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Impact of global greening on the natural atmospheric CO_2 level

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Abstract

In this study we investigate the impact of greening on the Earth in terms of gross primary production (GPP) on the natural atmospheric CO_2 level. The total mass of CO_2 in the atmosphere is equal to the yearly amount of CO_2 that leaves the atmosphere (down flux), multiplied by the average time CO_2 remains in the atmosphere (residence time). The biological processes of photosynthesis and respiration are by far the most important components of the fluxes to and from the atmosphere. Since the preindustrial period the down flux has increased by 29% and the residence time by 16%. Together they fully explain the recent CO_2 rise, without assuming different behaviors for human-generated CO_2 compared to natural CO_2 and without the need for an ad-hoc model with multiple residence times. Based on the changes in the biosphere under the influence of higher temperatures, the present CO_2 level can be regarded as a natural level, so much larger than the assumed 280 ppmv. The current total GPP is probably not extraordinary, which makes it unlikely that the ice core records of Antarctica provide an accurate representation of the historical levels.

Keywords: CO_2, atmosphere, greening, GPP, climate

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1. Introduction

Global greening refers to the observed increase in the amount of green vegetation, such as plants and trees, across the planet. Long-term satellite records revealed a significant global greening of vegetated areas since the 1980s. In this contribution we refer to greening in terms of the increase in gross primary production (GPP), the rate of carbon fixation by photosynthesis. Global terrestrial gross primary production has gone up by more than 30% since 1900 (Haverd *et al.*, 2020; Lai *et al.*, 2024). Multiple studies have identified the growing atmospheric CO_2 concentration and climate warming as important drivers of this greening, with other factors being notable at the regional scale (Zhu *et al.*, 2016; Piao *et al.*, 2019; Chen *et al.*, 2022). A similar effect has been observed in the oceans, where increased levels of dissolved CO_2 lead to more photosynthesis by phytoplankton (Riebesell *et al.*, 2007).

Biological processes, particularly photosynthesis and respiration, have a dominant effect on the fluxes to and from the atmosphere. The impact of global greening on the atmospheric CO_2 level is therefore crucial in understanding the global carbon cycle and the causes of the CO_2 rise as measured in the last 65 years. Understanding the possible mitigating effects of forestation on the CO_2 level is also important. The CO_2 fertilization has been largely considered as an enhanced land carbon sink. By storing large amounts of carbon in the form of biomass, vegetation sequesters carbon. Therefore, an increase in vegetation is generally considered as a process in which CO_2 greenhouse gas is removed from the atmosphere, partly mitigating human emissions.

It is true that especially new vegetation is a net sink, however this does not mean that an increased level of vegetation automatically leads to a lower CO_2 concentration. For the impact on the atmospheric CO_2 concentration it is not sufficient to look at the short-term effect of a single flux. One also has to consider the impact of this change on the longer term and on other fluxes in the carbon cycle. We believe that the current way in which the global carbon budget is determined is not suitable for properly assessing the impact of changes in the fluxes.

The conventional approach to examining the carbon cycle and explaining changes in atmospheric CO_2 levels is based on bookkeeping. Typically, the current CO_2 concentration is accounted for by aggregating the annual differences between the amount of CO_2 entering and leaving the atmosphere over an extended period of time, starting in 1750. This is, for example, the method used in the annual determination of the Global Carbon Budget (Friedlingstein *et al.*, 2023). The CO_2 level change in each year is explained by summing the human emissions from different sources and natural emissions from land and oceans, and subtracting natural absorptions from land and oceans. The conclusions are however colored by the all-determining assumption that without human perturbation, the natural inflows and outflows are always in perfect balance with each other. This leads to the conclusion that every year roughly half of the human-produced CO_2 accumulates in the atmosphere, while the other half is absorbed by the land and oceans.

