000 pages of well documented projections. These are the Third and Fourth Reports of the *US National Climate Assessment*, which summarise the impacts of climate change on the United States, now and in the future. These reports were produced by a team of more than 300 experts guided by a 60-member ***Federal Advisory Committee*** and were extensively reviewed by the public and independent experts, including federal agencies and a panel from the ***US National Academy of Sciences*** (but if you would rather get your information from videos, take a look at the YouTube videos listed in Table 3).

Restricting ourselves to just the headline statements in these *National Climate Assessment* reports, some of the long-term effects of global climate change in the United States are projected to be as follows:

- The global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the Earth's climate is to those emissions.

- Temperatures will continue to rise but this "…will not be uniform or smooth across the country or over time …"

- Frost-free seasons (and growing seasons) will lengthen; these have been "… increasing nationally since the 1980s, with the largest increases occurring in the western United States, affecting ecosystems and agriculture. Across the United States, the growing season is projected to continue to lengthen…" by a month or more, if heat-trapping gas emissions continue to increase.

- "… Average US precipitation has increased since 1900, but some areas have had increases greater than the national average, and some areas have had decreases. More winter and spring precipitation is projected for the northern United States, and less for the Southwest, over this century …"

- "… Droughts in the [US] Southwest and heat waves (periods of abnormally hot weather lasting days to weeks) everywhere [in the US] are projected to become more intense, and cold waves less intense everywhere … Summer temperatures are projected to continue rising, and a reduction of soil moisture, which exacerbates heat waves, is projected for much of the western and central US in summer. By the end of this century, what have been once-in-20-year extreme heat days (one-day events) are projected to occur every two or three years over most of the nation …"

- Hurricanes will become stronger and more intense. "… The intensity, frequency and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Categories 4 and 5) hurricanes, have all increased since the early 1980s … Hurricane-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm …"

- Sea level will rise by 1 to 8 feet by the end of the 21st century. "Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 8 feet by 2100. This is the result of added water from melting land ice and the expansion of seawater as it warms … In the next several decades, storm surges and high tides could combine with sea level rise and land subsidence to further increase flooding in many regions. Sea level rise will continue past 2100 because the oceans take a very long time to respond to warmer conditions at the Earth's surface. Ocean waters will therefore continue to warm and sea level will continue to rise for many centuries at rates equal to or higher than those of the current century …"

- "… The Arctic Ocean is expected to become essentially ice free in summer before mid-[21st]-century …"

The *Third* (Melillo *et al*., 2014) and *Fourth* (Wuebbles *et al*., 2017) *National Climate Assessment Reports* predict the following ***regional*** effects on the US:

- "… **Northeast**. Heat waves, heavy downpours and sea level rise pose growing challenges to many aspects of life in the Northeast. Infrastructure, agriculture, fisheries and ecosystems will be increasingly compromised. Many states and cities are beginning to incorporate climate change into their planning …"

- "… **Northwest**. Changes in the timing of streamflow reduce water supplies for competing demands. Sea level rise, erosion, inundation, risks to infrastructure and increasing ocean acidity pose major threats. Increasing wildfire, insect outbreaks and tree diseases are causing widespread tree die-off …"

- "… **Southeast**. Sea level rise poses widespread and continuing threats to the region's economy and environment. Extreme heat will affect health, energy, agriculture and more. Decreased water availability will have economic and environmental impacts …"

- "… **Midwest**. Extreme heat, heavy downpours and flooding will affect infrastructure, health, agriculture, forestry, transportation, air and water quality, and more. Climate change will also exacerbate a range of risks to the Great Lakes …"

- In the **Southwest**, increased heat and drought, linked to climate change, have already increased wildfire occurrences, while declining water supplies and insect outbreaks have reduced agricultural yields, and "… health impacts in cities due to heat, and flooding and erosion in coastal areas are additional concerns …".

