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Reappraisal of the Place of Cultivated Plants in the World Carbon Budget

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Abstract

The impact of agriculture on the atmospheric CO_2 remains underestimated due to the systematic exclusion of annual crops from carbon budgets. Considered too ephemeral, these crops are nevertheless responsible for the absorption and storage of approximately one-third of the carbon biofixed by photosynthesis, with half-lives that are not limited to a single season but extend on average over 8.9 years. The kinetics of variation in carbon capture and release by cultivated plants over the half-century were simulated to complete the probabilistic calculation of the carbon budget components. In 2023, all cultivated plants (crops, grasslands, and forest plantations) had a stored carbon half-life of 17.6 ± 0.7 years. They had removed 39.2 ± 0.5 billion tons of CO_2 ($GtCO_2$) per year from the atmosphere, more than global emissions from hydrocarbon combustion. This net anthropogenic sink of −31.0 ± 1.9 $GtCO_2$ compensated 82% of those emissions. The time distribution allowed by this simulation suggests that cultivated plants have absorbed a cumulative net stock of 123.3 ± 3.9 billion tons of carbon (GtC) in 2023, or 14% of the atmosphere. Given the importance of this component of the carbon budget, both in duration and quantity, rural activities should be integrated into carbon budgets to define resulting climate strategies. This recognition would allow for the fair reward of the work of farmers and foresters as part of the ecological transition, particularly through remuneration mechanisms such as carbon credits.

Keywords

CO_2, Agriculture, Forestry, Carbon Budget, Ocean, Annual Crops

1. Introduction

The evolution of Earth's climate has long been a subject of particular attention. Decision-makers strive to identify the most influential factors to predict their evolution and act on them, when possible, particularly if they pose risks to humanity. The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). Its mandate is to impartially assess international scientific, technical, and socio-economic information on climate change. Since its first report in 1990, and regularly every 5 - 6 years, the IPCC issues a synthesis report that summarizes the contributions of three working groups involving hundreds of specialists. These assessment reports serve as a reference for scientists and decision-makers around the world and are the basis for policies implemented by most OECD and European Union countries.

This scientific production, at the heart of international climate negotiations, aims to alert decision-makers and civil society. Since the IPCC's creation, all its reports have been adopted in plenary session by all 192 countries represented. The IPCC's annual budget of approximately five million euros in 2012 increased to six million euros in 2021. It is funded by the 195 UN member states who contribute "independently and voluntarily". Several hundred scientists participate in the preparation of reports that present the situation of climate change as the consequence of emissions, particularly of carbon dioxide, and recommend binding restrictions on the use of fossil fuels.

Global warming, which has been occurring for half a century at a rate of 0.19˚C every 10 years (Met Office Hadley Centre, 2024), is believed to be a greenhouse-type process and the consequence of the emission of CO_2 produced by the combustion of fossil fuels into the atmosphere since the beginning of the industrial era. The atmospheric CO_2 content (ACC) has increased from 270 parts per million by volume (ppm) in the mid-19th century to 420 ppm. This increase appears to be due to the release of products from the combustion of fossil fuels, coal, oil, and gas, which has intensified since then. The increase in global temperatures observed over the same period is believed to be due to these emissions, which are presented as pollution.

According to the most recent scenarios, which assume a warming of 1.5˚C, global sea levels could rise by between 0.26 and 0.77 m by the end of this century. Such an increase would be detrimental to populations living on low-lying coasts. Strong measures should be taken quickly to prevent the enrichment of the atmosphere with carbon dioxide from causing lasting global climate change in the coming decades. According to the 5th report, a doubling of the ACC would cause a 2.8˚C increase in the average tropospheric temperature, currently 14.5˚C. This average warming is significant compared to that following a glaciation, which is 4˚C.

Most governments have embraced this view and renew their endorsement at the annual COP (Conference of the Parties). One consequence is the allocation of tradable emission permits that must not be exceeded subject to penalty (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 that carry out carbon capture and storage (CCS) emitted, avoided, or removed directly from the atmosphere. Sites emitting more than 0.1 million tons of CO_2 ($MtCO_2$) per year must offset their emissions with a CCS system or purchase emission permits or carbon credits.

CCS through geological burial for several centuries is being adopted by most industrialized countries to achieve carbon neutrality by 2050. It appears to be the means to fulfill the promises made by governments and renewed at successive COPs. If the agenda is not compliant and the promises are not kept, penalties are imposed. However, countries sometimes denounce previously signed binding agreements, as was the case with Canada, which denounced the Kyoto Protocol in 2011.

The development of CCS through landfilling is sometimes perceived as compatible with the continued use of fossil fuels, raising questions about its actual contribution to carbon neutrality. Its principle is also widely criticized by those who would like to "decarbonize" the global economy and who view CCS and emission permit quotas as pollution rights.

Carbon capture and storage in plant products marketed by crops, livestock, and forestry, based on FAO (n.d.) statistics, has been estimated (Muller-Feuga, 2024a) at 21 billion tons of CO_2 ($GtCO_2$ or $PgCO_2$) per year in 2022. Subsequently, the non-commercial parts carrying these productions were taken into account (Muller-Feuga, 2024b), which increased the carbon capture and storage by whole cultivated plants (CCSP) to 41.0 ± 0.6 $GtCO_2$/year and the average storage duration weighted by carbon weights to 26.3 ± 2.0 years in 2022. These figures were much higher than those in the literature: 3.2 times the continental sink of Friedlingstein et al. (2022) estimated at 12.8 ± 3.3 $GtCO_2$/year, and 2.1 times that of Pan et al. (2024) estimated at 19.8 $GtCO_2$/year. The analysis was completed by that of the evolution over 50 years (Muller-Feuga, 2025) of the CCSP and the restitutions by respiration, fermentation and combustion to which they give rise. It showed that plant cultivation constituted an average sink of 39.9 $GtCO_2$/year removed from the atmosphere during the ten years preceding 2022 and offset the 36 $GtCO_2$ emitted by the combustion of fossil hydrocarbons. It also showed that the global ocean was a growing source of 10.6 $GtCO_2$/year on average during the last decade.

These differences appear to be due to the failure to take annual plant crops into account in carbon budgets. We noted a specific provision in the document describing the methods and guidelines (IPCC, 2006a, 2006b) for researchers. In Chapter 5: "Cropland," is written "The change in biomass is only estimated for perennial woody crops. For annual crops, increase in biomass stocks in a single year is assumed equal to biomass losses from harvest and mortality in that same year, thus there is no net accumulation of biomass carbon stocks". This was confirmed by the 2019 edition of the guidelines (IPCC, 2019). Among cultivated plants, it is explicitly recommended to consider only perennial woody crops such as tea, coffee, oil palm, coconut, rubber trees, fruits and nuts, and polycultures such as agroforestry systems (e.g. Walker et al., 2021). This significantly reduces the proportion of plants entering the carbon budgets at the origin of the climate protection policy. However, carbon remains included in plant biomass during the few months to few centuries that separate the start of growth from mineralization causing its return to the atmosphere in the form of CO_2.

This exclusion of annual plants on the pretext that their carbon is rapidly released does not correspond to reality, except in the very rare case where the crop is burned. Even in this extreme situation, the underground parts, which are a significant part of the biomass, persist for several decades. The death of the annual plant following harvest does not imply the disappearance of the carbon they have accumulated. Cereals, including corn, wheat, and rice, which account for just under half of global agricultural production, have virtually infinite storage life under the right humidity and temperature conditions, whether as grains or processed into biscuits, pasta or noodles. In addition to stabilizing prices, this allows for their long-distance transportation and the creation of strategic reserves for populations affected by crises or located far from production areas.

According to the FAO Cereal Supply and Demand Bulletin (FAO, 2025), global cereal production forecasts were 2,849 million tons in 2024, capturing 3.8 $GtCO_2$/year from the atmosphere. Utilization forecasts for 2024-2025 are projected at 2,868 million tons. By the end of the 2025 season, global cereal stocks are expected to reach 873.3 million tons. The stock-to-use ratio of 30.1% suggests a rotation period of approximately three years.

For rice, the main Asian cereal, the closing stock of each production year represents one-third of utilization, which helps control world prices (FAO, 2018). This assumes a complete rotation at least every three years. Japan recently opened its strategic rice reserves to cope with soaring prices, which nearly doubled following the poor 2023 harvest. Of a total of approximately one million tons, 210,000 tons have been sold (The Mainichi, 2025). This is the first time since their creation in 1995 that these reserves have been consumed, representing a storage period of 30 years.

More generally, the global rice consumer price index shows a persistent upward trend, which is encouraging countries to import and build up reserves. The example of the Sahel demonstrates the extent to which food reserves are an important component of food security worldwide. The number of undernourished people in the world was 733 million in 2023, representing 9.1% of the global population (FAO, 2024). The rotation of global food reserves is a strategic issue for ensuring food security and addressing current and future crises.

Thanks to their intrinsic capacities and conservation techniques, stocks constituted by annual plants persist well beyond the harvest year, and there is no obvious justification for excluding them from carbon balances given the importance of their contribution. Cultivated plants fix carbon dioxide from the atmosphere and constitute a CCS device both in terms of quantities and duration. Here we provide the necessary updates and corrections, and examine their consequences.

