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The Recognition of Carbon Capture and Storage by Plants

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Abstract

The postulate that CO_2 is responsible for global warming is accepted by most governments which put in place restrictions and compensation for emissions of this gas. This resulted in the development of a carbon market and of the practice of carbon capture and storage (CCS), mainly by geological burying. CCS by plants, which allows the return of CO_2 to the atmosphere, should be preferred to CCS by burying which contributes to its lithification. Plant production captures this gas directly from the atmosphere using solar energy and stores it for a few months to a few centuries. Plant CCS figures are calculated for the world, the United States, Europe, France and Kenya, then compared to CCS ambitions. They show that agriculture and forestry absorb 21GtCO_2/year, more than half of global emissions by combustion of fossil hydrocarbons. This CCS function devolved to the peasantry complements that of supplying humanity with essential foodstuffs and should constitute a new source of remuneration for professions which often struggle to transmit, invest and innovate to ensure their future.

Keywords: carbon dioxide, capture, storage, photosynthesis, CCS, burying, plants, agriculture, forestry

1. Introduction

The atmospheric CO_2 content (ACC) increased from 270 parts per million by volume (ppm) in the mid-19th century to 420 ppm nowadays. This increase appears to be due to the release into the atmosphere of products from the combustion of fossil hydrocarbons, coal, oil and gas, which has since intensified. The increase in global temperatures observed over the same period would be due to these emissions according to the UN and its group of experts IPCC who equate them with pollution and call for their reduction. Most governments have adhered to this point of view and renew their approval at the annual COP (Conference of the Parties). One of the consequences is the allocation of tradable emission permits not to be exceeded (Kyoto protocol-1997) within the framework of a global carbon market. In order to move closer to neutrality, emitting activities are encouraged to purchase such permits from those which capture and store of CO_2 emitted, avoided, or taken directly from the atmosphere. Sites emitting more than 0.1 million tonnes (Mt) of CO_2 per year must offset their emissions through a carbon capture and storage (CCS) system or by purchasing emission permits, or carbon credits. Cultivated plants, which sustainably fix carbon dioxide from the atmosphere, constitute a CCS system. In what follows we compare that by burying and that by plants.

1.1 CO_2 Emissions

Figure 1 shows the distribution of CO_2 emissions by combustion of fossil hydrocarbons over the last half century for some countries and groups of countries as provided by the English association Global Change Data Lab (GCDL) (Ritchie, Rosado, & Roser, n.d.). Global emissions reached 37.15 billion tonnes (Gt) CO_2/year in 2022, increasing despite a decline in 2020 during the health crisis. The main emitting countries are China (11.40 GtCO_2/year), the United States (5.06 GtCO_2/year), India (2.83 GtCO_2/year), the European Union of 27 (2.76 GtCO_2/year). France (297.53 MtCO_2/year) and Kenya (24.85 MtCO_2/year) are mentioned for the purposes of this analysis.