A major concern about climate change is that tiny perturbations in critical thresholds may cause irreversible changes in the climate system that could dramatically alter the Earth's planetary environment as we know it (McCarthy *et al*., 2001). The United Nations Framework Convention on Climate Change (UN, 1992), in Article 2, obligates signatory nations to stabilise greenhouse gas (GHG) concentrations in the atmosphere at a level that "… would prevent ***dangerous anthropogenic interference*** (DAI) with the climate system…" (Mann, 2009). McCarthy *et al*. (2001) identified a number of ***reasons for concern*** (RFCs)(and see Smith *et al*. 2009). These are points-of-no-return, which, once exceeded, plunge the world into new dynamics. They have been defined over recent years as ***tipping points*** (Lenton *et al*., 2008; IPCC, 2014) Among the tipping points that are most discussed are (Fig. 5; Russill & Nyssa, 2009; Lenton *et al*., 2019; Randers & Goluke, 2020):

- The Arctic sea ice melts.
- Greenland becomes ice-free.
- The West Antarctic ice sheet disintegrates.
- Siberian permafrost thaws.

- The Amazon rain forest dies back due to drought and fires.
- Boreal forests suffer damaging fires and new pests and diseases.

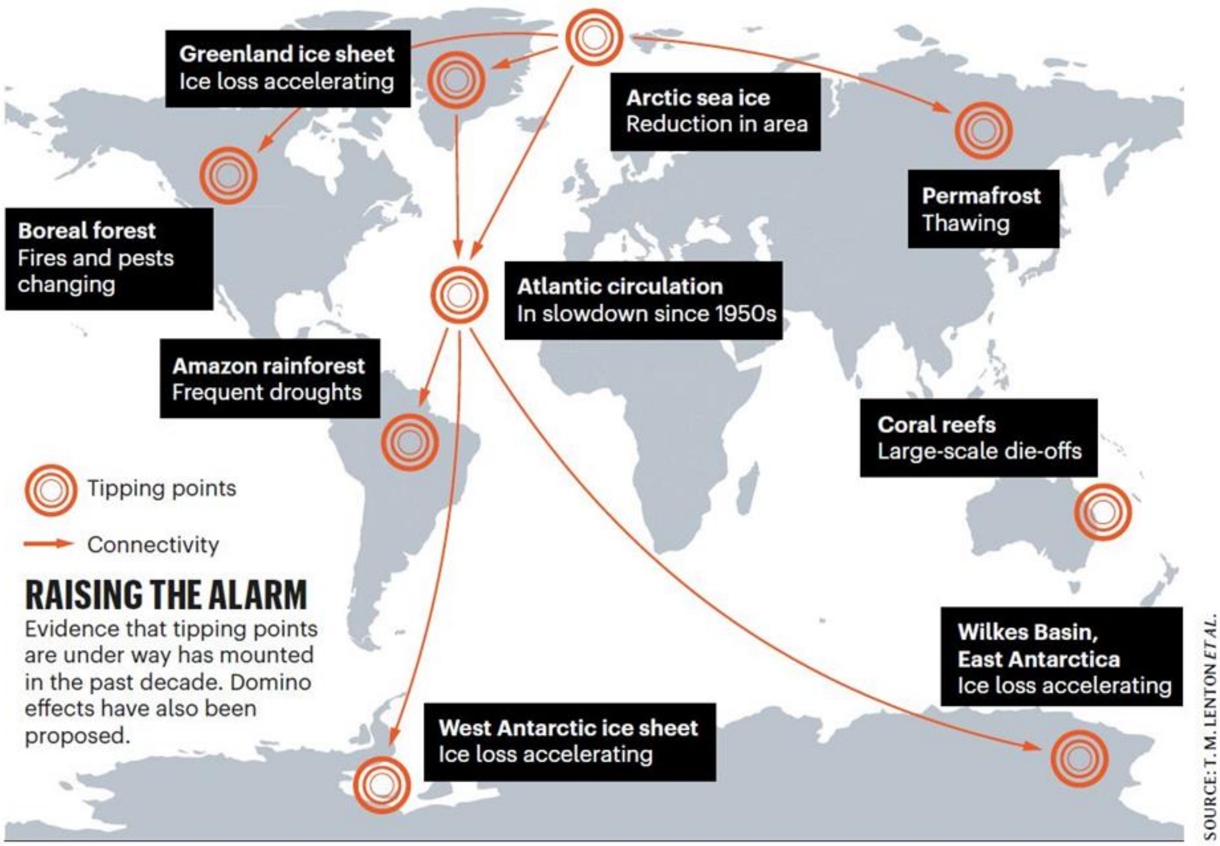

Fig. 5. Raising the alarm. Potential tipping points in the climate system (from Lenton *et al*., 2008, 2019).

