Climate, carbon, solutions and perspectives

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Abstract. We note that the recommendations proposed by activists, politicians and some scientists for CO_2 management are highly unbalanced: they mainly focus on reducing consumption and CO_2 emission more than measures to increase carbon sequestration, even though these are much simpler, more effective and cheaper than implementing a carbon footprint limitation at global level. We will present in this paper ways of sequestering atmospheric carbon, some of which currently occur without human involvement, while others could be used or used more intensively to reduce the concentration of CO_2 in the atmosphere. There are many viable and realistic methods of atmospheric carbon sequestration provided that this objective becomes a priority. Each of these methods plays a role in the global effort to mitigate climate change by removing CO_2 from the atmosphere and storing it in various natural and engineered reservoirs. The effectiveness and scalability of each approach can vary based on ecological, technological, and economic factors.
Key Words: climate change, CO_2, carbon sequestration, atmosphere, Paleogene, Neogene.

Introduction. While solar variability does influence Earth's climate, scientific evidence overwhelmingly supports the conclusion that human activities, particularly the emission of greenhouse gases such as CO_2 and methane, are the primary drivers of recent global warming. Multiple lines of evidence, including direct measurements, paleoclimate data, and advanced climate models, support the consensus view that human-induced emissions are responsible for the majority of the observed warming since the mid-20th century. This consensus is reflected in reports from scientific organizations such as the Intergovernmental Panel on Climate Change (IPCC), which consistently highlight the role of human activities in driving climate change and emphasize the urgent need for mitigation efforts to limit future warming and its associated impacts. We will present in this paper ways of sequestering atmospheric carbon, some of which currently occur without human involvement, while others could be used or used more intensively to reduce the concentration of CO_2 in the atmosphere.

Climate, CO_2 and Solar Radiation. The hypothesis that warming of the planet is primarily caused by solar radiation rather than human activity is often associated with arguments from climate skeptics or those who deny the significant impact of human-induced greenhouse gas emissions on global warming (Petrescu-Mag et al 2022). This hypothesis is typically based on the points presented below.

Natural Solar Variability. Proponents of this hypothesis argue that variations in solar activity, such as changes in solar irradiance (the amount of solar radiation received at Earth's surface) and solar cycles, play a dominant role in driving climate change. They suggest that increased solar activity leads to warming of the Earth's surface, while periods of decreased solar activity correspond to cooler temperatures.

Historical Climate Data. Some proponents point to historical climate records, including periods of warming and cooling throughout Earth's history, as evidence that natural factors, including solar variability, are the primary drivers of climate change. They argue that current warming trends may be part of natural climate cycles rather than solely attributable to human activities.
Uncertainty in Climate Models. Critics of the consensus view on anthropogenic climate change often highlight uncertainties and limitations in climate models used to simulate future climate scenarios. They argue that these models may not adequately account for the complex interactions between various factors influencing climate, including solar radiation, clouds, aerosols, and natural climate variability.
Lack of Correlation with CO_2 Levels. Some skeptics question the correlation between atmospheric carbon dioxide (CO_2) levels and global temperatures, suggesting that other factors, such as solar radiation, may have a stronger influence on climate variability.

Carbon Dioxide. Throughout Earth's history, carbon dioxide (CO_2) levels in the atmosphere have fluctuated, leading to significant climatic and geological changes. We will present in the next sections the periods of the geological past characterized by high concentrations of carbon dioxide in the atmosphere.

The Early Earth. During the Archean Eon (Archaeozoic) (4 to 2.5 billion years ago), the Earth's atmosphere was primarily composed of CO_2, with levels possibly thousands of times higher than today. This high CO_2 content was due to volcanic activity and lack of oxygen-producing organisms.

The Paleozoic Era
Ordovician Period (485 to 443 million years ago). CO_2 concentrations were relatively high during this period, likely around 4,000 to 4,500 parts per million (ppm). This contributed to a warmer climate and extensive marine life (Berner 1999; Berner & Kothavala 2001; Royer et al 2004; Veizer & Godderis 2015).
Carboniferous Period (358 to 298 million years ago). CO_2 levels peaked during this period, reaching as high as 2,000 to 3,000 ppm. This high CO_2, coupled with the proliferation of vast forests, led to the formation of extensive coal deposits (Berner 1999; Berner & Kothavala 2001; Royer et al 2004; Veizer & Godderis 2015).