2. Material and Methods

2.1. Photosynthesis

Plants directly capture atmospheric CO_2, then polymerize the carbon into biomass using the photosynthesis process that gave rise to life on Earth 2.5 billion years ago. The resulting carbon feeds heterotrophs, which degrade it through respiration. It is also mineralized through fermentation, ignition and combustion. These polymerization and mineralization reactions are grouped under the same reversible chemical Equation (1).

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

E is the visible light energy in the direction of photosynthesis (from left to right) and the metabolic or combustion energy in the direction of respiration (from right to left). This equation expresses that CO_2 consumption, oxygen production, and the production of organic matter in the form of hexoses correspond molecule for molecule.

Photosynthesis implements a chain of enzymatic processes involving carbonic anhydrase and rubisco for the entry of this gas into the plant cell, followed by a series of reactions modulated by visible light. This reaction (1) lacks other essential but minor assimilable elements such as nitrogen, phosphorus, iron, etc. However, this reaction (1) is retained here because we limit our analysis to carbon.

Hexose is the basic building block of plant matter, and its quantity can be measured by the dry plant biomass (dm) according to the stoichiometry of the chemical reaction (1). The carbon/dry-matter ratio (C/dm) it provides varies with the type of biomass and should be adjusted for each case. Indeed, it is 0.40 for glucose, 0.44 for cellulose, 0.64 for hemicellulose, and 0.66 for lignin. Despite this variation and for conservative simplification, we retain the value of 0.4 provided by reaction (1) for all biomasses. One ton of dry plant biomass from primary production contains 0.4 tons of carbon (C/dm) and required 1.47 tons of CO_2 (CO_2/dm) taken from the atmosphere. In the opposite direction, one ton of dry organic matter releases 1.47 tons of CO_2 during its mineral degradation through respiration, fermentation or combustion.

Although the efficiency of converting solar energy into biomass is in the order of a few percent, the resulting plant production is a significant carbon sink. Controlling all or part of the food chain, agriculture, livestock farming, forestry, hunting, fishing, and aquaculture, do feed, clothe, warm, shelter, entertain, etc. humanity. Here, we consider the net primary production, after autotrophic respiration, of these activities, which remove carbon dioxide from the atmosphere and store it in the form of biomass. As such, they are involved in the carbon cycle and budget.

A distinction is made between stock and flow, the latter being the derivative with respect to time of the former. In annual budgets, only the flow of captured and stored atmospheric CO_2 is taken into account. It is proportional to the quantity of plant biomass produced annually and then harvested for later use elsewhere. Conversely, the stock measured in tons of carbon is the quantity of carbon stored in a place at a given time. Only the flow creates a CCS system measured in tons of CO_2 that can be compared to those by burying (Muller-Feuga, 2024a).

2.2. The Atmospheric CO_2 Budget

The world CO_2 absorption by cultivated plants photosynthesis (noted AW), and world CO_2 emission by respiration of those that feed on them, fermentation or combustion (noted EW) are the plant components of the global atmospheric carbon budgets. They are compared to equivalent components from literature, land sink (noted SLAND) and land use change emission (noted ELUC). The variation in atmospheric CO_2 (noted ACV) and emissions from fossil fuel combustion (noted EFOS) complete the carbon exchanges between the world continents, atmosphere, and oceans. The budget of CO_2 is given by Equation (2) which describes the equilibrium between these 4 components and where the sources are positive and the sinks negative. Given the extreme complexity of the ocean's behavior, heterogeneous in three dimensions and over time, its contribution OC is the unknown of this equation.

$$-\mathrm{ACV} - \mathrm{AW} + \mathrm{EW} + \mathrm{EFOS} = \mathrm{OC} \tag{2}$$

The estimate of AW is based on the stoichiometry of reaction (1) in the direction of photosynthesis from left to right whereas EW results of the same reaction in the direction of respiration from right to left. This approach is of accounting nature and does not use digital models based on satellite or field-measured data, but relies only on agricultural and forestry commercial productions statistics declared by governments and collected by the Food and Agriculture Organization of the United Nations (FAO).

2.3. Capture and Storage Durations

The history of carbon in agricultural and forestry products is divided into the period of capture by photosynthesis (CP) and the period of restitution by mineralization (RM). Harvest marks the transition between the two periods CP and RM. The first period (CP), which separates the beginning of plant growth, sowing, planting, or previous harvest (n − 1), from harvest (n), gradually builds up the carbon pool through photosynthetic capture of CO_2 from the atmosphere. This period lasts from a few months for annual plants to a few decades for trees. Since the weight growth over time of fruits and vegetables generally exhibits an S-shaped curve (e.g., Tijero et al., 2021), the amount of CO_2 captured is assumed to be distributed over time according to an increasing normal cumulative distribution.

During the second period (RM), mineralization occurs after harvest, during which the polymerized carbon is mineralized and returned to the atmosphere as CO_2 through food ingestion followed by digestion and respiration, fermentation, or combustion. The organic matter is stored on shelves, in bulk, or in the soil, then ingested, fermented, or burned. This period varies from a few days for perishable fruits and vegetables to several centuries for structural timber. As for CP, we assume that this CO_2 restitution is distributed over time according to a decreasing normal cumulative distribution.

Pending more suitable probabilistic laws, the normal law is chosen here for its continuity, easiness of handling and aptitude to well describe the phenomena influenced by many factors, none of which is predominant. The probabilistic simulation of the temporal distribution of plant carbon described in Muller-Feuga (2024b) is taken up and updated.

Since the normal distributions are centered, the mean and median carbon storage half-lives (DSC) are equal to the sum of half the maximum growth time (PC/2) and half the maximum restitution time (RM/2) according to Formula (3).

$$\mathrm{DSC} = (\mathrm{CP} + \mathrm{RM})/2 \tag{3}$$

Freshly harvested fruits and vegetables have a reduced transport and marketing time to preserve their taste and freshness. Temperature control during transport and storage can significantly increase the time between harvest and consumption. This shelf life varies from 3 days to a few weeks at room temperature or in the refrigerator. It can go up to 3 months, which allows to get through the unproductive season. In the freezer, food generally keeps for a year or more. In addition to temperature, the shelf life of food depends on its water content which governs its decomposition. This content varies from 10% to 20% in cereals, 60% to 75% in meats and animal flesh, 80% to 90% in fresh fruits and vegetables. Reducing the water content to extend storage time can be achieved through various techniques such as drying, brining, and vacuum packaging.

The quantity of CO_2 captured and stored by a set n of plant biomasses CS_n of fresh weight P_i, is equal to the sum noted Σ of the anhydrous weights of the harvests multiplied by the CO_2/dm ratio noted k, in accordance with Equation (4), where TE_i is the water content of the biomass P_i.

$$\mathrm{CS}_n = k \cdot \Sigma n\,(1 - \mathrm{TE}_i)\,P_i \tag{4}$$

The water contents TE_i documented by various cross-referenced sources allow the dry weight P_i of these plant products to be calculated using Formula (4). **Figure 1** shows the variation of the maximum restitution duration RM of crop products placed on the market as a function of their water content TE. We distinguish between fresh fruits and vegetables for which the RM is from a few days to a few months, semi-preserved products for which the RM is from a few months to a few years, and dried products for which the RM is from a few years to indefinitely.

Since the nutritional value and safety (freshness) of foods decrease with age, consumers are guided in their choices to ensure food safety and limit waste. Best-before dates (BBD) are mandatory information on food products. We considered our maximum restitution duration RM to be equal to BBD when available.

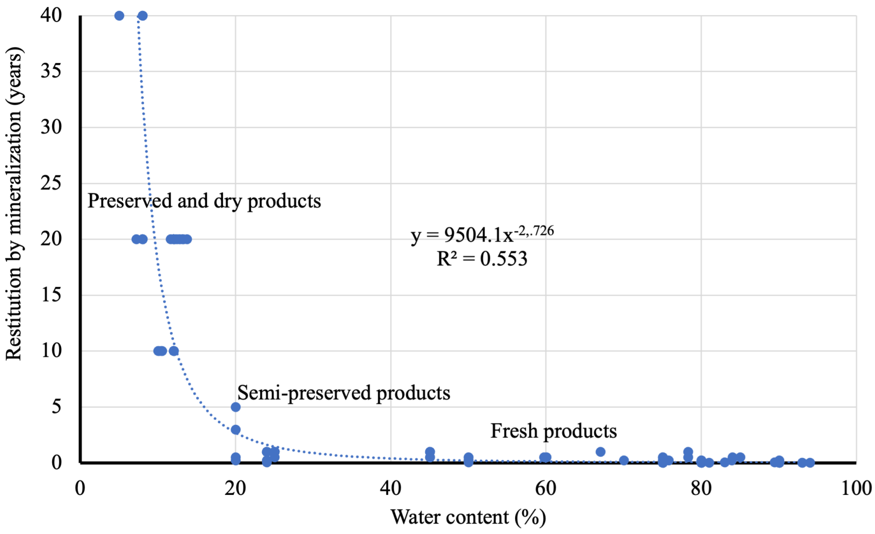

Figure 1. Post-harvest restitution times (RM) of commercial crop products vs their water content in 2023.