The greatest fear is that these tipping points, singly or in combination, could cause runaway climate change, contributing to mass extinction of species (not excluding humans), dramatic sea level rise, extensive droughts and the transformation of forests into vast grasslands.

Lenton *et al*. (2019) state that (the emphasis is ours): "… In our view, the evidence from tipping points alone suggests that we are in a state of ***planetary emergency***: both the risk and urgency of the situation are acute … We argue that the intervention time left to prevent tipping could already have shrunk towards zero, whereas the reaction time to achieve net zero emissions is 30 years at best. Hence, we might already have lost control of whether tipping happens. A saving grace is that the rate at which damage accumulates from tipping - and hence the risk posed - could still be under our control to some extent. ***The stability and resilience of our planet is in peril***. International ***action*** - not just words - must reflect this.".

None of this makes particularly comfortable reading (especially so for my children and grandchildren) because it makes the point very starkly that nobody escapes, everybody suffers, and we've got to do something about it, ***NOW***.

5. Climate change and what we might do about it

There are also a great many published resources that deal with potential methods of mitigation of global warming and climate change. Griscom *et al*. (2017) made a comprehensive analysis of 20 conservation, restoration, and/or improved land management natural climate solutions; these being actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands. They showed that most such actions, when implemented effectively, offer additional benefits such as water filtration, flood risk reduction, improved soil health, improved habitat biodiversity, and enhanced climate resilience, and concluded that "… existing knowledge … provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change…". We will discuss some of these additional benefits elsewhere (Moore *et al*., 2021).

Here, we will use 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) as the basis for further discussion of options for removing CO_2 from the atmosphere and sequestering it reliably. 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**, or NETs. NETs are technologies that remove and sequester CO_2 from the atmosphere with the intention of mitigating climate change. NETs have previously received less attention than 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 2050.

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 produce energy from biomass, while capturing and storing the resulting CO_2 emissions, and increase carbon stocks in soils, forests, and wetlands by pro-active conservation.
- 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 a number of conclusions that outline the main thrust of the research agenda it goes on to develop, and which we quote directly below because they quantify the task ahead:

- **Conclusion 1**: Negative emissions technologies are best viewed as a component of a ***mitigation portfolio***, rather than a way to decrease atmospheric concentrations of carbon dioxide only after anthropogenic emissions have been eliminated. Indeed, a different publication concludes that any attempt to solve the global climate change problem must be based on a portfolio approach that incorporates a full spectrum of strategies based on nature-based solutions, ***and*** alternative energy contributions ***and*** industrial mitigation (Anderson *et al*., 2019). In her article about direct air capture on the iNews website, Madeleine Cuff (Cuff, 2020) points out that while trees can absorb CO_2, there is not enough land on the planet to create a carbon sink of trees the size humanity needs. Cuff's solution is to turn to "… giant machines that can suck CO_2 out of the atmosphere …". Our solution is to make more sustainable use of the other 70% of the planet, its ***oceans***.

- **Conclusion 2**: Four negative emissions technologies are ready for large-scale deployment: afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and bioenergy with carbon capture and storage (BECCS). These NETs have low to medium costs (\$100/t CO_2 or less) and substantial potential for safe scale-up from current deployment.

- **Conclusion 3**: Current negative emissions technologies with direct costs that do not exceed \$100/t CO_2 can be safely scaled up to capture and store substantial amounts of carbon, but significantly less than ~1 Gt/y CO_2 in the United States and ~10 Gt/y CO_2 globally. These levels represent a substantial fraction of the total emissions of ~6.5 Gt CO_2 [emitted] in the United States and more than 50 Gt CO_2 [emitted] globally, but they may be difficult to attain because they require unprecedented rates of adoption of agricultural soil conservation practices, forestry management practices, and waste biomass capture.