A major problem with this approach is the high degree of uncertainty and inaccuracy of both the natural flows to and from the atmosphere and the size of the carbon reservoirs in the oceans and on land. In the calculation of the Global Carbon Budget only the increase in atmospheric concentration and annual human emissions are accurately known. The natural flows to and from the atmosphere are not directly related; rather, they have different causes and occur at different times and/or places. Most of the CO_2 is transformed into other carbon compounds on land and in the sea through complex and chaotic processes. The amount of CO_2 stored in the oceans and on land is so large that relatively little CO_2 uptake or release cannot be measured. An annual change of the carbon mass in the oceans of only 0.013% is enough to explain the full 5 PgC/yr increase of the CO_2 level. A small imbalance, even for many years, is quite possible and would have no noticeable impact on the subsurface reservoirs. Thus, we cannot measure the natural fluxes with sufficient precision, nor can we assume that influx and outflux are in balance. Summarizing the results over a long period of time makes the problem even worse. The inaccurate bookkeeping method makes it impossible to draw conclusions about the impact of human emissions on the increase of CO_2 in the atmosphere.

2. Method

In this study we investigated the causes of the increase in CO_2 concentration by examining the changes in fluxes and residence times since the preindustrial period. The mass in the atmosphere is equal to the total yearly absorption (down flux), multiplied by the average time that the CO_2 remains in the atmosphere (residence time). Changes in the down flux and residence time are therefore directly related to changes in the atmospheric concentration. An explanation of why both the down flux and the residence time have increased could provide a better understanding of the recent changes in the CO_2 concentration and more generally in the global carbon cycle.

Here we assume that CO_2 in the atmosphere behaves like a first-order container system, where the rate of outflow is proportional to the mass within the container. This behavior is true for all gases in the atmosphere, including CO_2; however, the IPCC and many others make an exception for excess CO_2, meaning CO_2 that is not part of the normal natural cycle, but has been added to the system by humans. While the residence time of natural CO_2 is approximately 4 years, a much longer residence time is used for human CO_2: *'The removal of human-emitted CO_2 from the atmosphere by natural processes will take a few hundred thousand years (high confidence)'*

(IPCC, 2015, p. 469). This leads to the conclusion that approximately 45% of human CO_2 accumulates in the atmosphere.

Several studies have indicated that this exception is illogical and incorrect and that the use of multiple residence times makes no sense, as the atmosphere can be regarded as a well-mixed container and that nature cannot distinguish between different sorts of CO_2 based on their origin. Fluctuations in the natural cycle due to seasonal effects or volcanic eruptions are often greater than the amount of excess CO_2 from human emissions in one year, which makes it impossible to conclude whether the CO_2 is 'excess' or 'natural' (Segelstad, 1998; Harde, 2017, 2019; Salby and Harde, 2021). In this study, we will not directly address this exception or the use of multiple residence times for excess CO_2, as our analyses are at first based solely on natural changes in CO_2 fluxes with no excess CO_2 involved. The description of the atmospheric carbon cycle with only natural flows as a first order system is, as far as we know, undisputed.