The Mesozoic Era
Jurassic Period (201 to 145 million years ago). CO_2 concentrations were moderately high, estimated to be around 1,800 to 2,200 ppm. This period saw the dominance of dinosaurs and lush vegetation, indicating a relatively warm climate (Berner 1999; Berner & Kothavala 2001; Royer et al 2004; Veizer & Godderis 2015).
Cretaceous Period (145 to 66 million years ago). CO_2 levels remained elevated, possibly between 1,000 to 2,000 ppm. This warm period supported diverse marine life, including abundant plankton and coral reefs, as well as the proliferation of flowering plants (Berner 1999; Berner & Kothavala 2001; Royer et al 2004; Veizer & Godderis 2015).

The Cenozoic Era
Paleogene Period (66 to 23 million years ago). CO_2 levels gradually declined from the late Cretaceous, but remained relatively high compared to today, likely around 400 to 700 ppm. This period saw the evolution of mammals and the spread of grasslands (Zachos et al 2001; Beerling & Royer 2011).
Neogene Period (23 million years ago to present). CO_2 levels continued to decline, reaching levels similar to those of the present day. However, fluctuations occurred due to factors such as tectonic activity and the growth of ice sheets during glacial periods (Berner 1999; Berner & Kothavala 2001; Royer et al 2004; Veizer & Godderis 2015).

Nowadays. According to NASA, the Earth's atmosphere is predominantly composed of the following gases, in percentages: Nitrogen (N_2), approximately 78% of the volume of the atmosphere, Oxygen (O_2), about 21%, Argon (Ar), about 0.93%, Carbon dioxide (CO_2), about 0.041% (or 410 ppm), other gases: including neon, helium, methane, krypton, hydrogen and other compounds in very small amounts. In addition to these main gases, the atmosphere also contains variable amounts of water vapor, dust particles, pollen, and other substances (NASA Earth Science Division 2021).

Carbon dioxide is a danger to the biosphere both in too high and too low a concentration. The level of CO_2 required by plants, minimum minimorum, is 150-180 ppm. Proxy records indicate, however, that the Earth's atmospheric carbon dioxide concentrations did not fall below about 200–250 parts per million during the past 24 million years (Pagani et al 2005, 2009). According to Gerhart & Ward (2010), during the Last Glacial Maximum (18000-20000 years ago) and previous glacial periods, atmospheric CO_2 dropped to 180–190 ppm, which is among the lowest concentrations that occurred during the evolution of land plants. At a CO_2 concentration lower than these, life disappears. The stabilization of atmospheric carbon dioxide concentrations near this minimum value suggests that strong negative feedback mechanisms inhibited further drawdown of atmospheric carbon dioxide by high rates of global silicate rock weathering (Pagani et al 2009). The current level of CO_2 in the atmosphere is 400-410 ppm (0.041%) (Anwar et al 2020). The optimal concentration from the point of view of plant physiology would be 1000-1500 ppm (Castilla 2013). Concentrations of 1000 ppm are used in greenhouses to increase the yield (Ahamed et al 2019).

Scientists believe that Earth has not seen CO_2 levels exceed 400 ppm since the Pliocene era, roughly 3.6 million years ago. This increase in CO_2 appears to be correlated with average temperatures (Figure 1 and Figure 2). The rapid rise in CO_2 is too significant for the oceans to absorb and buffer in timescales relevant to human life. It takes around 1,000 years or more for the surface ocean to mix with the deep ocean (Siegel et al 2021). We have enough data to calculate the average annual increase in atmospheric CO_2 from 1960 to 2023:

$$2023 - 1960 = 63 \text{ years}$$
$$410 \text{ ppm } CO_2 - 316 \text{ ppm } CO_2 = 94 \text{ ppm } CO_2$$
$$94/63 \text{ years} = 1{,}492 \text{ ppm } CO_2 \text{ yearly}$$

This alarming situation calls for urgent action on the part of humanity.