- **Conclusion 4:** If the goals for climate change mitigation 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 CO_2 globally by mid-century and ~20 Gt/y CO_2 globally by the century's end.

We do not disagree with the findings of this NASEM report in any way, BUT we believe there are several ***alternative biotechnologies*** which have not been considered in NASEM (2019), or indeed elsewhere.

The specific technologies considered by NASEM (2019) were as follows.

Coastal Blue Carbon, namely, the "… 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. These approaches are sometimes called "blue carbon" even though they refer to coastal ecosystems instead of the open ocean …" The report does 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. We wish to remedy this exclusion.

Terrestrial carbon removal and sequestration. Meaning land use and management practices such as afforestation/reforestation, changes in forest management, or changes in agricultural practices that enhance carbon storage in agricultural soils. This is possibly the most conventional aspect as photosynthetic carbon capture by trees and other green plants 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.

Bastin *et al*. (2019) mapped the global potential tree coverage and estimated that the world's terrestrial ecosystems could support an additional 0.9 billion (0.9×10^9) hectares of continuous forest (corresponding to more than a 25% increase in presently forested area) and that such a change has the potential to cut the atmospheric carbon pool by about 25%. We all like trees and we are in favour of planting more of them, but there are negative aspects to these estimations that indicate that the value of Green Carbon as a means of sequestering carbon from the atmosphere on the long term basis required for full and lasting benefit has been seriously overestimated. This is discussed in **Section 7**, below.

Bioenergy with carbon capture and sequestration (BECCS). Energy production using plant biomass to produce electricity using liquid fuels (derived from plant oils), and/or heat by direct burning effectively only recycles today's CO_2 back to the atmosphere (in contrast to fossil fuels, which make a net increase of ***ancient*** CO_2 to today's atmosphere. If combined with capture and sequestration of any CO_2 produced when using the bioenergy, the whole process can provide a net reduction of CO_2 in the atmosphere.

Direct air capture. Uses chemical processes that capture CO_2 from ambient air and concentrate it, so that it can be injected into a storage reservoir.

Carbon mineralisation. In which 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 rocks to mineralise in the pores. This might employ supercritical CO_2 in deep sedimentary geological formations. CO_2 usually behaves as a gas in air at standard temperature and pressure, or as a solid called dry ice when cooled and/or pressurised sufficiently. ***Supercritical CO_2*** is a ***fluid state phase*** that occurs when CO_2 is held at or above its critical temperature and critical pressure [view YouTube video at https://www.youtube.com/watch?v=-gCTKteN5Y4].

6. Plant trees for the intrinsic value of forests

Photosynthetic carbon capture by trees is widely considered to be possibly our most effective strategy to limit the rise of CO_2 concentrations in the atmosphere, and there are several ambitious targets to promote forest conservation, afforestation, and atmosphere restoration on a global scale (Masson-Delmotte *et al*., 2019; Bastin *et al*. (2019). We all like trees and we are all in favour of planting more of them, but as any mycologist would point out, there is a negative side to these strategies that seems to be escaping notice. This is that forests do not only contain trees that can store gigatonnes of carbon in the wood they make; forests also contain wood-decaying fungi that can (and do) digest that wood, releasing greenhouse gases, including CO_2, in the process.

Chlorinated hydrocarbons also make a normal every-day contribution to the degradation of timber by forest fungi. The fungal chloromethane contribution to the atmosphere has been estimated at around 150,000 tonnes per annum (Watling & Harper, 1998), which, in the year of that publication, was about 60% ***more*** than was released into the atmosphere by industrial coal burning furnaces worldwide.

Of course, the ultimate end-product of food digestion by all aerobic living things, including those wood-digesting fungi, is CO_2. On a global scale, completely natural decomposition of dead wood in the world's forests releases billions of tons of CO_2 to the atmosphere each year, a similar magnitude, in fact, to the annual CO_2 emissions from fossil fuel combustion (Rinne-Garmston *et al*., 2019).