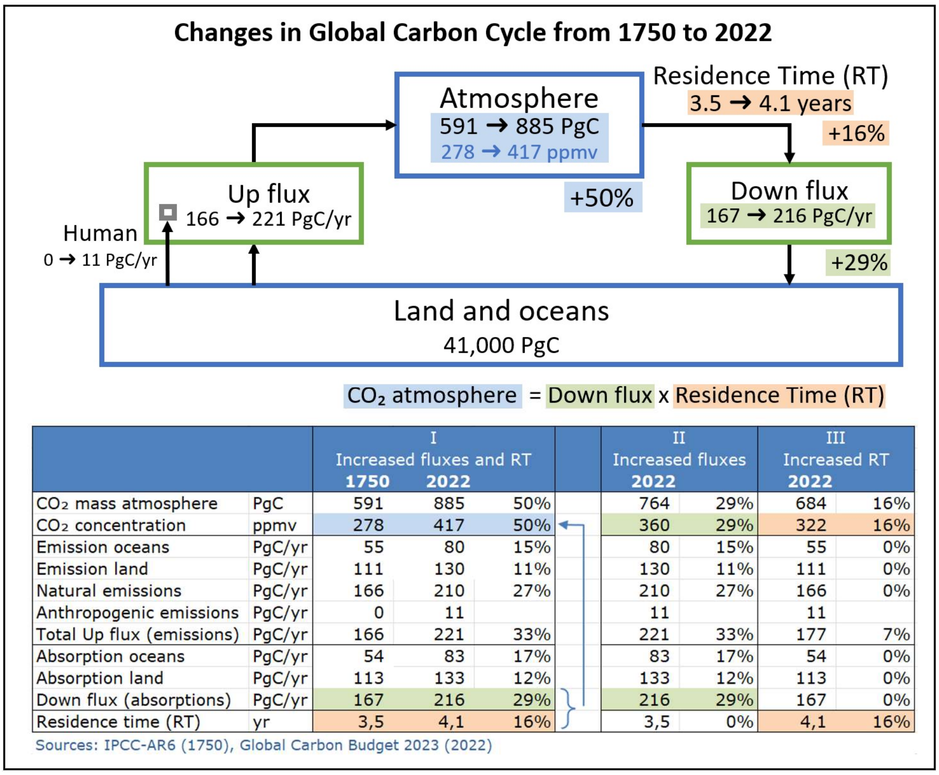
For our analysis, two processes are important: first, the buffering capacity of the oceans. The atmosphere, which acts as a container for CO_2, interacts with the land and oceans, which hold a significantly larger amount of carbon. Oceans are by far the largest carbon stock. The oceans contain far more carbon than would be predicted solely from gas solubility. Based on Henry's Law, CO_2 in the atmosphere is in equilibrium with dissolved CO_2 in the water. The vast majority of dissolved CO_2 reacts with water to form carbonic acid, which breaks down into bicarbonate and carbonate ions (and other carbonate complexes), that cannot exchange with the atmosphere. As the carbon mass in the oceans (Dissolved Inorganic Carbon) is approximately 50 times greater than that in the atmosphere, this set of equilibrium reactions enables the oceans to buffer changes in the atmospheric CO_2 concentration. A perturbation such as a single emission or absorption will affect only the short-term CO_2 concentration. With a relatively short residence time of approximately four years, most of the perturbation is eventually neutralized by this process (Stallinga, 2023).

A second important element for understanding the impact of global greening on the atmospheric CO_2 level, is the fact that the large fluxes to and from the atmosphere are primarily the result of interactions with the terrestrial and oceanic biospheres, based on photosynthesis and respiration. Due to the direct influence of the sun on the process of photosynthesis, the net in- and out-fluxes exhibit great diurnal and annual fluctuations. At night, respiration-related emissions predominate, but during the day, a significantly greater photosynthetic flux leads to net absorption. Additionally, the seasonal cycle of carbon is influenced by the growth and decay of vegetation. In spring and summer photosynthesis predominates, during which CO_2 is absorbed from the atmosphere. During fall and winter much of the absorbed CO_2 is released back into the atmosphere. At a constant residence time the atmospheric CO_2 level is proportional to the magnitude of the down flux. Alterations in sunlight-driven biological fluxes are, therefore, critical to the increased CO_2 levels.

Given that we are interested in the impact of greening over a period of decades and centuries, we can exclude processes with a much longer time frame, such as exchanges with sediments and rocks and the Earth's interior.

3. The impact of greening

The greening of the Earth leads to an increase in natural absorption: more trees/phytoplankton means more photosynthesis and thus more absorption. The increased absorption is reflected in Figure 1, which shows the most important atmospheric CO_2 levels and fluxes from 1750 (IPCC, 2021) and 2022 (Friedlingstein *et al.*, 2023). The atmospheric residence time for each year was calculated by dividing the CO_2 mass by the total absorption in that year. The uncertainty of the natural fluxes and residence times is estimated at ±20% (IPCC, 2015). The concentration in the atmosphere has increased by approximately 50% since 1750 (blue background). This growth is a combination, on the one hand, of the 29% increase in absorption from 167 to 216 PgC/year (green background) and, on the other hand, of the 16% increase in the residence time from 3.5 years to 4.1 years (orange background). Column I shows the original data. Column II shows the impact on the CO_2 level, only based on the increased fluxes. Column III shows the impact if only the residence time would have changed, so without global greening.