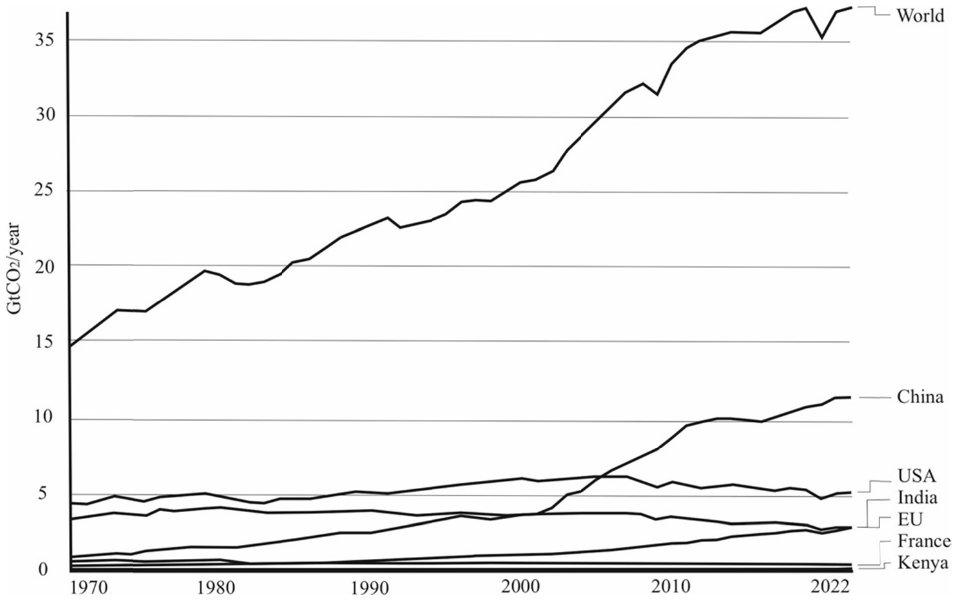

Figure 1. Variations over the last half century in carbon dioxide emissions by combustion of fossil hydrocarbons, in $GtCO_2$/year

Source: Global Change Data Lab (2023).

While the share of the most industrialized countries, which have an increasing use of low-carbon energies, has been decreasing since 2010, that of other countries, including China and India, which are actively constructing flame power plants, has been increasing since 2000. These emissions include those of other human activities and other greenhouse gases (GHG) which are grouped under the term "land use change" in IPCC reports without considering CCS by agriculture and forestry at the right level.

1.2 CCS by Burying

CCS by geological burying for several centuries is retained by most industrialized countries to achieve carbon neutrality in 2050. It appears to be the means of fulfilling the promises made by governments and renewed at successive COPs. If the agenda is not compliant and promises are not kept, penalties are provided. But it happens that countries denounce the binding agreements signed previously, as was the case of Canada which denounced the Kyoto protocol in 2011.

CCS by burying implements a chain of complex technological building blocks. In particular, the capture of CO_2 before or after combustion has been the subject of research for several decades. Its technology involves amine-based solvents or membranes. For example, a pilot of 4,000 tCO_2/year from steel production gases has just been commissioned on the ArcelorMittal site in Dunkirk (ArcelorMittal, n.d.). The gases first circulate in two 20-meters-high columns through a chemical solvent which fixes the CO_2. The next step regenerates the solvent and recovers more than 90% purified CO_2.

The purified gas is then compressed or liquefied for transport to a location for geological storage or use. Almost all solutions involve injecting of CO_2 into oil or gas wells. The geological storage sites are also old mines or diapirs. But all these solutions do not allow the recycling of CO_2 after centuries of storage. It is in fact an acid in the presence of water which reacts and combines with the geological substrate under the effect of temperature and pressure, which contributes to its lithification.

The use of CCS by burying does not necessarily imply a renunciation of fossil fuels. Also, its principle is widely criticized by proponents of global warming by CO_2 who would like to "decarbonize" the world economy. They consider CCS and emission permit quotas as rights to pollute.

1.3 World

Carbon neutrality assumes a CO_2 capture and storage capacity equivalent to fossil emissions, *i.e.*, approximately 37.15 $GtCO_2$/year. As this objective seems out of reach in the short term, a 55% emissions reduction milestone is planned for 2030. In July 2023, the total capacity of global projects under development, construction and operation was 361 $MtCO_2$/year, or 1% of fossil emissions. This modest capacity is increasing by almost 50% compared to 2022, according to the report on the global state of CCS (Global CCS, n.d.). Depending on the projects, the costs of CCS by burying vary between 90 and 140 US$ per tCO_2 with the share of capture representing between 50 and 80% of this cost. The most active countries in this area are those whose development is the most advanced (United States, EU, United Kingdom, Japan), or which produce oil (Saudi Arabia, Qatar, United Arab Emirates).

It seemed interesting to also look at a country with a low level of industrialization and seeking to escape poverty. We chose Kenya for its location in Africa where many countries have this profile. Incidentally, this is where human adventure commenced.