In recent years, an increasing number of studies have warned against too great a reliance on tree planting. For example, Boysen *et al*. (2017) noted that using biomass plantations to sequester carbon would reduce biodiversity, because they are likely to be monocultures of fast growing species quite different from the native species. Furthermore, such plantations are likely to occupy scarce agricultural land that might otherwise be used for primary food production. These authors concluded: '…that this strategy of sequestering carbon is not a viable alternative to aggressive emission reductions.' In the rest of this section, we will discuss some more recent research that also, but for different reasons, casts doubt on the viability of tree planting as a method of long-term sequestration of carbon from the atmosphere.

Fig. 6. Photographs of the same tree in summer (top) and winter (bottom) emphasising how deciduous trees shed their leaves at the end of the year. So, by the time the snow comes, all the leaves, flowers and fruit of the summer season have been digested and their carbon returned to the atmosphere. Open access images from https://pixabay.com/.

Even though photosynthetic carbon capture by trees is most often the first thought in the minds of those hoping to limit the rise of CO_2 concentrations in the atmosphere, the problem with carbon capture by green plants (trees, kelp forests and peat mosses alike) is that it is **temporary**. When the plants die the plant-debris is subject to decay and digestion and the ultimate end-product of digestion is the release of CO_2 back to the atmosphere. On a global scale, the world's forests release billions of tons of CO_2 to the atmosphere each year. In the temperate zones, we can all observe for ourselves every year that the decomposition of seasonally shed leaves, petals, ripe fruit, and dead wood releases CO_2 to the atmosphere in the same year it was fixed (Fig. 6).

And even when the tree trunk itself dies, there are all those wood decay fungi in every forest waiting to help things along (Fig. 7). If you hope that terrestrial green plants can effectively sequester carbon from the atmosphere, and meet the ambitious targets to promote forest conservation, afforestation, and restoration on a global scale, you are bound to be disappointed, because you are expecting too much of them. And this applies as much to moorland and peat bogs as to forests.

According to the very useful Wikipedia article [at this URL: https://en.wikipedia.org/wiki/Peat] 'Peat, also known as turf, is an accumulation of partially decayed vegetation or organic matter. It is unique to natural areas called peatlands, bogs, mires, moors, or muskegs… The peatland ecosystem is the most efficient carbon sink on the planet… In natural peatlands, the annual rate of biomass production is greater than the rate of decomposition, but it takes thousands of years for peatlands to develop the deposits of 1.5 to 2.3 m, which is the average depth of the boreal [northern] peatlands' (like those in Britain).

Fig. 7. Felled logs colonised by mycelia of *Trametes versicolor* (Basidiomycota; commonly called Turkey Tail in the United States) (A, B, C) and *Hypholoma fasciculare*, D, commonly known as the Sulphur Tuft. Early in the season the mycelia reach the end of the log and the differentiating sporophores outline the separate decay columns in the timber (A), which are formed by mycelia belonging to different compatibility groups. Sporophores are formed on these surfaces later in the season (B, C and D). Photographs by David Moore of logs in the Lovell Tree Collection Arboretum at Jodrell Bank Discovery Centre, Cheshire (https://www.jodrellbank.net/).

Overall, in the northern hemisphere, peatlands cover an area of about 3.7 million km^2; 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. It is projected that 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) as the peatlands warm up (Hugelius *et al*., 2020).

Unfortunately, planting trees on peatland will not 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. Significantly, this decline was not compensated for by the gains in carbon contained in the growing trees. This was a continuation of a long term study of the effects of planting two native tree species (*Betula pubescens* and *Pinus sylvestris*), which have a wide Eurasian distribution, in *Calluna vulgaris* moorland with podzol and peaty podzol soils in Scotland. The study demonstrated 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 authors state that: 'The results are of direct relevance to current policies, which promote tree planting on the assumption that this will increase net ecosystem C storage and contribute to climate change mitigation. Ecosystem-level biogeochemistry and C fluxes must be better quantified and understood before we can be assured that large-scale tree planting in regions with considerable pre-existing [soil organic carbon] stocks will have the intended policy and climate change mitigation outcomes' (Friggens *et al*., 2020).