		I Increased fluxes and RT			II Increased fluxes		III Increased RT	
		1750	2022		2022		2022	
CO_2 mass atmosphere	PgC	591	885	50%	764	29%	684	16%
CO_2 concentration	ppmv	278	417	50%	360	29%	322	16%
Emission oceans	PgC/yr	55	80	15%	80	15%	55	0%
Emission land	PgC/yr	111	130	11%	130	11%	111	0%
Natural emissions	PgC/yr	166	210	27%	210	27%	166	0%
Anthropogenic emissions	PgC/yr	0	11		11		11	
Total Up flux (emissions)	PgC/yr	166	221	33%	221	33%	177	7%
Absorption oceans	PgC/yr	54	83	17%	83	17%	54	0%
Absorption land	PgC/yr	113	133	12%	133	12%	113	0%
Down flux (absorptions)	PgC/yr	167	216	29%	216	29%	167	0%
Residence time (RT)	yr	3,5	4,1	16%	3,5	0%	4,1	16%

Sources: IPCC-AR6 (1750), Global Carbon Budget 2023 (2022)

Figure 1: An overview of the most important CO_2 levels and fluxes from 1750 and 2022. Columns I show the original data, including their percentual change. Columns II show the impact on the CO_2 concentration with only global greening. Columns III show the impact on the CO_2 concentration without global greening. (IPCC, 2021; Friedlingstein et al.*, 2023).*

The 29% increase of the down flux alone indicates that greening of the Earth contributes to an increase in the atmospheric concentration. Due to more vegetation, the absorption flow has increased from 167 PgC/yr to 216 PgC/yr. The growth of the downward flux since the preindustrial period is only possible if the upward flux has increased more than that. Based on the historic levels and fluxes, we can conclude that this is the case. The total emissions have increased by 33%, from 166 to 221 PgC per year, which is also much more than the growth in the anthropogenic emissions alone.

Given the facts that the fluxes to and from the atmosphere are largely determined by the biological processes and that the atmosphere can be regarded as a first order container, in general we can conclude that the CO_2 level is directly related to the biological activity of the Earth. In Figure 2 we have given a simplified illustration of this mechanism, with CO_2 in the atmosphere presented as water in a reservoir (also acting as a first order process).

To understand the long-term impact of greening on the natural CO_2 concentration we assume the following two (hypothetical) steady states.

1. A stable situation with a constant concentration of ~280 ppmv, as assumed to be the case before any human influence. In this situation the total respiration is equal to total photosynthesis (GPP). As the down flux is proportional to the concentration, it follows that also the GPP is stable, so no greening or browning.

2. A stable situation similar to 1, but with a larger total GPP, so more greenness. This could be the result of more favorable conditions with respect to e.g. temperature, water availability and nutrition. The GPP level is supposed to be stable long enough so that the total respiration is again equal to the total photosynthesis, but at a higher level. As the concentration is proportional to the down flux, the concentration is now also at a higher level.

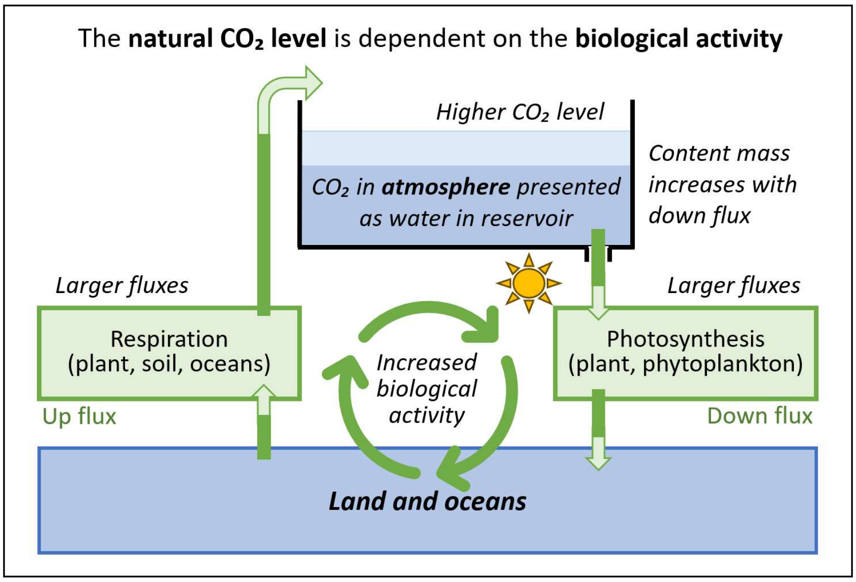


Figure 2: This simplified illustration demonstrates the importance of the Earth's biological activity for the natural CO_2 level in the atmosphere. Larger fluxes due to an increase in the yearly photosynthesis and respiration will lead to more CO_2 in the atmosphere (and vice versa).