1.4 USA

In September 2023, 15 CCS by burying were in operation for a total of 22 $MtCO_2$/year, or 0.4% of national emissions. The incentive for the development of CCS is strong in the United States. Congress (Congressional Budget Office, 2023) allocated US$5.3 billion from 2011 to 2023, primarily managed by the Department of Energy (DOE), for CCS research and achievement. There is also US$3.4 billion from the American Recovery and Reinvestment Act in 2009, and US$8.2 billion from the Infrastructure Investment and Jobs Act of 2021 for the period 2022-2026. In addition, companies that capture and store CO_2 receive tax credits for each tonne sequestered. This is a strong incentive in favor of CCS since US$1 billion in tax credits were requested between 2010 and 2019. An envelope of US$5 billion from the federal budget is planned for these 2023 tax credits to 2027. The Inflation Reduction Act concludes that it could increase U.S. CCS deployment from 200 to 250 $MtCO_2$/year by 2030. The DOE Carbon Negative Shot aims to reduce the cost at US$100 per tCO_2. The EPA (Environment Protection Agency) is responsible for ensuring that storage is effective and sustainable. Agriculture and forestry are not identified in this context.

1.5 European Union of 27 (EU)

According to GCDL (Ritchie, Rosado, & Roser, n.d.), the EU's total fossil emissions have tended to decline since 1980. In 2022, they have decreased by 31% compared to 1990, according to the Environment Agency (European Environment Agency, 2024). At the end of 2020, the EU adopted a new climate objective for 2030 providing for a 55% reduction in its fossil emissions compared to 1990, *i.e.*, an objective of 2.13 $GtCO_2$/year. The President of the European Commission declared in March 2023 that the EU should permanently store 300 $MtCO_2$/year by 2050, which seems difficult to achieve without the use of CCS by plants.

The average price of Europe carbon credits (Toute l'Europe, 2023), resulting from auctions in a market which brought in 19 billion euros in 2020, increased from €37/tCO_2 in February 2021 to €90/tCO_2 in March 2023. The EU would like to set a carbon credit price high enough to encourage emitting industries to reduce their emissions. The revenue is distributed to Member States which must use at least 50% of the amounts for climate and energy-related measures (100% for aviation-related quotas).

1.6 France

During his speech on December 11, 2023, in Toulouse, the President of the French Republic (Macron, 2023) identified CCS as an important challenge with the objective of reducing industrial fossil emissions by 10% by 2030. As 88.5 $MtCO_2$/year are eligible for CCS, the stated objective is to implement a CCS of 8.9 $MtCO_2$/year. Onshore storage sites in France were identified in 2020 by ADEME (El Khamlichi et al., 2020) for a potential of 24 $MtCO_2$/year, higher than the announced objective. It was probably lowered for fear of societal opposition such as that against the exploitation of shale gas (Wikipedia, 2023b). On this occasion, the contribution of forests and oceans to emissions reduction was mentioned, but not that of agriculture.

The costs of CCS by onshore burying in France were estimated by ADEME at €100-150/tCO_2 in 2020, significantly above European market prices.

1.7 Kenya

According to the World Bank (La Banque Mondiale, n.d.), this country has "lower middle income, the only one in East Africa, the others being poorer". With 54 million inhabitants, this country is ranked 164th by GDP/capita, at $2,099. Known for its safaris and tourism, its economy has suffered severely from the covid crisis.

2. Material and Method

Plants directly capture atmospheric CO_2 to polymerize the carbon into biomass according to the process of photosynthesis at the origin of life, which appeared on earth 2.5 billion years ago. The carbonaceous material thus obtained nourishes the heterotrophs which degrade it by respiration. It is also mineralized by combustion. These polymerization and mineralization reactions are grouped under the same reversible chemical Equation (1),

$$6CO_2 + 6H_2O + E \leftrightarrow C_6H_{12}O_6 + 6O_2 \quad (1)$$

where, E is the energy of visible light in the direction of polymerization (from left to right) and the metabolic or combustion energy in the direction of mineralization (from right to left). This equation expresses that the consumption of CO_2, the production of oxygen and the production of organic matter in the form of hexoses correspond molecule for molecule. Hexose is the constituent element of plants, and its quantity is proportional to the biomass dry matter (dm).