2.4. Quantities Captured and Stored

Emerged land is cultivated to meet the needs of humanity and its livestock for food plants (cereals, vegetables, fruits, etc.), textiles (cotton, flax, hemp, etc.), recreation (tobacco, grapes, flowers, etc.), heating and construction. In the following, we use FAO statistics (n.d.) relating to agricultural, livestock, forestry, aquaculture, and fisheries production. The organic material thus obtained feeds animals and microorganisms which mineralize it through digestion, fermentation and respiration. Some of it is directly mineralized through deliberate or accidental combustion. These productions, responsible for continental CO_2 absorptions by photosynthesis AW, are described in Muller-Feuga (2024b) and updated here in terms of quantities and storage durations.

The primarily food use of agricultural products prolongs carbon storage in the form of animal biomass and their waste, whose carbon contents are approximately 18% and 9% by weight, respectively. The lifespan of animal carbon before being released to the atmosphere through respiration ranges from one week in the liver to six weeks in hair (Tieszen et al., 1983). Fecal matter in the form of compost or manure is mineralized in the environment, with a few months of estimated carbon lifetime. This animal extension is not considered here, which minimizes the carbon storage duration.

The average carbon lifetimes of necromasses correspond to the average carbon residence time before mineralization by soil decomposers. For forests, these retention times vary between 0.9 and 152 years (Wang et al., 2017). They increase with latitude (x4) and decrease with temperature (x10) and rainfall (x4). We selected the durations for temperate regions, which represent a compromise between high and low latitudes, where the maximum organic carbon residence time is 75 years for logged forest soils and 40 years for crop and grassland soils (Balesdent & Recous, 1997; Pellerin et al., 2019).

2.5. Kinetics Simulation

The normal distribution Equations simulating the kinetics of capture and restitution of atmospheric CO_2 are, for capture:

$$C(t, n) = (Ha_n/2)\cdot[1 + \mathrm{erf}\,\{(t - n + CP/2)\ /\sigma/\sqrt{2}\}] \tag{5}$$

and for restitution:

$$R(t, n) = (Ha_n/2)\cdot[1 - \mathrm{erf}\,\{(t - n - RM/2)\ /\sigma/\sqrt{2}\}] \tag{6}$$

where t is the historical time in years, n is the harvest year, Ha_n is the atmospheric CO_2 mass captured by the harvest of year n, erf is the error function of the normal distribution, and σ is the curvature which was adjusted manually. If $t \le n$, the CP capture duration applies, and the erf function is added. If $t > n$, the RM restitution duration applies, and the erf function is subtracted.

This probabilistic simulation is applicable to plants with a single harvest, such as annual plants and trees felled for fuel and construction wood, and to perennial plants, such as sugarcane, tea, coffee, cocoa, oil palm, rubber trees, fresh and dried fruits, which are exploited by multiple annual harvests. In the latter case, the CP capture period covers previous multiple harvests, which varies depending on the species between 2 and 80 years. Let us remember that perennial woody crops are the only ones considered in carbon budgets excluding annual plants.

The theoretical kinetic of annual capture and storage by whole plants modeled by Equation (5) and Equation (6) allowed us to construct three 118 × 127 matrices, which we call [C(t, n)] for capture, [R(t, n)] for restitution, and [C(t, n) + R(t, n)] for the complete cycle, where t is between years 1961 and 2079, and n is between years 1932 and 2059. Row vectors t contain the masses formed by successive harvests Ha_n as a function of time n, and column vectors n contain the captured, harvested, and then restituted masses of year n as a function of time t (see **Figure 2**).

The net continental plant balance is equal to −AW + EW, where AW is the flux absorbed by plants and EW the flux restituted from plants. Numerically, it is taken equal to the variation from one year to the next, noted Δ, of the sum of row vector t of the matrix [C(t, n) + R(t, n)], noted Σ_t, reduced by the sum of row vector t-1 of the same matrix.

Restitutions EW was calculated according to Equation (7).

$$EW_t = \Delta\ \Sigma_t\ \{[C(t, n) + R(t, n)] - AW\} \tag{7}$$

The quantity of CO_2 captured in year t AW_t is equal to the sum of the harvests of year t, noted Ha_t, and the intermediate captures of the plants growing during the year and preparing the harvests to come, noted Cin_t, in accordance with Equation (8).

$$AW_t = Ha_t + Cin_t \tag{8}$$

The intermediate captures of year t, noted Cin_t, are equal to the variation from one year to the next, noted Δ, of the sum of row vector t of the matrix [C(t, n)] after deduction of the harvests Ha_t, noted Σ_t, reduced by the same sum of row vector t-1, hence the Equation (9).

$$Cin_t = \Delta\ \Sigma_t\{[C(t, n)] - Ha_t\} \quad (9)$$

The stock of carbon taken from the atmosphere by plants in year n is the sum of the row vector t of the matrix [C(t, n) + R(t, n)] from year n minus 40, for which capture has not yet begun, to year n.

3. Results

The total amount of CO_2 captured by whole plants is calculated based on FAO decadal statistics (n.d.) describing marketed agricultural, livestock, and forestry products. These quantities are converted to anhydrous products, then multiplied by their carbon content (40%), then by the CO_2/C mass ratio (3.37), then by the whole plant/commercial part ratio.

3.1. Crops 2023

Production statistics for the 160 global crop products include herbaceous and shrubby plants grown for food (cereals, vegetables, fruits, etc.), textile fibers (cotton, flax, hemp, etc.), or recreation (tobacco, grapes, flowers, etc.). Fresh weights are described under "Production," then "Crops and Animal Products". **Table 1** shows the durations and quantities of these commercial products broken down into the three categories described above. In 2023, the average water content (TE) weighted by carbon weights of crop products was 45.6%. We considered the maximum restitution duration RM for cereals and other dry products to be 20 years.

Table 1. Capture durations CP, restitution durations RM as weighted by carbon weights, and dry weights of the 160 global crop products marketed in 2023 (source: FAO, n.d.).

	CP	RM	Dry weight
	year	year	Mt
Preserved and dry products	9.3	17.7	3,926.3
Semi-preserved products	6.9	0.8	421.2
Fresh products	7.8	0.1	1,030.2
Total	4.4	15.6	5,377.8

3.2. Fodder 2023

Fodders are mostly annual plants, the cuttings of which are stored for 0.8 to 3 years to wait for maturity and get through unproductive periods. They are transformed into meat, milk, offal, eggs, honey, etc. by the animals that feed on them and mobilize their carbon. The restitution in the form of CO_2 is done by respiration of livestocks as well as by mineralization of their excrement and non-food products (skins, wax, silk, etc.). It lasts between 40 days (eggs) and 100 years (beeswax). The 48 global livestock products are listed in the form of quantities of meat, milk, eggs consumable by humans expressed in tons described in the statistics "Production - Quantity" and "Primary Livestock". These products are mainly intended to supplement 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 of plants from grasslands, foliage, and crops by ruminant and monogastric animals. Protein levels vary between 3.2% for milk and 32% for meat products.

According to Mottet et al., 2017, global livestock consumed 6 Gt/year of anhydrous fodder in 2010. After updating based on demographics, these anhydrous fodders are calculated by applying an average conversion rate (dry weight of fodder/fresh weight of livestock product) of 4.33 for all species combined. Some of the crops described in the previous section are intended for animal feed. These are cereals (wheat, corn, sorghum, etc.) used in livestock feed. To avoid counting them twice, a 14% reduction is applied to fodder calculated on the basis of animal products marketed (**Table 2**). This is the share of fodder that can be consumed by humans, according to the work cited above.

Table 2. Capture durations CP, restitution durations RM as weighted by carbon weights, and dry weights of the 48 global livestock products marketed in 2023 (source FAO, n.d.).

	CP	RM	Dry weight
	year	year	Mt
Preserved and dry products	0.9	18.5	145.4
Semi-preserved products	0.7	0.6	4,200.6
Fresh products	2.0	0.2	2,125.0
Total	1.3	0.8	6,461.5

3.3. Forestry 2023

Statistics on the quantities of wood produced worldwide are available in the "Forests" section of the FAO "Data" (n.d.). These "Production - Quantity" of firewood, sawlogs, pulpwood, and industrial wood, expressed in m^3, are converted into dry tons (**Table 3**). For this purpose, a density of 0.6 t/m^3 is used for conifers and 0.7 for non-conifers.

Table 3. Capture durations CP, restitution durations RM as weighted by carbon weights, and anhydrous weights of the 8 global forestry products marketed in 2023 (source FAO, n.d.).

	CP	RM	Dry weight
	year	year	Mt
Preserved and dry products	40.0	53.3	1,240.0
Semi-preserved products	40.0	2.0	4,200.6
Fresh products	0.0	0.0	2,125.0
Total	44.0	18.3	2,589.8

3.4. Other 2023

In addition to these products from cultivated plants, we should add the uptake by wild plants and animals. The mass of unexploited organic matter (primary forests, necromasses, soil heterotrophs, peats, hedges, etc.) is relatively stable, and its flow occurs at the margins of the carbon polymerization-mineralization cycle. Unexploited plant covers have a photosynthesis-respiration balance close to neutral over time, with what is photosynthesized during the day being degraded at night or in the shade of the canopy by decomposing organisms or by combustion. We did not take these carbon masses into account, which gives our figures a conservative value. Similarly, we considered the variations in carbon masses from aquatic products (fishing and aquaculture) and land-based animal populations (humans and livestock). They were lower by a factor of 1000 than those of the three main terrestrial plant productions, so they were subsequently neglected.