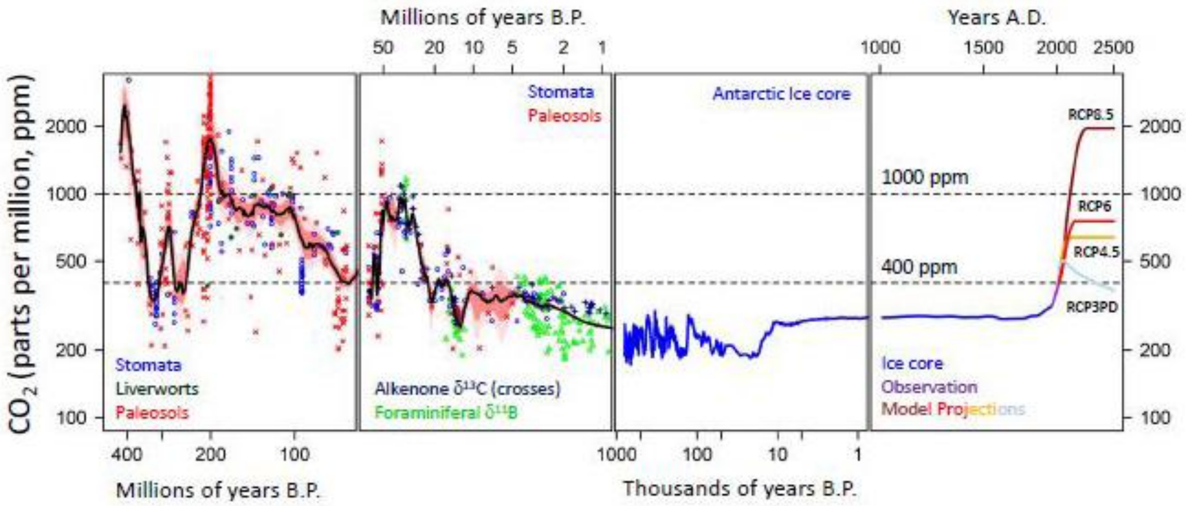

Figure 1. CO_2 levels over the past 500 million years. Foster et al – Descent into the icehouse (cited by Mulhern 2020).

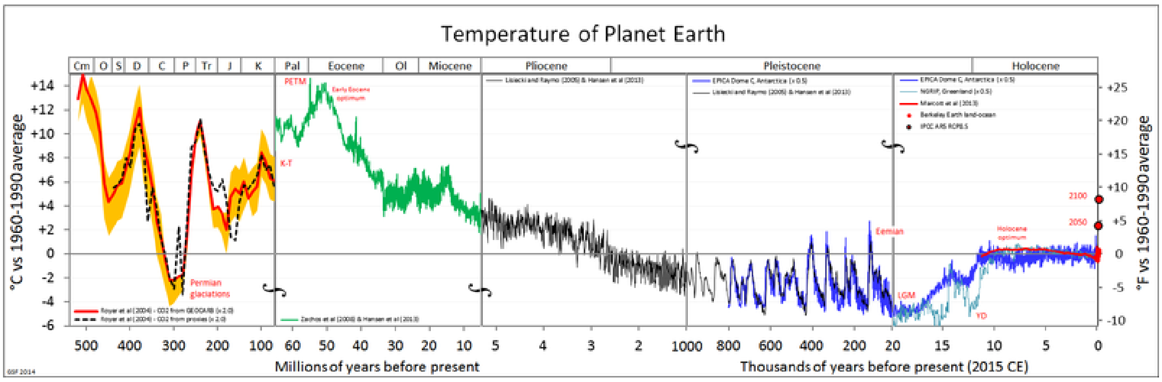

Figure 2. Temperature estimates over the past 500 million years. By Glen Fergus (cited by Mulhern 2020).

We note that the recommendations proposed by activists and scientists for CO_2 management are highly unbalanced: they mainly focus on reducing consumption and CO_2 emission more than measures to increase carbon sequestration, even though these are much simpler, more effective and cheaper than implementing a carbon footprint limitation at global level. We will next present ways of sequestering atmospheric carbon, some of which currently occur without human involvement, while others could be used or used more intensively to reduce the concentration of CO_2 in the atmosphere.

Carbon sequestration. Carbon sequestration refers to the process of capturing and storing atmospheric CO_2 to mitigate climate change.