The mosses (typically species of *Sphagnum*)that thrive in peatlands retain rainwater, so in addition to carbon sequestration, an important function of peatlands is the stabilisation of water flows from hills, which reduces the risk of flash flooding. Peat bogs also filter and clean catchments around lakes used as domestic water reservoirs. As a traditional source of domestic fuel, and more recently as a source of horticultural composts, peat bogs have been greatly damaged by peat mining and most are certainly in urgent need of conservation. But the mosses grow slowly and although one hectare of healthy peatland holds as much carbon as one hectare of tropical rainforest, they offer only limited promise for carbon sequestration. The Wikipedia entry goes on to explain that the water table of *Sphagnum* moss bogs must be maintained close to the surface to maintain the deeper layers of peat as a stable carbon sink. If they are drained or disturbed (by erosion or peat mining) the deeper layers are oxidised, and historical CO_2 is returned to the atmosphere. It comes down to deciding how much of your land do you want to cover in permanently waterlogged, and preferably frozen, peat bog?

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. Consequently, the aim of peatland restoration is to reduce the extent of these emissions as a contribution to the 'net zero future' (Natural Capital Committee, 2020). The authors of the Natural Capital Committee report refer to the huge publicity given to the UK's plans for planting 11 million trees to sequester carbon emissions, but they warn that conserving carbon in soils is equally or more important. The report states that '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*** 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/]. 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).

The overall conclusion seems to be that mass tree planting will harm the environment if not planned properly. Forests are only effective CO_2 sinks when they grow biomass or extend their area ***and 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 (Fig. 6). And when the tree dies there are legions of animals, bacteria and, especially, fungi (Fig. 7) just waiting for the chance to digest the forest's biomass and convert it back to atmospheric CO_2 as quickly as possible. ***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.

Indeed, it has been suggested that 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).

Sadly, our present forests are currently suffering from the effects of the climate changes that have already occurred. Many forested areas are dying due to drought, often amplified by more devastating wildfires, and virulent, newly emerged, and invasive pests and diseases (Demeude & Gadault, 2020). The threat to forests is worldwide and, in many cases, can be traced to invasions of non-native bark and ambrosia beetles which carry symbiotic fungi to feed their larvae within galleries they bore into the tree. It is the sudden appearance of pathogenicity in the fungus that is the new and currently uncontrollable threat to forest ecosystems, and fruit and timber industries, around the globe. Triggered by climate change, some invasive bark and ambrosia beetle/fungus symbioses are shifting from non-pathogenic saprotrophy in their native ranges to a prolific tree-killing in invaded ranges (Moore *et al*., 2020). We cannot rely on forests to mitigate the effects of climate change; they're dying because of it!

Despite all these negative reports and seemingly pessimistic facts regarding trees, 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).

China is currently the world's single largest emitter of CO_2, being responsible for approximately 27% of global fossil fuel emissions in 2017. Several Chinese provinces have established a pattern of rapid afforestation of progressively larger regions, with provincial forest areas increasing by between 0.04 million and 0.44 million hectares per year during the past 10 to 15 years (Wang *et al*., 2020). This large-scale expansion of fast-growing plantation forests is estimated to correspond to a Chinese land biosphere sink equivalent to about 45 per cent of annual anthropogenic emissions in China over that 10 to 15 year period. Though this sound extremely encouraging, Wang *et al*. (2020) also state that the afforestation effort "… contributes to timber exports and the domestic production of paper …", which means that the carbon sequestration is only temporary because the longevity of this impressive carbon sink is entirely dependent on the effectiveness and efficiency of future paper and timber ***recycling*** programmes. If these products are rapidly discarded, burnt or composted, the sequestered carbon they represent will be returned to the atmosphere.

Brienen *et al*. (2020) suggest that the lack of persistence of sequestered forest carbon raises the necessity of curbing greenhouse gas emissions; we, of course, would prefer to offer **an alternative *bio*technology** for really long-term carbon sequestration, as well as curbing the emissions. So, what about engineering solutions for 'aggressive emission reductions' to limit the rise of CO_2 concentrations in our atmosphere?