This illustrates that in steady state situations with photosynthesis and respiration in balance, the level of greenness, in terms of GPP, defines the CO_2 level in the atmosphere. A larger GPP is only possible if also the CO_2 concentration is at a higher level.

During a period of greening that leads to the transition from state 1 to state 2, the increase in photosynthesis per year is larger than the resulting respiration, as the respiration partly lags the photosynthesis. The respiration increases, partly immediately by plant respiration, partly at later stages when leaves and other biomass degenerate. This delay qualifies new vegetation as a net sink.

The concentration can only increase if the up flux is larger than the down flux, so the greening alone cannot be the initial cause of the increasing concentration. Following correct bookkeeping, an increase of the concentration is only possible if in some period of time the sum of the total respiration and any other emission is larger than the total photosynthesis. This is apparently the case in the past decades given the yearly increase if the CO_2 mass in the atmosphere of approximately 5 PgC. Although new vegetation is a net sink, it is nevertheless an important element in the rising CO_2 concentration, as it leads to a structural increase in respiration. Ultimately greening can lead to a new steady state situation with larger up and down fluxes and a higher atmospheric concentration.

The greening of the Earth is mostly the result of the increased CO_2 concentration, but estimates show large variations from 44% (Chen *et al.*, 2022) to 74% (Zhu *et al.*, 2016) and 86% (Haverd *et al.*, 2020). Other factors include climate warming and nitrogen deposition. This means that the CO_2 concentration can be characterized as positive feedback for greening. If the atmospheric CO_2 level increases for any reason, this can lead to more greening. The extent to which this happens, however, will depend on many (local) circumstances.

Increased greenness, along with a higher concentration of atmospheric CO_2, imply that both the biosphere and the atmosphere contain more carbon than there was originally. This change could be the result of a net flux from the oceans and soil due to higher temperatures (Lee, 2011; Palmer et al., 2019). Another possible explanation involves the ocean's buffer capacity, which results from the combined equilibrium reactions of Henry's Law and the carbonate system. A reduction in concentration due to more absorption is in time compensated by increased emissions from the oceans. During the transition phase to a higher GPP level, the atmosphere and biosphere apparently behave as a net sink and the oceans and soil as a net source of CO_2.

The 16% change in residence time from 3.5 to 4.1 years indicates a nonlinear behavior of the carbon system, where the ratio of the atmospheric carbon mass and the down flux has increased over the years. Therefore, a greater partial pressure is needed for the same uptake rate. There could be many causes for this behavior, but satellite observations indicate that it can be related to constraining factors in the fertilization. CO_2 is just one limiting factor of photosynthesis; other factors include phosphorus, nitrogen, and water availability. With increasing CO_2 levels, the fertilization may be slowed down, due to the constraining effect of soil nutrients and soil water (Wang *et al.*, 2020). So, the increase in residence time can at least partly be linked to the increased greenness of the Earth. The larger residence time can also be connected to the reduced solubility of CO_2 in the oceans, which is generally inversely proportional to temperature. Several studies have suggested that higher temperatures due to climate warming result in not only more emissions, but also reduced absorption with a consequently longer residence time (Essenhigh, 2009; Harde, 2017, 2019). It is evident that further research into the various underlying mechanisms and interactions is necessary to enhance our understanding of this part of the increase in CO_2 levels.

4. Potential causes

Although the greening of the Earth since the preindustrial period developed parallel with the CO_2 level in the atmosphere, it was not the initial cause of this increase. Several studies have indicated that global warming since the Little Ice Age was the main initial driver of increased CO_2 levels (Humlum, Stordahl and Solheim, 2013; Harde, 2019; Koutsoyiannis, 2024b). Since 1750 the average global temperature has increased by approximately 1.1 K (IPCC, 2021) which has led to more emissions from the ocean and, more importantly, from the soil (Lee, 2011; Palmer *et al.*, 2019). This means that the great impact of global greening on CO_2 is closely related to the controlling role of climate warming in explaining the increased carbon dioxide level in the atmosphere. A higher temperature not only increases emissions from soil and oceans, it has also a direct positive impact on global greening and reduces the solubility of CO_2 in the oceans. The impact of temperature on the CO_2 level is supported by investigations of the causal relationship showing that changes in CO_2 concentrations are not the cause of temperature changes; rather, changes in temperature can potentially cause variations in CO_2 levels across all time scales (Koutsoyiannis *et al.*, 2023).