Natural Carbon Sinks

Terrestrial Ecosystems and Marine Ecosystems

Forests: Trees absorb CO_2 through photosynthesis and store carbon in biomass (trunks, branches, leaves, and roots) and soil. Forest conservation and reforestation are critical for enhancing carbon sequestration.

Grasslands and Savannas: These ecosystems store carbon in soil and plant biomass. Sustainable land management practices can enhance their carbon storage capacity.

Wetlands and Peatlands: These areas are highly effective carbon sinks, storing large amounts of carbon in waterlogged soils. Preserving and restoring wetlands are vital for carbon sequestration.

Agricultural Lands: Practices such as no-till farming, cover cropping, and agroforestry can increase carbon storage in soils.

Oceans: The largest carbon sink on Earth, oceans absorb CO_2 from the atmosphere. Carbon is stored in dissolved forms and in marine organisms.

Mangroves, Seagrasses, and Salt Marshes: These coastal ecosystems, known as "blue carbon" habitats, sequester significant amounts of carbon in plant biomass and sediments.

Animal Organisms and Human Population: It is estimated that the total biomass of all animals on Earth sequesters around 2 gigatons of carbon (Benitez et al 2022). This figure highlights the significant role animals play in the global carbon cycle, an example from the marine ecosystem (Figure 3).

Geological Carbon Sequestration

Carbon Capture and Storage (CCS). CO_2 is captured from industrial sources or directly from the air and injected into deep geological formations such as depleted oil and gas fields, unmineable coal seams, and deep saline aquifers for long-term storage (Albertz et al 2023). Similar events occurred naturally on a large scale in the late Carboniferous and early Permian (collapsed biomass underground), resulting in today's coal and other fossil fuel deposits (natural gas and crude oil).

Technological Approaches

Bioenergy with Carbon Capture and Storage (BECCS). Biomass is used to produce energy, and the resulting CO_2 emissions are captured and stored geologically (Almena et al 2022). This approach can result in negative emissions.

Direct Air Capture (DAC). Technologies that directly capture CO_2 from the ambient air (Erans et al 2022). The captured CO_2 can be stored underground or utilized in products (Figure 4).