3.5. Non-Commercial Parts

Non-commercial plant biomass inherent to crops, such as leaves and stems for the aboveground portion, and roots and exudates for the belowground portion, must also be taken into account. These parts remain *in situ* and enrich the soil with organic carbon. The storage half-lives DSC of these necromasses correspond to the average residence time of carbon before mineralization by decomposer organisms.

The weights of the aboveground parts were calculated based on an average harvest index of 0.42 (Hay, 1995). The root system is estimated to account for 30% of crop plant biomass, 65% of grassland plants, and 15% of total tree biomass (Blume et al., 2015). Consequently, the whole plant/commercial part ratios are 1.72, 2.07, and 1.57 for crops, forages, and forest products, respectively.

3.6. Storage Durations 2023

Storage durations half-lives were calculated on these bases for the biomasses cultivated in 2023 after addition of non-commercial parts (**Table 4**).

Table 4. Capture durations CP, restitution durations RM and mid-life storage durations DSC in years for whole plants harvested in 2023. Means are weighted by biomass carbon weights. SD = standard deviation.

	CP	RM	DSC	SD
Crops	4.4	25.8	15.1	0.3
Forages	1.3	21.1	11.2	0.1
Forests	44.0	38.9	41.4	3.7
Weighted mean	9.4	25.8	17.6	0.7

According to Formula (3), the half-life DSC of carbon absorbed by all cultivated plants is 17.6 ± 0.7 years. The DSC of exploited trees is the longest with 41.4 years. The DSC of forage plants is the shortest, at 11.2 years, which is sufficient to be included in carbon budgets. Crops have an intermediate DSC of 15.1 years. Following these results, the theoretical kinetic of 2023 CCSP is simulated using Equation (5) and Equation (6) with the parameters in **Table 5**.

Table 5. Parameters of the simulation using Equation (5) and Equation (6) of the variation of carbon stocks as a function of time in 2023.

	Units	Notations	Values
Harvest of year 2023	$GtCO_2$/year	Ha	36.4
Curvature capture	year	σc	1.4
Maximum duration of capture	year	CP	9.4
Curvature restitution	year	σr	4.0
Maximum duration of restitution	year	RM	25.8

Figure 2 shows the kinetics of atmospheric CO_2 captures and restitutions following the 2023 harvests. It describes the elements of the 2023 column vector of the matrix [C(t, n) + R(t, n)]. The CO_2 mass removed by the 2023 harvest extends over approximately 40 years. The kinetics are highly asymmetric, with restitution taking thrice the time of capture. This delay in restitution results in an accumulation of carbon masses from successive harvests, the production of which is increasing.

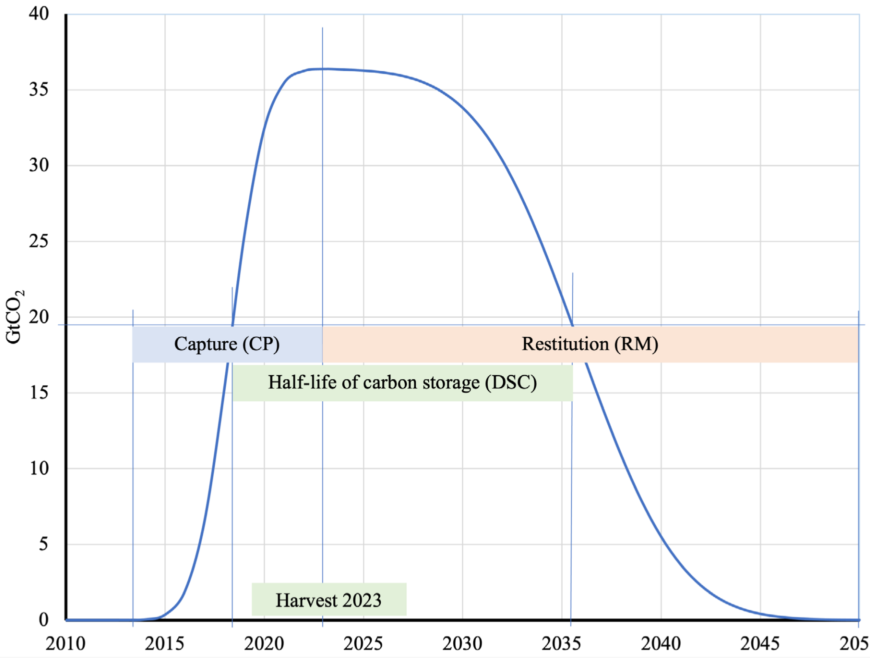

Figure 2. Simulated kinetics of CO_2 mass ($GtCO_2$) in whole plants bearing the 2023 harvests during capture by photosynthesis (CP) and restitution by mineralization (RM), and half-life of the carbon mass (DSC).

3.7. Net Balance 2023

In addition to the carbon of harvested plants, there is that of future harvests currently being built up. This intermediate capture, denoted Cin, was −2.7 $GtCO_2$/year according to (9), bringing the total capture of global whole cultivated plants (AW) to −39.1 ± 0.5 $GtCO_2$ (**Table 6**). Formula (7) gives an EW restitution of 8.2 ± 1.8 $GtCO_2$/year in 2023, i.e. a net balance of global cultivated plants of −31.0 ± 1.9 $GtCO_2$/year taken from the atmosphere.

Table 6. CO_2 captured and stored by the 2023 harvests of commercial products and whole plants of global agriculture, livestock, and forestry and their standard deviation (SD), in $GtCO_2$/year.

$GtCO_2$/year	Commercial products	SD	Whole plants	SD
Crops	7.9	0.2	13.6	0.5
Forages	8.2	0.5	16.9	0.5
Forests	3.8	0.4	6.0	0.5
Intermediate captures (Cin)			2.7	0.8
Total	19.8	0.3	39.1	0.5

3.8. World CCSP Over the Half-Century

Except for harvests Ha, the other parameters σ, CP, and RM in **Table 5** were retained to simulate carbon variations from 1932 to 2059, which is a questionable but simplifying hypothesis. It appears acceptable given that the relative proportions of agricultural and forestry products have not changed much over the half-century, unlike the quantities.

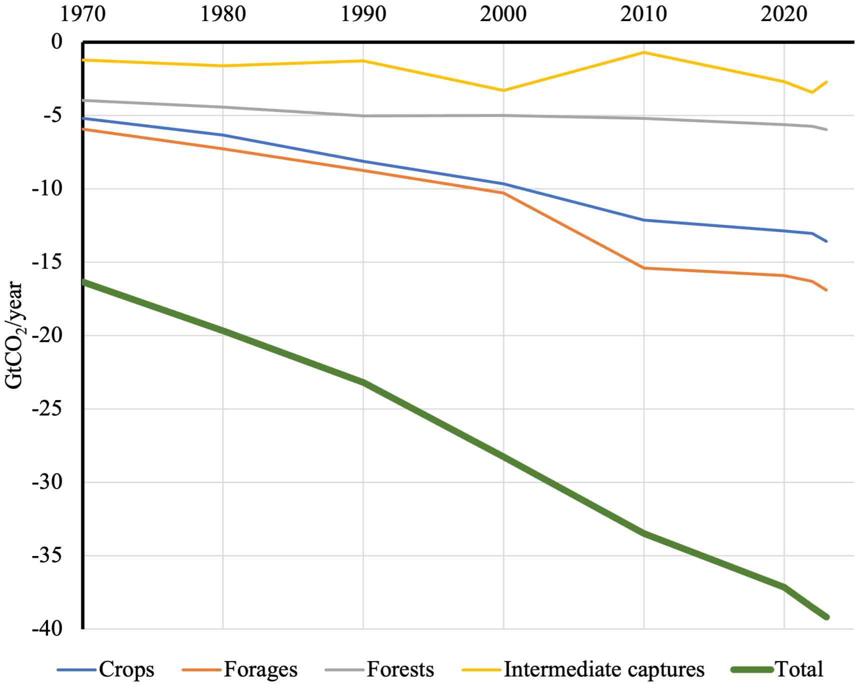

Figure 3. Global CO_2 uptake by whole plants cultivated from 1970 to 2023 ($GtCO_2$/year; based on FAO, n.d.).

To describe the variations in global CCSP over the past half-century (**Figure 3**), it was necessary to go back to 1940 to include all restitutions in process in 1970, and to anticipate to 2030 to include all captures in process in 2023. To do this, we extrapolated to 1940 using the linear regression AW = 0.4198·n − 809.39 and to 2030 using the regression AW = 0.4883·n – 945.42, where n is the year considered. This is an acceptable hypothesis given the high value of the coefficients of determination (R2 ≥ 0.985).

Recall that CCSP are sinks and that their values are negative in Formula (2) of the atmospheric budget. Only an unexplained bump due mainly to fodder breaks the linearity around 2010. The final hook marks the recovery following the COVID-19 pandemic.

Figure 4 depicts the variation of column vectors of the matrix [C(t, n) + R(t, n)] over the half century.