Most current research on 'aggressive emission reductions' is focussed on the integration of new technologies to capture CO_2 from flue gasses in power plants, which are responsible for about 80% of the worldwide CO_2 emissions (Romano *et al*., 2013). Methods based on exposing flue gas to water under suitable conditions ('hydrate-based processing') is a promising and high efficiency technology for CO_2 capture, but the high cost of maintaining suitable conditions for hydrate formation is preventing wide industrial application of this technology (Li *et al*., 2019).

So, if expanding the forests and capturing CO_2 from flue gases are unlikely to save us, are we doomed? Well, no, actually; we just need to change our focus; turn away from trees (but still plant them; forests are good for us in so many ways) and concentrate on ***shellfish*** (Moore, 2020; Moore *et al*., 2021; Heilweck & Moore, 2021).

The central thrust of the argument presented in the review you are reading now 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 $CaCO_3$*** as an aspect of their normal growth cycle.

The overwhelming advantages of calcifying organisms in this respect derives from their long evolutionary history (Moore, 2021). We will not discuss this here, but the essence of the story is that when the first precellular living things evolved they employed calcium ions to carry signals in many different processes. When all those processes were finally brought together in the first proper cells it became essential for these to develop precise control over their internal Ca^{2+} levels. Subsequently, at several to many times during the Earth's history the seas have become calcium-rich and in those calcium-rich waters the cells were in danger of having their calcium-control mechanisms over-stretched. While some cells coped with this by evolving improved calcium-control, the calcifiers followed a different evolutionary pathway to detoxify the calcium by reacting it with a waste product of their metabolism (CO_2) to make $CaCO_3$ shells, and by so doing they solved everybody else's 'excess calcium' problem. We should stress that using $CaCO_3$ this way was a specific evolutionary innovation and was far from an inevitable way to provide protection, which is the other function of these shells. Any fungus could make chitin reinforced with melanin for protection, any plant could make cellulose + lignin, and animals could make chitin and/or keratin and/or collagen, and even bone (which is a calcium + phosphate salt). So, calcifying organisms evolved in the distant past to detoxify the excess ***calcium*** as the carbonate salt in their environment, and we could harness them today to detoxify excess $\boldsymbol{CO_2}$ in our environment. They have a good track record for environmental engineering.

The review paper entitled *Rebuilding marine life* (Duarte *et al*., 2020) indicates that achieving the UN's Sustainable Development Goal 14 (to conserve and sustainably use the oceans, seas and marine resources for sustainable development) "… will require rebuilding the marine life-support systems that deliver the many benefits that society receives from a healthy ocean …". But they finally conclude that "… Rebuilding marine life represents a doable Grand Challenge for humanity, an ethical obligation and a smart economic objective to achieve a sustainable future …". In the opinion of Duarte *et al*. (2020), recovery rates seen in past studies of conservation interventions suggest that "… substantial recovery of the abundance, structure and function of marine life could be achieved by 2050, if major pressures — including climate change — are mitigated …". And in their letter to the journal *Science*, Gordon *et al*.(2020) assert that "… Marine restoration projects are undervalued …". In their final paragraph they conclude that "… [marine] restoration projects could help maintain species survival and ecosystem services, ultimately providing humanity with the breathing space to stabilize the climate …" (Gordon *et al*., 2020).

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. Forested land could be cleared again, but the reversion to intensive tillage would reverse any gains in soil carbon sequestration achieved by the afforestation. Similarly, restored coastal wetland could be drained again for agricultural use, losing any advantage gained by the wetland restoration. "… Although temporary CO_2 storage will have some climate benefit, scientific and economic requirements to ensure the permanence of storage within ecosystems are substantial …", but while we would offer easily cultivated calcifying organisms as candidates to provide these benefits, NASEM (2019) offers only bioenergy with carbon capture and sequestration (BECCS), direct air capture, and carbon mineralisation. Cultivation of coccolithophores, corals, crustacea and molluscs on a massive scale would make a massive and continued ameliorative contribution to the planetary ecosystem (Moore, 2021; Moore et al. 2021).It is the ***certainty*** and ***permanence*** of the removal of CO_2 from the atmosphere by these organisms that would make a biotechnology using calcifying organisms so attractive.

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