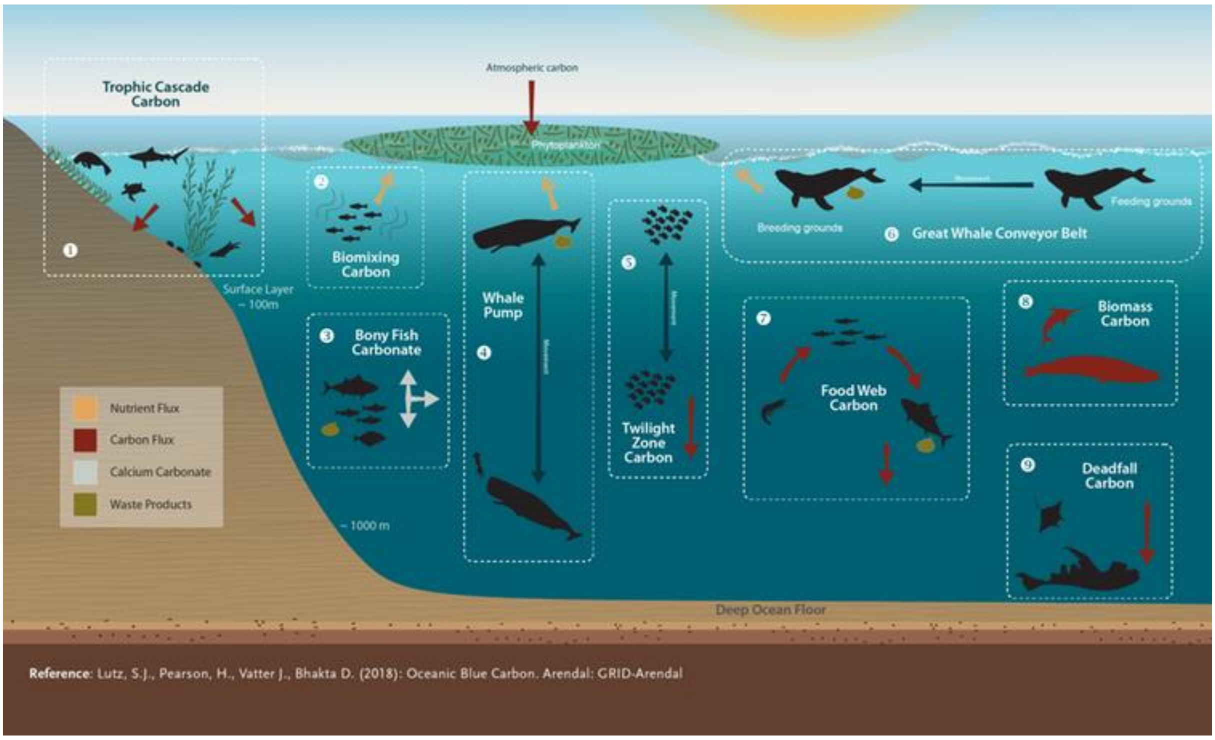

Figure 3. Living organisms contain biomass carbon, present in all marine animals. Whales, for instance, with weights reaching up to 50 tons and lifespans surpassing 200 years, can amass substantial carbon reserves over extended durations (Lutz et al 2018).

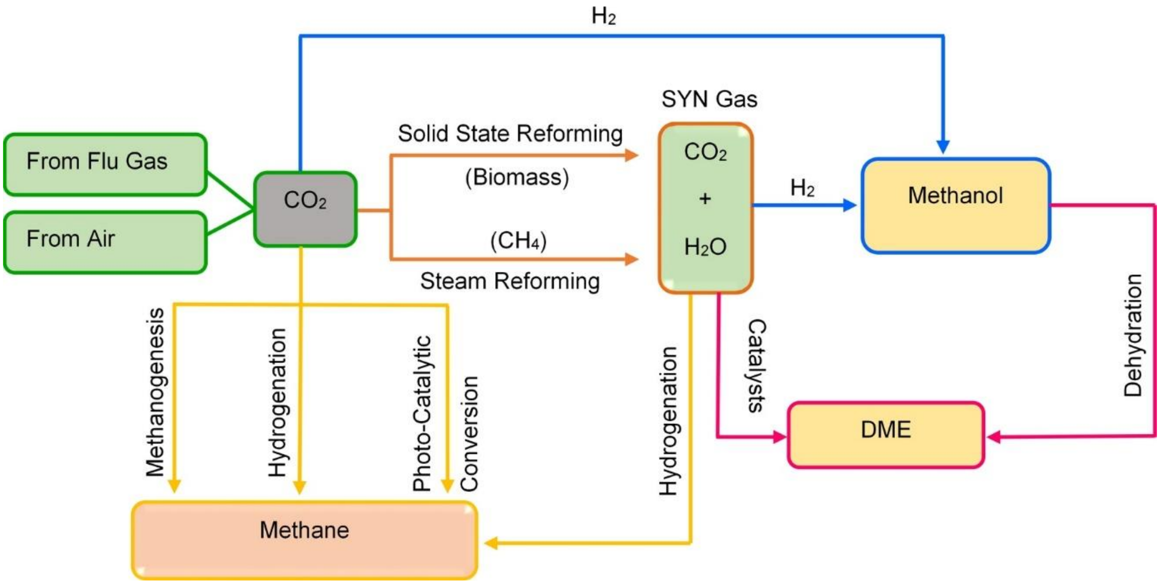

Figure 4. CO_2 utilization: Turning greenhouse gas into fuels and valuable products (Anwar et al 2020).

Enhanced Weathering and Ocean-based Techniques

Enhanced Weathering/Mineral Weathering. Certain minerals naturally react with CO_2 to form stable carbonates (Vienne et al 2022). This process can be accelerated by spreading finely ground silicate rocks on land or in oceans.

Ocean Fertilization/Iron Fertilization. Adding iron to ocean waters to stimulate the growth of phytoplankton, which absorb CO_2. When these organisms die, they sink, potentially sequestering carbon in deep ocean sediments (Denman et al 2006).

Urban and Built Environments

Green Infrastructure. Urban forests, green roofs, and green walls can sequester carbon while also providing other environmental benefits.

Building Materials. Innovative materials like biochar (Zhang et al 2022), green concrete (Grădinaru et al 2019), carbon-negative concrete (Chen et al 2022), and timber (Hart & Pomponi 2020) can store carbon for extended periods.