The photosynthesis reaction (1) implements enzymatic chain processes involving in particular carbonic anhydrase and rubisco for the entry of this gas into the plant cell, then a series of reactions mainly modulated by visible light. Although the efficiency of transforming light energy into biomass is of the order of a few%, the resulting plant production is at the base of the animal food chain. Mastering all or part of this chain, peasant activities such as agriculture, forestry, hunting, fishing and aquaculture, feed humanity, clothe it, warm it, shelter it, etc.

It is necessary to distinguish between the stock and the flow, only the latter being considered to measure the fixation of atmospheric CO_2. The stock of organic matter in place (unexploited primary forests, necromasses, soil heterotrophs, peat, hedges, etc.) is relatively stable and plays a marginal role in the carbon polymerization - mineralization balance. Flow is the amount of plant biomass produced per unit of time, then harvested for use elsewhere later. It is the latter which captures and stores atmospheric CO_2 and constitutes a CCS to be accounted for in the same way as others.

The absorption of CO_2 by plant biomass therefore obeys the following proportionality:

$$A = k \sum_{i=0}^{n} (1 - Ei) \cdot Pi \quad (2)$$

where, *A* is the total CO_2 absorption of a sector or territory, *k* is a proportionality factor, *n* is the number of biomasses produced, *Pi* is the biomass of order *i* of the sector or territory, and *Ei* is its water content. Thus, to calculate the quantity of CO_2 *A* fixed by a plant biomass *Pi*, we start by removing its water by applying the hydration coefficient *Ei*, then we multiply by the CO_2/dm ratio, *i.e.*, 1.47 tonne of CO_2 per tonne of biomass dry matter, entering the composition of the proportionality coefficient *k*.

In what follows, we consider marketed agricultural and forestry production as described by FAO statistics (FAO, 2024). They detail the production of crops, livestock and forests responsible for continental absorption of CO_2 by photosynthesis.

According to the stoichiometry of Equation (1), one tonne of anhydrous biomass (dm) fixes 0.4 tonne of carbon (C/dm). This ratio varies with the type of molecule considered between 0.4 for glucose and 0.6 for ethanol and will have to be adjusted according to the type of biomass, or even the species. We apply a C/dm ratio of 0.45 for herbaceous plants and 0.5 for wood which enters the composition of the coefficient *k* of Equation (2) to estimate the carbon stored by three families of plant production: crops, fodder and forests.

2.1 Crops

These are herbaceous plants cultivated for food (cereals, vegetables, fruits, etc.), their textile fibers (cotton, linen, hemp, etc.) or for pleasure (tobacco, grapes, flowers, etc.). The statistics concerning them are described in the "Productions" section, then "Crops and animal products". The water contents *Ei* of the plant products used here (Teneur en Eau des Aliments, n.d.) made it possible to obtain an average water content by weighting the "Production-Quantity" statistics for "Primary Crops" for the year 2022. The weighted average *Ei* of 50% of water thus obtained is put as a common factor in the coefficient *k* of Equation (2) which takes the value of 0.82 to be applied to crops expressed in tonnes.

2.2 Fodder

The quantities of meat, milk and eggs consumable by humans expressed in tonnes are described in the "Production-Quantity" and "Primary Livestock" statistics. These products are mainly intended to supplement the human diet with quality proteins and a set of micro-nutrients such as vitamins A, B-12, riboflavin and mineral salts. They result from the conversion by ruminant and monogastric animals of plants from meadows, foliage and crops. According to Mottet et al. (2017), global livestock consumed 6 Gt/year of anhydrous fodder for an animal protein production of 74,601 Mt/year in 2010. This corresponds to a protein/animal product ratio of 6.5%. The feed conversion rate giving the weight of anhydrous fodder per weight of animal protein is 80 for all species combined to be included in coefficient *k* of Equation (2).

Some crops described in the previous section are intended for animal feed and is also included in this calculation. According to Mottet et al. (2017), 14% of the tonnage of fodder of global livestock is consumable by humans and must be deducted from fodder calculated on livestock products to avoid double counting. The coefficient ***k*** of Equation (2) for fodder takes the value 7.44 to be applied to the sum of the quantities of unprocessed livestock products consumable by humans expressed in tonnes.