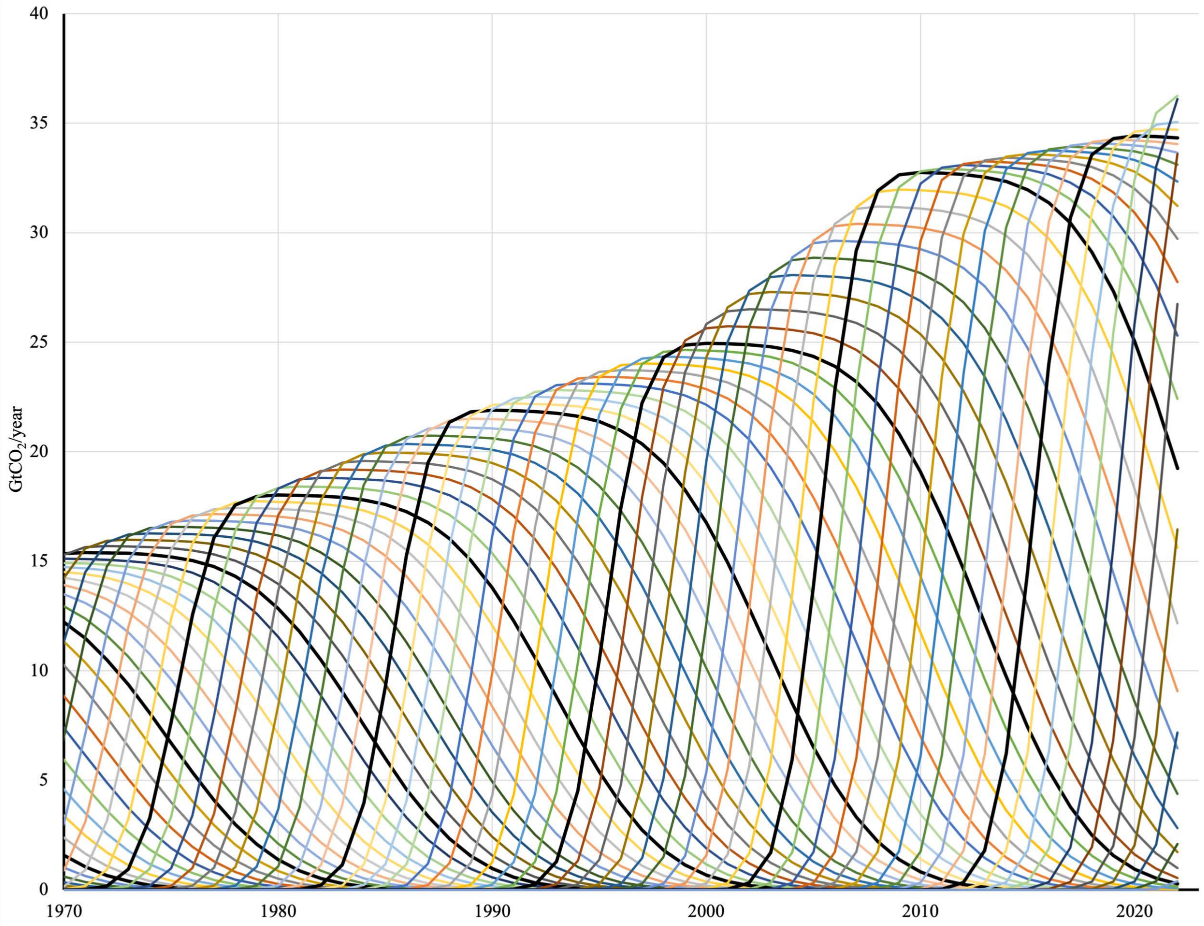

Figure 4. Kinetics of carbon capture and storage by cultivated whole plants (CCSP) worldwide between 1970 and 2023 ($GtCO_2$/year). The thick black lines correspond to decadal years.

3.9. Cumulated Carbon Stocks from Cultivated Plants

The CCSPs of successive annual harvests described in **Figure 4** accumulated the anthropogenic carbon stocks absorbed by the cultivated plants present in soil, buildings, stores and on shelves. **Figure 5** shows the evolution of these anthropogenic stocks which reached 123.3 ± 3.9 GtC in 2023. The final hook could be related to the COVID-19 pandemic. Compared to atmospheric CO_2 and despite its sharp increase, those stocks have doubled in half a century, from 7% to 14%. Over the half-century, they were multiplied by 2.5, as much as fossil emissions (x2.5) and more than the human population (x2.2). This does not include the wild stocks (primary forests, necromasses, soil heterotrophs, peats, hedges, etc.), the estimation of which feeds discussions.

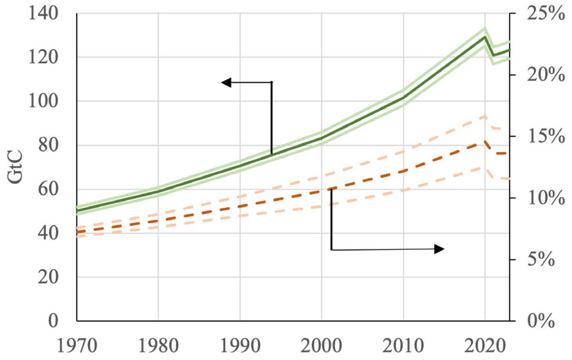

Figure 5. Global stocks of carbon (GtC) accumulated by cultivated plants during the half century (left axis—solid lines). Average in dark green, plus and minus the standard deviation in light green. Ratio of those plant stocks over atmospheric stock (right axis—dotted lines). Average in dark red, plus and minus the standard deviation in light red.

The other components of the carbon budget identified in Equation (2) are examined below. These are the emissions from fossil fuel combustion (EFOS) and the variation in mass of atmospheric CO_2 (ACV).

3.10. Fossil Fuel Emissions

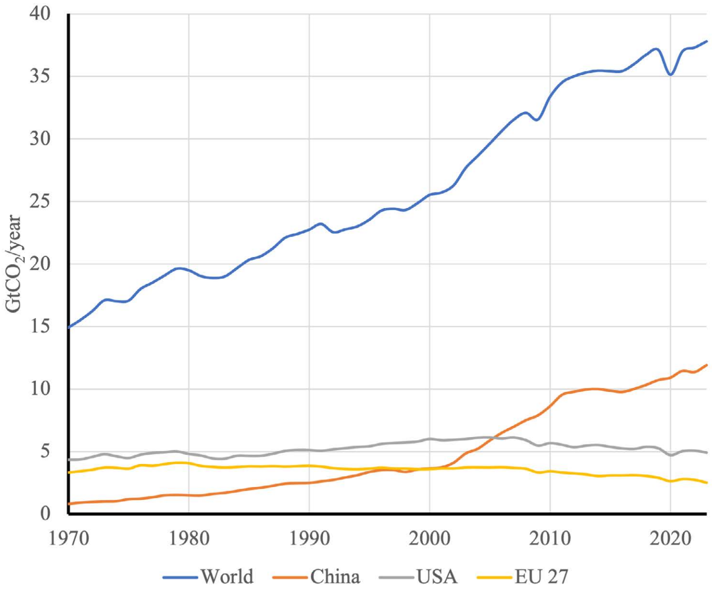

Figure 6. Half-century variations in carbon dioxide emissions from fossil fuel combustion, in $GtCO_2$/year (Source: Ritchie et al., 2023).

Figure 6 shows the distribution of CO_2 emissions from fossil fuel combustion over the last half-century for selected countries and groups of countries, as provided by the UK-based Global Change Data Lab (GCDL). Global emissions reached 37.8 $GtCO_2$/year in 2023, an increase despite a decline in 2020 during the health crisis. These CO_2 emissions include "other greenhouse gas emissions, energy mix, as well as other indicators of potential interest", with no capture reducing them. The main emitting countries are China (11.9 $GtCO_2$/year), the United States (4.9 $GtCO_2$/year), India (3.1 $GtCO_2$/year), the European Union of 27 (2.5 $GtCO_2$/year). While the share of the most industrialized countries, which are increasingly relying on low-carbon energy sources, has been declining since 2010, that of other countries, including China and India, which are actively equipping themselves with combustion-fired power plants, has been increasing since 2000.

3.11. The Atmosphere

The variation in atmospheric CO_2 content (ACC) measured by Keeling et al. (2001) at the Mauna Loa Observatory (MLO) on the Big Island of the Hawaiian archipelago since 1958 shows a clear upward trend of more than 2 ppm/year and exhibits annual oscillations with an average increase of 6 ppm from August to April (the boreal cold season) and an average decrease of 4 ppm from the warm April to August (the boreal season). Although located far from the coast and at high altitude, these records indicate a strong influence from the Northern Hemisphere continents, which emit the largest quantities of this CO_2 and actively capture it through photosynthesis. **Figure 7(a)** depicts the kinetics of atmospheric CO_2 mass. The smoothed CO_2 flux to the atmosphere denoted ACV varies linearly as **Figure 7(b)** shows.

To determine the variation of atmospheric CO_2 mass ACV, we multiplied the ACCs measured by the MLO by 7.84 $GtCO_2$/ppm, then smoothed those values by a polynomial of order 2 (**Figure 7(a)**) and took the derivative (**Figure 7(b)**), i.e. the linear regression ACV = 0.2198·n − 425.14 ($R^2 = 0.99$), where n is the date in years, which gives 19.5 ± 0.7 $GtCO_2$/year in 2023.