Plant-based CO_2 Drawdown and Storage as SiC. The concept of using plant-based mechanisms to draw down atmospheric CO_2 and subsequently storing it as silicon carbide (SiC) represents a promising approach to carbon sequestration (Thomas et al 2021, Figure 5). This method involves several key processes and advantages, as we shall see in the followings.

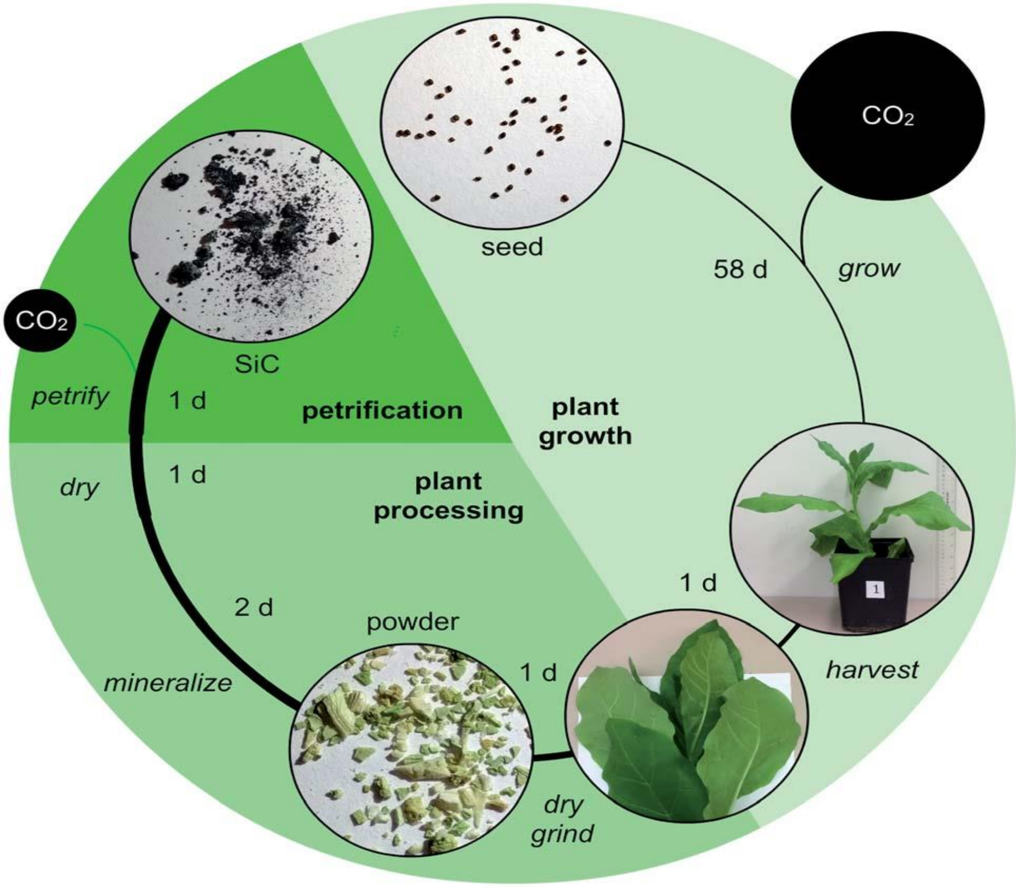

Figure 5. An artificial carbon cycle producing SiC from plants. This cycle involves three processes: plant growth, plant processing, and biomass petrification comprised of six steps (grow, harvest, dry, grind, mineralize and petrify) (Thomas et al 2021).

Photosynthesis for CO_2 Capture: Plants naturally absorb CO_2 from the atmosphere during photosynthesis, converting it into biomass. This is a primary and effective method of carbon capture, leveraging the extensive reach of vegetation across the globe.

Biomass Conversion: The biomass produced by plants can be processed into useful materials. Through pyrolysis (thermal decomposition in the absence of oxygen), plant biomass can be converted into biochar, a stable form of carbon that can enhance soil fertility and sequester carbon for extended periods.

Production of Silicon Carbide (SiC): SiC is a highly stable compound with diverse industrial applications, known for its durability and thermal resistance. The process involves: i) extracting silicon from biomass or biochar; ii) reacting the extracted silicon with carbon from the same biomass source under high temperatures to form SiC.