2.3 Forests

Statistics on the quantities of wood produced worldwide are available in the "Forests" section of "Data" in (FAO, 2024). These "Production-Quantity" of firewood, sawlogs, pulpwood and industrial wood are expressed in m^3 and must be converted into tonnes. For this, a density of 0.55 t/m^3 is applied as well as the average humidity level of 35%. Under these conditions, the coefficient k of Equation (2) for forestry takes the value 0.65 to be applied to the sum of the quantities of primary wood expressed in m^3, excluding processed products.

3. Results

Global plant production has enabled the capture and storage of 21 $GtCO_2$/year in 2022 (Table 1), which offsets more than half of emissions from the combustion of fossil hydrocarbons in the world. The highest contribution is that of Fodder (51%) followed by Crops (37%), then Forests (12%).

Table 1. Carbon Capture and Storage ($GtCO_2$/year) by cultivated plants for some countries and groups of countries, and compensation rate for their fossil emissions in 2022

	Crops	Fodder	Forests	Total CCS	% Fossil emissions
World	7.88	10.71	2.61	21.21	57
USA	0.55	1.22	0.30	2.07	41
EU	0.48	1.60	0.33	2.41	87
France	0.10	0.22	0.03	0.36	121
Kenya	0.02	0.05	0.02	0.09	354

With 21 $GtCO_2$/year, the CCS by plants constitutes the most efficient CCS system of the planet. Especially, it exceeds 50 times the global CCS by burying described above. In comparison, the ocean absorbs 5.9 $GtCO_2$/year according to Muller-Feuga (2023), 6.6 $GtCO_2$/year according to Fay et al. (2023), and 10.6±1.5 $GtCO_2$/year according to Friedlingstein et al. (2022), or between two and three times less than the CCS by plants.

In the United States, CCS by plants offsets 41% of emissions. Surprisingly, this important contribution is not considered in the quest for carbon neutrality. Photosynthesis is only considered for the use of CO_2 extracted from combustion gases, after capture by sophisticated physicochemical processes.

Almost all EU emissions (87%) are offset by CCS by plants. Europe considers a priority to find adequate financial rewards to promote carbon removal in the different sectors of agriculture, forestry and industry (Margaras & Jensen, 2022) but has still not recognized CCS by plants. Several countries are aware of the important role of plant crops but are nevertheless raising the question of certification, on a scientific basis accepted throughout the EU, of CO_2 capture by plants and the duration of storage.

France is highly decarbonized, with most of its electricity being of nuclear origin. Without any incentive or modification of practices, the French peasantry captured and stored 121% of national emissions in 2022, *i.e.*, 40 times the CCS objective for 2030, and four times the industrial emissions eligible for CCS.

The absence of consideration of agriculture and forestry in the compensation of CO_2 emissions would remain an injustice if there was not some sign of recognition underway which marks a significant evolution towards a repair of this oblivion harming peasantry. Thus, since 2020, the French government has identified a so-called voluntary carbon offset market (Ministère de l'Agriculture et de la Souveraineté Alimentaire, 2022) which provides that "… farmers can put the carbon credits that they have released, and certified by the low-carbon label, on the voluntary carbon offset market". At the France Grandes Cultures congress held in February 2023 (La France Agricole, 2023), the Association for the Promotion of Sustainable Agriculture announced a minimum price of €50 per stored tCO_2 (carbon credit) paid to the farmer. The average of field crops is credited with around 1.5 tCO_2/ha/year captured and stored, which is ten times lower than our estimate of around 13 tCO_2/ha/year for grain corn and 12 for wheat. Soil Capital mentions €33 per tCO_2 paid to the farmer in 2022, which represented on average €5,000 per farm per year. The remuneration of CCS by plants, on the average basis of €100 per tCO_2, would generate 23 billion euros of additional revenue to be added to the 57 billion euros of products sold in 2021, *i.e.*, an increase in French peasant income of around 40%.