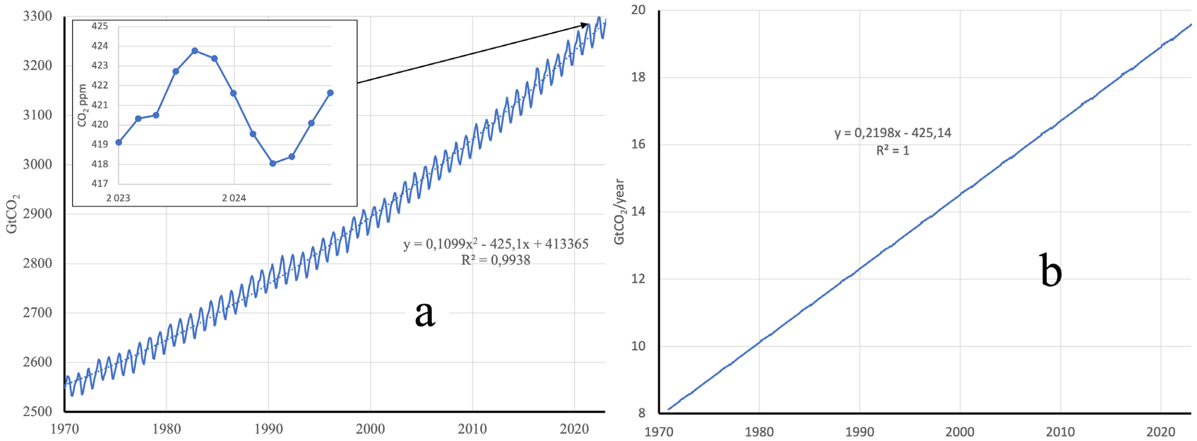

Figure 7. Evolution of the atmospheric CO_2 mass ($GtCO_2$) over the half-century on the left (a) with details of year 2023 on the top left (ppm), and its smoothed annual increase (ACV) on the right (b) ($GtCO_2$/year) as based on MLO data set.

3.12. Carbon Budget

The global budget according to Formula (2) of CO_2 exchanges in 2023 (**Table 7**) shows that plants exploited by humans are the planet's main CO_2 sink. The average half-life DSC weighted by carbon weights of this sink is 17.6 years and exceeds 40 years for forest products. According to our modelling, carbon capture by cultivated plants could offset a very significant—or even the majority—of fossil EFOS emissions, which calls for a reassessment of the respective roles of carbon sinks.

Table 7. Elements of the budget of CO_2 exchanges and their standard deviation (SD) in 2023 ($GtCO_2$/year). Sources are positive and sinks negative.

Budget component	Notation	Value	SD
Variation of atmospheric CO_2	ACV	−19.5	0.7
Capture by cultivated plants	AW	−39.2	0.5
Restitutions from plants	EW	8.2	1.8
Emissions by fossil combustions	EFOS	37.8	1.0
Contribution of world ocean	OC	12.7	3.0
Algebraic sum		0.0	

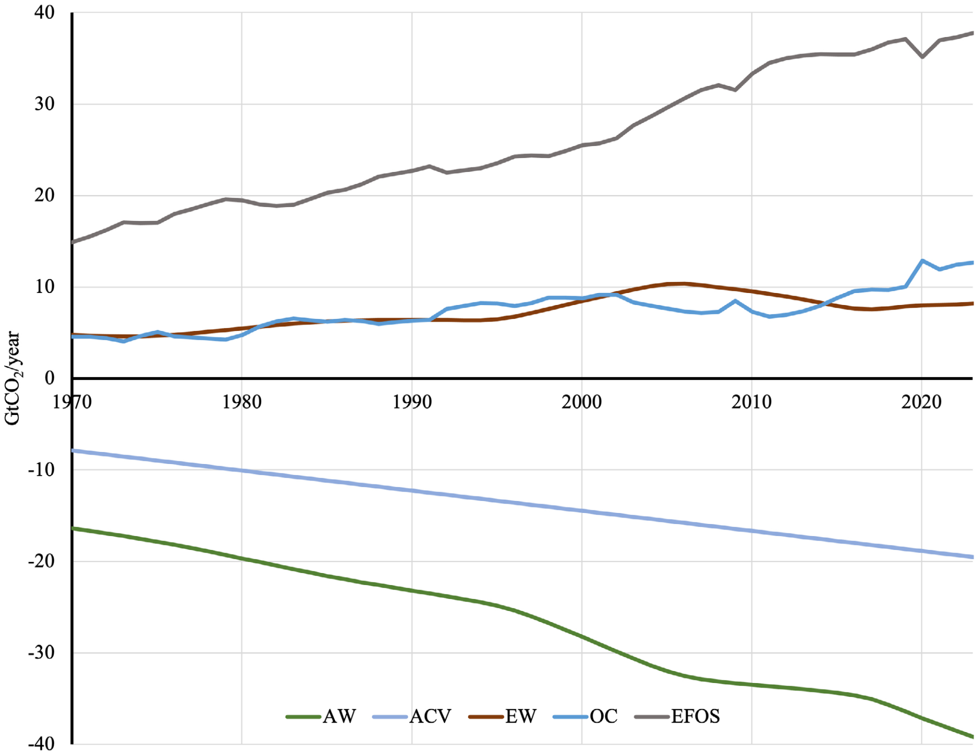

Figure 8. Variations over the half-century of the five components of the CO_2 exchange budget (AW plant captures; ACV atmospheric variation; EW restitutions from plants; OC ocean contribution; EFOS fossil emissions). Sources are positive and sinks negative. Their algebraic sum is nil.

The net plant balance −AW + EW was an anthropogenic sink offsetting 82% of fossil EFOS emissions in 2023. The components of the global budget according to Formula (2) vary as **Figure 8** illustrates during the half century. These components are increasing in absolute value.

4. Discussion

Absorption by cultivated plants (AW) and fossil hydrocarbon combustion emissions (EFOS) followed the evolution of the human population, which increased from 3.7 billion in 1970 to 8.1 billion in 2023. The three quantities more than doubled over the period while maintaining the same proportions.

This analysis highlights significant differences with the results presented in the literature. For year 2023, **Figure 9** compares the components of the atmospheric CO_2 budget resulting from our calculations with those proposed by Friedlingstein et al. (2023). Components **1** (ACV) and **4** (EFOS) obtained from public statistics, are similar. However, there are significant differences between components **2** (AW), **3** (EW) and **5** (OC). Our estimate of capture AW, which includes annual crops, is significantly higher (x5) than those excluding them. It was three times higher than that of Pan et al. (2024) estimated at 12.8 $GtCO_2$/year during the 2010s. Our capture by cultivated plants (AW) almost entirely offset alone total anthropogenic emissions estimated at 41.46 $GtCO_2$ by Ritchie & Roser (2024) in 2022, including 37.15 $GtCO_2$ from energy and industrial combustion of fossil hydrocarbons (Global Carbon Budget). Jia et al. (2025) estimated the organic carbon sink constituted by global soils at 6.7 ± 3.3 $GtCO_2$/year between 1992 and 2020, which is of the same order as that of Friedlingstein et al. (2023). In comparison, our restitution from plants is twice that of the cited authors. Finally, let us recall here that our net plant balance $-AW + EW$ was an anthropogenic sink of -31.0 ± 1.9 $GtCO_2$/year, more than 6 times that of Friedlingstein et al. (2023), offsetting 82% of fossil emissions EFOS in 2023.

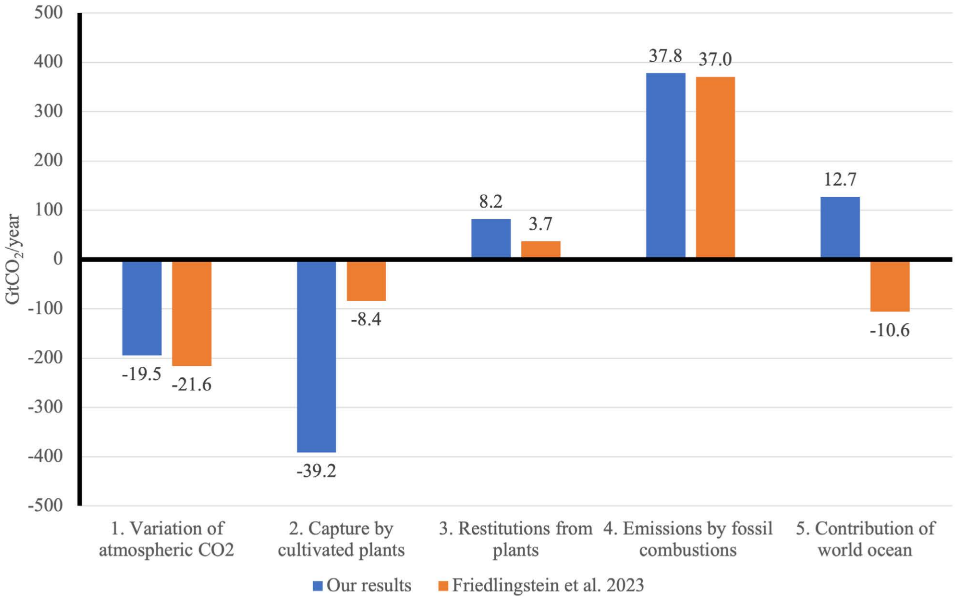

Figure 9. CO_2 sinks (negative) and sources (positive) calculated here and compared to those of the cited authors excluding annual crops, in billion tons of CO_2 per year for the world in 2023. The algebraic sum is zero in both cases.