Based on the obvious impact of global greening on the CO_2 level, e.g., as observed in the seasonal cycles, we think that the present paradigm that human emissions are the sole cause of the increasing CO_2 level is untenable. The increased down flux observed since preindustrial times due to greening of the Earth leaves no other conclusion then that most of the CO_2 increase has a natural cause. In the present widely accepted hypothesis excess CO_2, that is CO_2 emitted on top of the natural equilibrium, accumulates partly in the atmosphere and remains there for a very long time. It is argued that there is a relatively short residence time of 4.1 years for natural CO_2, and multiple (much longer) residence times for excess CO_2 (IPCC, 2015). As previously mentioned, there is no physical justification for assuming multiple residence times for a part of the CO_2 in the uncompartmentalized well-mixed atmosphere, nor can we explain why a perturbation of human CO_2 would lead to a change in residence time.

However, we think there is no need for an ad-hoc model to describe the behavior of excess CO_2 in the atmosphere. Temperature induced global greening explains the observed CO_2 rise well, without the need for any extraordinary assumptions. The increase in GPP due to more greening can fully explain the observed increase of the down flux, and the constraining factors in the CO_2 fertilization combined with the reduced solubility of CO_2 in the oceans are plausible explanations for the observed increase in residence time. The close interaction of the expanding biosphere and higher temperatures is described in detail in a mathematical framework based on reservoir routing. Without any ad-hoc assumptions the results of this framework are in excellent agreement with real-world data (Koutsoyiannis, 2024a).

Assuming the same behavior for excess CO_2 as for natural CO_2, the contribution of human activities to the increase in CO_2 can be estimated based on its contribution to the down flux. A stable level of 9.6 PgC per year for fossil CO_2 (Friedlingstein *et al.*, 2023) leads to an almost equal down flux. With a residence time of 4.1 year, it has resulted in an increase of almost 40 PgC in the atmosphere, or 19 ppmv. This finding is consistent with the more accurate estimate of 4.3% of the concentration (i.e., 38 PgC or 18 ppmv in 2022) based on actual historical emissions (Harde, 2019). Under the influence of the positive feedback from the CO_2 fertilization, the effective contribution to the CO_2 increase may have been higher.

An important element of the present hypothesis is land use change, such as deforestation and the conversion of forests into agricultural land. This change is regarded as a form of emission similar to the burning of fossil fuels. This is true when the carbon stored in trees is released into the atmosphere, which represents 1.3 PgC/yr in 2022 (Friedlingstein *et al.*, 2023). On the other hand, deforestation has also led to a 4.4% reduction in the global terrestrial GPP of 130 PgC/yr (Krause *et al.*, 2022), and thus a relatively smaller down flux of approximately 5.7 PgC/yr, and a smaller CO_2 concentration. The combined contribution to the down flux due to the release of carbon from deforestation and the resulting reduction in GPP, can together be estimated at -4.4 PgC/yr. With a residence time of 4.1 years, this contribution has been responsible for 18 PgC less in the atmosphere, or -9 ppmv.

5. Conclusions

It may seem contradictory that the greening of the Earth is associated with a higher concentration in the atmosphere. After all, plants absorb more CO_2 from the atmosphere. But global greening is being initiated by and combined with global warming. Higher temperatures have direct effects on greening and on the emissions from soil and oceans. Greening is not the initial cause, but it leads to a larger down flux and ultimately also to a larger up flux. An increase in the fluxes to and from the atmospheric container results in a higher level, so we can say that the combination of global warming and global greening has led to more CO_2 in the atmosphere. The greater down flux since 1750 explains 29% of the 50% increase in CO_2, and the longer residence time could well be the result of constraining factors in the CO_2 fertilization combined with the reduced solubility of CO_2 in the oceans. This confirms that natural factors play a dominant role in increasing CO_2 concentrations, while human factors have only a limited influence.