In a recent article Muller-Feuga (2023), we estimated that photosynthesis set 29 $GtCO_2$/year, or 85% of global fossil emissions in 2020. These excessively high figures resulted from an error in the use of FAO statistics consisting in not distinguishing between the primary cuts of standing trees and the processed products resulting from these cuts, which amounted to counting the exploited biomass twice. This error was corrected and Figure 2 describes the evolution of CCS by plants over the last half century. It highlights the progression of fossil emissions and global absorption of CO_2 by plants in a proportion of 54 to 63% depending on the years.

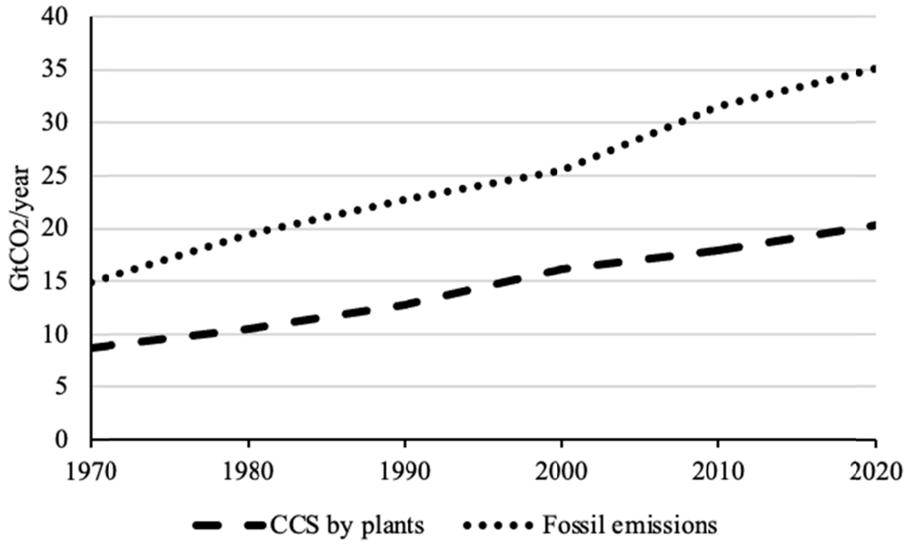

Figure 2. Evolution over the last half century of CO_2 emissions from combustion of fossil hydrocarbons and CCS by plants ($GtCO_2$/year)

At the same time, the world population doubled from 3.7 billion to 8.0 billion. Mainly due to this growth, the agricultural area per capita was reduced by half, from 1.2 to 0.6 ha/c. Plant production is going through a prosperous period as shown by NASA satellites that measure leaf area (Hille, 2016). The greening of the earth over the last 35 years was stated, 70% of which is attributed to CO_2 fertilization. The increase in the ACC from 300 to 420 ppm is the main cause of the improvement in overall agricultural production yields per unit area (Haverd et al., 2020), which more than doubled, from 0.5 to 1.3 t/ha/year, in half a century, according to 2019 FAO statistics. Thanks to this outperformance, production per capita has increased from 0.51 to 0.60 t/c/year over the last half century, which has significantly contributed to reducing difficulties in accessing food.

4. Discussion

The consideration of CCS by plants is intended to extend to all plant production placed on the market. The duration of storage varies between a few months (fruits and vegetables) and several centuries (construction timber). The remuneration of CCS by plants would represent a significant gain for the peasantry who would now have the mission, in addition to the existential supply of essential foodstuffs for humanity, to avoid or compensate for CO_2 emissions to limit climate change for which this gas would be responsible.

Note here that there are other plant resources, cultivated or not, which could constitute CCS by plants. This is how cultivated macroalgae contributed 60 $MtCO_2$/year (0.2%) worldwide in 2020. Sargassum which naturally invades the equatorial Atlantic could be harvested at sea then transformed into biofuel and fertilizer, which would reduce the use of fossil fuels and, simultaneously, the disastrous strandings on the eastern coasts of America and the Caribbean islands. The processing of this sargassum could produce 8,500 barrels of crude oil per day according to Marx et al. (2021), for a CCS of 1.9 $MtCO_2$/year, or 20% of the French objective for 2030.