Our contribution from the global ocean **5** is a source, whereas it is a sink for the cited authors. These differences result directly from the almost universal absence of annual plants in literature budgets, regardless of any other consideration. They are likely to change the way we view some aspects of climate policies adopted to date.

4.1. Other Approaches

Given the significance of the differences between our values and those in the literature, we verified their relevance using several approaches. We found only one publication in the literature describing the share of annual plants in global CCS (Wolf et al., 2015). Based on the same sources as us (FAO, n.d.), their net primary production of harvested annual plants and forages required 28.2 $GtCO_2$/year in 2011, compared to our 27.6 $GtCO_2$/year for 2010, which is quite consistent. The orders of magnitude were three times higher than those of authors not taking annual plants into account (e.g. Le Quéré et al., 2013). However, Wolf et al. (2015) considered that the storage period did not exceed one year, with restitution by respiration immediately following harvest, which is consistent with the provision excluding annual plants. On the contrary, we consider that a half-life of carbon storage (DSC) of more than 10 years does not justify this exclusion and that annual plants have their full place in carbon budgets.

Knowing the absorptions by cultivated plants AW and their DSC, we might expect the restitutions from plants EW to be close to the AW/DSC ratio, or 2.2 $GtCO_2$/year in 2023. This figure is significantly lower than our EW value, probably due to the asymmetry of the kinetics around harvest.

We also approximated the order of magnitude of the restitution by cultivated plants EW by considering global dioxygen consumption. According to Huang et al. (2018), it would be about 48 GtO_2/year updated to 2023. The main contribution was due to the combustion of fossil hydrocarbons which consumed 38.2 GtO_2/year in 2015, or 41.9 GtO_2/year in 2023 modulated by the world population. The difference with the total global consumption of dioxygen, or 6.1 GtO_2/year, is due to the mineralization of organic matter by respiration, fermentation and combustion. According to reaction (1) taken in the direction of respiration from right to left, the CO_2 production resulting from this consumption of oxygen would be 8.4 $GtCO_2$/year, which is within the range of our EW assessment.

4.2. Methodological Differences

Our capture by plants is higher by a factor 3 to 5 than those in the literature and we are trying to understand the reason of such a difference. The first reason is the failure to consider annual plants on the pretext that their restitution would take place in the year following the harvest, which would cancel the capture. We have shown that this is not the case, the average half-life of annual plants weighted by carbon weights being 8.9 years. That of forage plants, most of them are annual, is 11.2 years. These durations are much longer than the year, dismissing the reasons for exclusion of annual plants which completely unbalanced the Equation (2).

There remain differences in the method of measuring quantities such as tree biomass and necromass. Our approach is based on the chemical composition of commercial products listed in FAO statistics. Most authors' carbon masses are constructed from field and satellite measurements per unit area and time, then extended by dynamic models to the global surfaces of the different plant covers thus characterized. It seems that this method faces problems of representativeness of the measurements characterizing each plant cover rather than the surfaces of these covers which are precisely defined thanks to satellite imagery. Estimates of continental and oceanic absorptions and emissions lack precision, which encourages controversies (e.g. Luyssaert et al., 2008; Gundersen, 2021; Luyssaert et al., 2021; Zhong et al., 2024). In our case, the sampling is extended to all commercially available products from plants, to which should be added the proportion of wild plants, if significant.

4.3. The Ocean

According to our calculations, the ocean would be an increasingly important source of CO_2 over the half-century. It would release 12.7 ± 3.0 $GtCO_2$ in 2023 and would account for the atmospheric increase with fossil emissions and plant restitutions. The role of a sink of 10.3 ± 0.4 $GtCO_2$/year attributed to the ocean (e.g., Fay et al., 2023) by authors who excluded annual plants would thus be called into question in both sign and magnitude. By choosing the notation Socean for "ocean sink", these authors prohibit themselves from conceiving the ocean other way than a sink (e.g., Rödenbeck et al., 2015). This conception would be corroborated by numerous offshore measurements of CO_2 fugacity and total inorganic carbon, which tend to show that the ocean absorbs a quarter of anthropogenic emissions (NOAA n.d. - SOCAT). Thus, offshore measurements may be insufficient to describe mass exchanges due to gaps in space and time, as well as limitations related to the accuracy of sensors and interpolation models, which fuels controversy (e.g., McGillis et al., 2004).

According to ice cores, CO_2 peaks follow temperature peaks 600 to 1,000 years later (e.g. Petit et al., 1999; Fischer et al., 1999; Caillon et al., 2003; Richet, 2021). This would be the time it takes for the global ocean to find a new thermal equilibrium with the atmosphere through mixing in all three dimensions. The ocean's delayed response to climate perturbations induce to look for the warming that caused the current outgassing well before the recent increase in global temperatures. The so-called "Medieval Climate Optimum," which occurred from the 10th to the 13th century, could be the cause of this outgassing, which was briefly interrupted or slowed by the "Dalton Minimum," or "Little Ice Age" (1790-1830).

The oceanic primary production (OPP) provided by algae is the basis of the aquatic food chain exploited by marine fisheries, which landed 81 million tons of products in 2022, stable since 1980. Aquaculture, increasing by more than 10% per year, produced 185.4 million tons of animals and 37.8 million tons of macroalgae in 2022 (FAO, 2024). OPP has been the subject of numerous studies, mainly using satellites measuring chlorophyll. Since 1970, most authors agree to consider OPP as stable and equal to 51 GtC/year (e.g. Carr et al., 2006; Johnson & Bif, 2021), with only events modifying deep water upwellings (e.g. El Niño) disrupting the annual rhythm. This is 4.8 times our estimate of uptake by cultivated plants AW, even though the ocean surface area is 2.4 times larger than that of the continents. Relative to surface area, ocean capture exceeds that of the continents by a factor of two. This demonstrates the extent to which aquatic life plays a key role in the global terrestrial ecosystem, consuming carbon and producing the oxygen and organic matter essential for animal life.

During glaciations, ice accumulated at the high and mid-latitudes of the continents which were shaped by several thousand meters of thickness, while sea level was more than 100 m below current levels. The increase in the ACC following glaciations is a consequence of the degassing of CO_2 from the ocean, which is a slow process involving the deep oceans. These cycles differ from the seasonal cycles of the ACC, whose oscillations are in opposition to those of temperature. According to ice cores, the atmosphere would lose 100 ppm, or 212 GtC, while the temperature would drop by about 8˚C on average during glaciations (Kobashi et al., 2013). This carbon mass would pass into the ocean, which would release it during postglacial warming. These exchanges represent a tiny fraction (0.5%) of the oceanic carbon stocks estimated at 40 TtC (Bopp et al., 2019). Since mid-19th century, the atmosphere has been enriched by 300 GtC which largely compensate the glaciation loss, thanks to the two main sources: fossil emissions and the ocean.

4.4. Surface Capture Yields

The global capture figures from our calculations (**Table 6**) are understated because they do not include the share of animal populations and wild plant covers. These covers include forests (tropical, temperate, boreal), tundra, Mediterranean scrub, tropical savannahs and prairies, temperate prairies, and deserts. According to Saugier et al. (2001), surface capture would range from 3.7 (deserts) to 43.1 (tropical forests) tCO_2/ha/year. The share of crops was only credited with 10.1 tCO_2/ha/year by these authors. The share of forests was greatly overestimated, and that of crops was significantly underestimated. Indeed, the average yield per unit area of cultivated whole plants was 19.4 ± 0.7 tCO_2/ha/year worldwide in 2023. Sugar crops (cane and beets) and palm oil lead the way with two to three times the average, followed by vegetable crops (onions, carrots, turnips, beans, eggplant, etc.), which yields are above average.

Unexploited continental vegetation is stable and plays a marginal role in capturing atmospheric carbon. Should unexploited old-growth forests still capture carbon, they would do so at levels far below those of most crops and forages. For example, current logging regulations in Brazil adopt a standard post-harvest recovery rate corresponding to a surface capture yield of 0.9 tCO_2/ha/year (Vidal et al., 2020), 20 times less than cultivated whole plants. The average capture of

French exploited forests was 3.3 tCO_2/ha/year (IGN, 2013), 6 times less.

Forest logging and fires do not result in a loss of capacity to capture and store CO_2. The soil stock remains in place for decades, while spontaneous or replanted regrowth continues to capture CO_2 before further logging 25 to 35 years later. If the forest is replaced by pastures or crops, the space it frees up captures CO_2 at levels more than 10 times higher.

4.5. Carbon Capture and Storage (CCS)

To achieve carbon neutrality, most governments are developing CCS capacity, primarily through deep geological burial. As of July 31, 2023, the total capacity of global CCS by burying projects under development, construction, and operation was 361 $MtCO_2$/year, or 1% of fossil fuel emissions. This modest capacity is up nearly 50% compared to 2022, according to the Global State of CCS report (Global CCS Institute, 2023). With carbon neutrality seemingly out of reach in the short term, a 55% emissions reduction milestone is planned for 2030.