In the present thinking about the carbon cycle there is no difference of opinion about the first order behavior for the natural carbon dioxide fluxes to and from the atmosphere. It is therefore remarkable that the growth of these fluxes is not considered as a viable explanation for the increased atmospheric concentration. The only reason we can think of this almost trivial aspect as being neglected is the bias of the human liability, which results from the flawed bookkeeping method that is used for the global carbon budget.

The quantifications in this study are based on the numbers as presented in Figure 1. Especially for the year 1750 the accuracy of the data is questionable. The atmospheric concentration in that year is based on ice core proxies from Antarctica, and the down flux is based on model calculations by the IPCC. Both are subject to considerable uncertainty. It is obvious that a more detailed modeling based on the changes in fluxes at different time frames is necessary to obtain a more accurate understanding of all the causes and interactions involved. However, an increase in the down flux of approximately 30% is in line with the results of the previously mentioned studies on global greening, which makes it evident that global greening is directly related to the increase in CO_2. It is likely that the overall increase of the CO_2 level can be attributed to the interplay between global warming and greening, with a relatively small anthropogenic contribution, without the need to presume a special behavior for excess CO_2 or the use of an ad-hoc model with multiple residence times in the well-mixed atmosphere.

The supposed CO_2 level of ~280 ppmv from before the Industrial Revolution is often used as a baseline for comparing current and projected CO2 concentrations, and as a reference point for assessing human-induced climate change. Due to the dominant role of natural changes in the biosphere under the influence of higher temperatures, one can conclude that the present CO_2 concentration can be regarded as a 'natural' level. The present atmospheric CO_2 level matches with the actual greenness of the Earth and is much larger than 280 ppmv. If we exclude human contribution to the down flux due to the use of fossil fuels, the natural equilibrium rate would still be well above 400 ppmv (2024).

Our conclusion that the natural atmospheric CO_2 level depends on the greenness of the Earth is at odds with the suggested stable CO_2 level from the ice core proxies of Antarctica. These proxies suggest that the natural equilibrium concentration has been stable for a very long time: between 260 and 280 ppmv in the last 10,000 years and between 180 and 290 ppmv in the past 800,000 years (Bereiter *et al.*, 2015). However, it is improbable that there have been no fluctuations in the Earth's GPP over the past 800,000 years, or that the GPP has ever been as high as it is today. It is for example estimated that 10,000 years ago, shortly after the end of the last glacial, the area of the globe covered with forests was approximately 50% larger than in 2018 (Ellis, Beusen and Goldewijk, 2020; Ritchie and Roser, 2024). The average GPP from forests is 29% larger than from grassland and 10% larger than from cropland, which indicates a greater CO_2 down flux and hence a higher atmospheric concentration than today (Krause *et al.*, 2022).

Although ice core measurements are incredibly valuable for providing trend information on CO_2 levels, temperature and other parameters, we have reason to believe that the absolute measured CO_2 values are much lower than the original concentrations, due to the dissolvement of CO_2 from the capsulated air in firn and ice into water (Jaworowski, 2007). Ice core reconstructions also give a very flattened representation, in which only slow changes are visible. In the data recorded over the past 800,000 years, a single observation in an ice layer represents a period of 10s to many 100s of years (up to 5000 years). Short fluctuations, even with much higher concentrations, are therefore not visible. Unlike the ice core records, direct measurements taken between 1800 and 1960 and proxies from plant stomata show much greater values and more variations, which is more in line with what could be expected from our findings (Kouwenberg, 2003; Beck, 2021).

The impact of global greening on the atmospheric CO_2 concentration has important implications for the present policy to mitigate climate change. Due to the relatively large impact of natural factors the human contribution to the increase in CO_2 is much smaller than presently assumed. With a single residence time for all carbon dioxide in the atmosphere the human contribution based on fossil fuels is approximately 4.3% or 18 ppmv. This contribution will not further increase if the human emissions are stabilized at the present level, and even the most rigorous net zero scenario can have only a very limited impact.

Competing interests

The author declares that he has no conflict of interest.

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