In the IPCC reports, neither chapter 3 of 2005 devoted to CO_2 capture (IPCC, 2005), nor the summary report mentions photosynthesis. We must go to the 251st page of the full Climate Change 2022 report (IPCC, 2022) to find this word and be reminded that plants capture CO_2 directly from the atmosphere, without drawing any practical consequences from it. It is as if this process at the basis of life did not exist. We want here to contribute to the repair of this omission which we believe voluntary as it is systematic. What looks like denial is probably intended to reinforce the demonization of this gas.

The agricultural sector is the subject of denigration for its emissions of CO_2, methane (CH_4) and nitrous oxide (N_2O). This sector would be responsible for 23% of global anthropogenic greenhouse gas (GHG) emissions, or 12 Gt of CO_2 equivalent/year (Marechal & Bellon, 2022). As if photosynthesis does not exist, detractors do not consider the emission-absorption balance which remained largely favorable to the peasantry with 9 $GtCO_2$/year removed from the atmosphere in 2022.

We also wish to place this analysis in its space-time context. Climate determinism remains inaccessible because it is dynamic, multifactorial, nonlinear, and random. We cannot claim to model future climates, much less explain their evolution by a single factor. Though being the heaviest atmospheric gas, CO_2 is in the minority with only 0.04% by volume. The influence of the astral environment on the climate is not sufficiently or never considered in the prosecution's arguments which maintain that the current increase in the ACC would be the cause of global warming and want to reduce emissions. They shame this gas by calling it a GHG.

The ACC has been divided by 100,000 since the origin of the Earth 4.5 billion years (Gy) ago, and this decrease continues inexorably. Since the appearance of life in Precambrian, it still reached 7,000 ppm (17 times more than today) in Cambrian 540 million years (My) ago, then 1,800 ppm (4.3 times more than today) in Jurassic (-200 My). No catastrophic warming has interrupted the development of life that appeared 3 Gy ago. Glaciations sometimes coincided with high ACC (Carboniferous-Permian), which indicates an absence of temperature control by CO_2.

The worrying decrease in the ACC during the history of the earth is due to the trapping of carbon at the bottom of oceans (lithification) in the form of limestone rocks (100,000 Tera $\{10^{12}\}$ tonnes of carbon) (Sorokhtin, Chilingar, & Khilyuk, 2007) and hydrocarbons fossils (approximately 1.6 TtC identified). The present increase of ACC is only a temporary respite in a slow and inexorable decrease.

However, below 100 ppm of CO_2, photosynthesis is compromised. That of C3 plants (wheat, rice, barley, beans, cassava, soya, …) is interrupted, and the yield of C4 plants (corn, sorghum, sugar cane, etc., *i.e.*, 30% of cultivated plants) and CAM decreases sharply (Wikipedia, 2023a). We have already come close to a CO_2 breakdown by dropping to 150 ppm in Carboniferous-Permian (-300 My) then in Pleistocene (-2.6 My to -11,700 years). For these reasons and to prolong the availability of this precious gas, CCS by plants should be preferred to that by burying which contributes to its lithification.

5. Conclusions

From this analysis, it appears that:

• CO_2 is a planetary wealth to be preserved because its depletion compromises life on earth over a geological period.

• The recycling of fossil carbon by combustion of hydrocarbons constitutes a temporary respite in this scarcity process.

• We must avoid burying CO_2, which contributes to its lithification and removes it from the life cycle.

• Increasing the ACC promotes crop production and reduces tensions over access to food products.

• We must recognize and prefer CCS by plants over periods ranging from a few months to a few centuries and generalize its consideration in carbon balances.

In addition to feeding, clothing and sheltering humanity, the peasantry contributes to the reduction of CO_2 emissions believed to be the cause of climate change. Here we propose an incomplete and perfectible approach to quantify this contribution which should be given a fair reward to help ensure the survival of these crucial occupations.

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