According to the Global CCS Institute (2023), when all global landfill CCS projects are operational, their capacity will be 100 $MtCO_2$/year, 440 times less than human-exploited plants, which constitute by far the largest CCS device on the planet. All of the European Union's emissions (2.51 $GtCO_2$/year) were offset by its cereal production alone in 2023 (−3.5 $GtCO_2$/year). The EU considers it a priority to find adequate financial rewards to promote carbon removal in the various sectors of agriculture, forestry, and industry, but has still not recognized CCSP. Several countries are aware of the important role of cultivated plants, but are nevertheless raising the question of certification, on scientific basis accepted throughout the EU, of CCSP.

France is highly decarbonized, with most of its electricity being nuclear generated. Without any incentive or change in practices, French agriculture captured 174 $MtCO_2$/year for 17.6 years, 64% of total national emissions in 2023, more than six times the CCS target for 2030, and twice the industrial emissions eligible for CCS.

The agricultural sector is criticized for its emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O). According to Maréchal (2022), for example, the sector is responsible for 23% of global anthropogenic greenhouse gas emissions, or 12 $GtCO_2$ equivalent/year. These authors do not consider photosynthesis, whose net capture-restitution balance is greatly favorable to the rural world.

The failure to take agriculture and forestry into account in the compensation of CO_2 emissions would constitute a persistent injustice if certain signs of recognition were not underway, marking a significant change towards correcting this harm caused to the rural world. Thus, since 2020, the French government has identified a so-called voluntary carbon offset market, which provides that "...farmers can put the carbon credits they have generated ... on the voluntary carbon offset market". At the rate of €100 per ton of CO_2, CCSP remuneration would generate €23 billions representing 40% increase in French farmers' income.

Kenya has a significant surplus and offsets its fossil fuel emissions more than three times over with plants cultivation. Like most countries seeking to escape poverty, it could sell its surplus to emitters through the global carbon market. At the previous price, this could generate €9 billions per year for local farmers.

The consideration of CCSP is intended to extend to all plant products placed on the market. Its remuneration would represent a significant source of income for farmers, whose mission would now be, in addition to providing essential foodstuffs for humanity, to avoid or offset CO_2 emissions to limit climate change for which this gas would be responsible.

It should be noted here that there are other plant resources, cultivated or not, that could constitute CCSP. Thus, cultivated macroalgae captured 8.0 $MtCO_2$/year worldwide in 2023. Sargassum, which naturally invades the equatorial Atlantic, could be harvested at sea and then transformed into biofuel and fertilizer, which would reduce the use of fossil fuels and, simultaneously, the disastrous strandings on the eastern coasts of Central America and the Caribbean islands. According to Marx et al. (2021), the processing of this sargassum could produce 8,500 barrels of crude oil per day for a CCSP of 1.9 $MtCO_2$/year.

4.6. Carbon Dioxide Scarcity

Mainly because of human population growth, agricultural land per capita (ha/c) has halved during the last half century, from 1.2 to 0.6 ha/c. Despite this, per capita production has increased from 0.51 to 0.60 t/c/year, preventing food shortages. Plant production is experiencing a boom, as evidenced by leaf area measurements and the greening of the Earth (NASA, 2016). The increase in ACC 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, according to 2019 FAO statistics (n.d.). This could also explain why the net cumulated carbon stock biofixed by cultivated plants has more than doubled, passing from 184 to 452 $GtCO_2$ removed from atmosphere.

Carbon dioxide dissolves in seawater with which it combines to form bicarbonate and carbonate partially insoluble ions. Carbon is distributed in the deep oceans in dissolved form by density drifts and in particulate form by gravity and drifts. Insoluble carbonates accumulate at the bottom along with organic matter to constitute the planet's main carbon stock in the mineral form of limestone rocks (1.4×10^5 TtC according to Sorokhtin et al., 2007) and in the organic form of fossil hydrocarbons (oil, coal, bitumen, and gas – approximately 150 TtC). The main coal reservoir was formed with the development of forests at the beginning of the Carboniferous period (−359 to −299 million years - My) when the ACC was three to four times higher than in present days.

Air-water exchange of CO_2 is a powerful regulatory process of the ACC, including for photosynthesis, since this gas is admitted into the plant cell in dissolved form before being polymerized. Given that the ocean contains approximately 50 times more carbon than the atmosphere, the ACC will be strongly affected by temperature variations when these have time to express. The oceans will tend to absorb atmospheric CO_2 in cold regions and periods and release it back into the atmosphere through outgassing in warm regions and periods.

Since Earth's early stage when atmosphere was predominantly composed of CO_2, the ACC has decreased by a factor of 2,000, and this decline continues inexorably at a rate of approximately 1 ppm every 80,000 years. It still reached 7,000 ppm in the Cambrian period (−540 My), then 1,800 ppm in the Jurassic period (−200 My). No catastrophic warming interrupted the development of life that appeared 3 billion years ago. The fact that glaciations sometimes coincided with high CO_2 concentration levels (Carboniferous-Permian) is another indication of the absence of control of temperature by CO_2.

This slow decrease in ACC by lithification will result in a cessation of life on Earth, if nothing interrupts it beforehand. Indeed, photosynthesis in plants with C3 photosystems (wheat, rice, barley, beans, cassava, soybeans, etc.) stops below 100 ppm and the yield of other plants (corn, sorghum, sugarcane, etc.) decreases sharply. The CO_2 breakdown was already approached when the ACC dropped to 150 ppm in the Carboniferous-Permian (−290 My) and then in the Pleistocene (−2.6 million to −11,700 years ago). The current rise in ACC is a respite from this slow decrease by lithification. If the anthropogenic origin is proven, it would result from the recycling of carbon trapped in the Earth's crust, a kind of reverse lithification a million times faster. The decrease of ACC could also be partly offset by degassing of the Earth's crust and volcanic activity (Burton et al., 2013). In any case, to prolong the availability of this precious gas, it is advisable to prefer CCSP to CCS by burial which contributes to its lithification.

5. Conclusion

The contribution of cultivated plants to the biofixation of atmospheric CO_2 is approached with a margin of uncertainty relating to both retention times and stored quantities. This is a delicate exercise due to the diversity of elements to be gathered, water content, storage times, quantities, which we have selected among the most relevant from the literature. When doubts arose, hypotheses minimizing both values were retained, which gives them a minor and conservative character. Subject to the precision and completeness of these elements and the quality of the statistics on which they rely, the CCSP by commercial products placed on the market in 2023 presented a half-life of more than 10 years, which makes it a component to be considered in carbon budgets. The same is true a fortiori when we include the non-commercial parts of whole plants which remain on site and enrich the soils with carbon, and which had a half-life of 17.6 years. They capture twice as much carbon dioxide and retain it almost twice as long as the commercial products they carried.

The kinetics of carbon capture and restitution over the half-century were simulated using a probabilistic approach, which notably enabled the matrix calculation of intermediate capture and restitution through biomass mineralization. The total quantities of carbon captured and stored during these rural productions were five times greater than those reported in the literature. The contribution of annual crops to the CCSP was found to be 77% with an 8.9 years half-life. Among them, cereals alone captured 60% of annual crops and 21% of all plants over a half-life of 10.4 years. The remainder is due to perennial crops (fruit trees, oil palms, etc.), the only ones considered by the authors cited in their carbon budgets.

These figures require further refinement and completion, precisions on their evolution over time and space, but they do depict major trends. They reveal the exceptional nature of the contributions of agriculture and forestry, which are not yet fully recognized. These activities mobilize atmospheric CO_2 at levels that make them by far the main CCS system in the hands of humans, without humans having to modify their practices to achieve this result. Moreover, they allow the return to the atmosphere of this gas, which is crucial for the planetary ecosystem, unlike geological CCS, which contributes to its lithification.

According to our simulation, anthropogenic fossil emissions would not be responsible for the increase in the atmospheric carbon content since they were almost entirely bioremediated by the capture of cultivated plants. This calls into question their influence on climate change, and the policies for their reduction. In addition to fossil emissions and those by restitution from plants, the other source responsible for the enrichment of the atmosphere would be the ocean. Indeed, contrary to most assessments, our results suggest that the ocean may not play the commonly attributed role of carbon sink but constitutes a source providing more than half of this enrichment.

Based on their significant carbon capture and storage durations, agriculture and forestry should be reevaluated by international organizations and governments. These ancestral activities, which feed, warm, cheer, and clothe humans, use photosynthesis, to which we owe our lives, and which remains the simplest and most efficient means of capturing and storing atmospheric CO_2. They should be rewarded for their carbon credits as part of the development of CCS, which would supplement their income so they can continue to operate, develop, and transmit their activities.

The convention that carbon captured by annual plants would be cancelled out by its release in the year following harvest favors long-term stocks and neglects their variation in stores, on shelves, and in the soil. By reducing the contribution of carbon fluxes from rural origin, the exclusion of annual crops from carbon budgets could lead to energy and climate policies disconnected from agronomic realities, and encounter incomprehension in the agricultural world and developing countries.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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