Carbon Storage: Storing carbon in the form of SiC offers long-term stability, as SiC is resistant to environmental degradation. This method not only locks away carbon but also provides valuable material for industrial use, creating a potential economic incentive for carbon sequestration.

The advantages of this technology are: i) environmental impact. This approach promotes sustainable agriculture and forestry practices, encouraging the growth of plant biomass and enhancing soil health; ii) economic potential. The production of SiC from biomass can create new markets and job opportunities, integrating carbon sequestration with economic development. iii) scalability. Leveraging natural processes and existing vegetation, this method can be scaled up to significant levels without requiring extensive new infrastructure.

Challenges: i) technological development. Efficiently converting biomass into SiC requires advanced technological processes and infrastructure, which may need significant investment and innovation. ii) economic viability: The cost-effectiveness of this method depends on the market value of SiC and the economic incentives for carbon sequestration.

Soil Carbon Sequestration

Biochar. Charcoal-like material produced from biomass through pyrolysis. When added to soils, it can enhance soil carbon storage and fertility (Li & Tasnady 2023).

Composting and Manure Management. Organic waste can be managed to enhance soil carbon content (Panettieri et al 2022).

Ecosystem Restoration

Reforestation and Afforestation. Planting trees on deforested or barren lands. Forests act as vital carbon sinks, absorbing CO_2 from the atmosphere through the process of photosynthesis and storing it as biomass. Here are two simple, natural, relatively inexpensive and effective examples of atmospheric carbon sequestration: i) afforestation of non-fertile lands, and ii) deforestation reduction through coercive measures and/or through financial incentives. CO_2 is the secret of the formation of organic matter from ancient times through photosynthesis:

$$CO_2 + H_2O \text{ ----> } C_6H_{12}O_6 + O_2$$

Earth's forests sequester a significant amount of carbon, playing a crucial role in the global carbon cycle. The total amount of carbon sequestered by Earth's forests is estimated to be between 450 and 650 gigatons of carbon (Abbas et al 2020). This carbon is stored in various components of the forest ecosystem, including biomass (living trees and plants), dead organic matter, and soil.

Breakdown of Carbon Storage in Forests:

Above-ground Biomass. This includes the carbon stored in the trunks, branches, leaves, and stems of trees and other vegetation. Tropical forests, which are the densest and most biodiverse, contribute the most to this storage.

Below-ground Biomass. Carbon stored in the roots of trees and plants. This below-ground component is essential as it contributes to the overall stability and resilience of the forest carbon pool.

Dead Organic Matter. Includes fallen leaves, dead trees, and other plant material that decompose and release nutrients back into the soil, while some carbon is retained in the form of partially decomposed organic matter.

Soil Organic Carbon. Forest soils can store a large amount of carbon, especially in the form of organic matter derived from decomposing plants and microorganisms. Boreal forests, in particular, have significant soil carbon stores due to slower decomposition rates in colder climates.

Regional Contributions:

Tropical Forests. Store approximately 50% of the carbon in forests globally due to their dense vegetation and extensive root systems.

Temperate Forests. Contribute significantly, though less than tropical forests, to global forest carbon storage.

Boreal Forests. Have substantial carbon storage, particularly in their soils, due to slower decomposition rates in cold environments.

Restoration of degraded lands. Improving soil health and vegetation cover on degraded lands to enhance their carbon storage capacity.

Conclusions. While high CO_2 levels in the past have been associated with warmer climates and different ecosystems, the rapid increase in CO_2 concentrations in recent centuries due to human activities has raised concerns about its impact on climate change and global ecosystems. Whether climate change is the result of human activity or more of changes in solar emissions remains a controversial topic. However, multiple lines of evidence, including direct measurements, paleoclimate data, and advanced climate models, support the consensus view that human-induced emissions are responsible for the majority of the observed warming since the mid-20th century. There are many viable and realistic methods of atmospheric carbon sequestration provided that this objective becomes a priority. Each of these methods plays a role in the global effort to mitigate climate change by removing CO_2 from the atmosphere and storing it in various natural and engineered reservoirs. The effectiveness and scalability of each approach can vary based on ecological, technological, and economic factors.

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