Research Article

SCC-Publishing

Michelets vei 8 B
1366 Lysaker, Norway

ISSN: 2703-9072

Historical CO_2 levels in periods of global greening

Frans J. Schrijver

Independent Scientist, Hattem, Netherlands

Correspondence:
frans.schrijver@gmail.com

Vol. 5.3 (2025)

pp. 107 - 118

Abstract

The increased atmospheric CO_2 level is widely recognized as a primary driver of global greening (a 30% increase in GPP since 1900). It raises the question whether such an increased CO_2 level is also a necessary condition for a large GPP. This paper evaluates whether CO_2 levels during historical periods of similar or more greenness as today, are consistent with the widely held view that CO_2 levels remained below 300 ppm over the past 800,000 years, as indicated by Antarctic ice core records. Employing Mitscherlich's Law, the research models the global GPP response to increasing CO_2, based on the mean value of eight different long-term GPP datasets. It illustrates a diminishing return of vegetation associated with rising CO_2, as additional factors such as nutrient and water availability impose constraints on the fertilization effect. Due to this diminishing return the average residence time of CO_2 in the atmosphere increases significantly with higher GPP values. High CO_2 levels, similar to today's, were therefore necessary for comparable GPP during green periods like 10,000 years ago. A CO_2 concentration of 280 ppm would only be possible if nature's response to CO_2 were fundamentally different from what we observe today, with other constraining factors exceptionally more favorable. Natural fluctuations of the atmospheric CO_2 concentration can be well explained, based on the strong temperature dependence of the degeneration of carbon compounds that are stored in large quantities in the soil and the oceans.

Keywords: CO_2, atmosphere, greening, GPP, climate, global warming

Submitted 2025-07-20, Accepted 2025-10-06, https://doi.org/10.53234/scc202510/06

1. Introduction

Global greening refers to the observed increase in the amount of green vegetation, such as plants and trees, across the planet. The terrestrial Gross Primary Production (GPP) has gone up by more than 30% since 1900. Multiple studies have identified the growing atmospheric CO_2 concentration as the dominant driver of this greening (Haverd *et al.*, 2020; Lai *et al.*, 2024). The present level of greenness in terms of GPP is, however, not exceptional. In the history of the Earth there have been many fluctuations in the amount of vegetation. As an example, we use the situation 10,000 years ago, when there was 50% more forest area on the planet than there is today (Ritchie, 2021). In this study we investigate the relationship between the (historical) levels of greenness in terms of GPP and the atmospheric CO_2 concentration. The general accepted belief, based on ice core records of Antarctica, is that CO_2 levels were much lower than today, typically around 280 ppm and for a period of 800,000 years less than 300 ppm (Lüthi *et al.*, 2008; Bereiter *et al.*, 2015). We want to determine how likely it is that these low concentrations match with a level of greenness that is equal or higher than the present level, or if a higher atmospheric concentration is needed to explain historical GPP levels.

For carbon dioxide the atmosphere can be regarded as a well-mixed container with natural up and down fluxes to and from land and oceans. At any moment t in time the residence time τ(t) is defined as the average time CO_2 remains in the atmosphere in years and is equal to the total atmospheric CO_2 mass c(t) divided by the global down flux $d_G(t)$ per year, which leads to:

$$c(t) = d_G(t) \cdot \tau(t) \quad (1)$$

The recent global greening is reflected in the increase of the carbon fluxes to and from the atmosphere, and a longer residence time, since 1750. See Table 1. The down flux has increased by 29% and the residence time by 16%. Together they explain the increase with 50% of the CO_2 level (Schrijver, 2024).

Table 1: Changes in the carbon cycle since pre-industrial period (IPCC, 2021; Friedlingstein et al., 2023)

		1750	2022	*%*
CO_2 mass atmosphere	PgC	591	885	50%
Natural emissions	$PgCyr^{-1}$	166	210	27%
Anthropogenic emissions	PgC	0	11	
Total emissions (up flux)	$PgCyr^{-1}$	166	221	33%
Total absorption (down flux)	$PgCyr^{-1}$	167	216	29%
Residence time	yr	3.5	4.1	16%

To draw conclusions on historical CO_2 concentrations, we must understand the impact of the global GPP to the down flux and to the residence time. The 2022 CO_2 level of 885 PgC is the result of a down flux of 216 $PgCyr^{-1}$, multiplied by the residence time of 4.1 years. If during periods of similar greenness in the past millennia the CO_2 level was only 590 PgC, it would imply a lower down flux and/or a shorter residence time at that time. To consider ice core records accurate, it is necessary to determine if a smaller down flux and/or a shorter residence time, combined with a high level of greenness, is reasonable.

2. GPP changes

The 'greening of the Earth' refers to the observed increase in the amount of green vegetation across large parts of the planet over the past decades. 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 GPP has gone up by more than 30% since 1900 (Haverd *et al.*, 2020; Lai *et al.*, 2024). 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)

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 86% (Haverd *et al.*, 2020). The most widely cited source estimates the CO_2 fertilization effect at approximately 70% (Zhu *et al.*, 2016). Other factors include nitrogen deposition (9%), climate warming (8%) and land cover change (4%)[1]. As atmospheric CO_2 concentrations have risen (now over 425 ppm, compared to ~280 ppm pre-industrially), plants can photosynthesize more effectively. CO_2 is a primary raw material for

[1] CO_2 is strictly speaking not a fertilizer as it is the primary raw material for photosynthesis. In the scientific literature there is, however, an abundant use of the term 'CO_2 fertilization effect', that can be defined as the enhancement of photosynthesis and subsequent growth in many plants due to increasing levels of atmospheric carbon dioxide.

photosynthesis, so higher availability allows plants to grow faster and often use water more efficiently (by reducing stomatal conductance).

The major part of all CO_2 that directly or indirectly flows from the atmosphere to land and sea each year, is the result of photosynthesis. The photosynthesis of plants on land is responsible for almost all the terrestrial down flux, 120 - 130 $PgCyr^{-1}$. The photosynthesis of phytoplankton in the oceans is comparable with the GPP on land: 100 - 150 PgC yr^{-1} (Huang *et al.*, 2021). This is larger than the CO_2 down flux to the oceans (80 - 90 PgC yr^{-1}), as it represents biological fixation of dissolved CO_2 within the ocean, which indirectly defines the exchange with the atmosphere. It is, however, clear that also in the oceans photosynthesis is an important component in the oceanic down flux.

Many studies though have found that the fertilization effect is weakening and greening is slowing down (Reich and Hobbie, 2013; Allen Jr., 2019; Terrer *et al.*, 2019; Wang *et al.*, 2020; Winkler *et al.*, 2021). The *ß*-factor is often used to characterize the plant response to increasing CO_2 concentration, where *ß* is defined as the relative increase in gross primary production (p) in response to an increase in atmospheric CO_2 concentration (c).

$$\beta = \frac{dp}{dc} \tag{2}$$

The global median *ß* during 1982 to 2015 was 16.1 ± 11.5% per 100 ppm, so 16% increase in photosynthesis per 100 ppm CO_2. Using multiple long-term satellite- and ground-based datasets, it was shown that global carbon fertilization effect declined across most terrestrial regions of the globe. During 1982 to 2015 ß decreased at a rate of $-0.92 \pm 0.12\%$ 100 $ppm^{-1}yr^{-1}$ (Wang *et al.*, 2020).

A declining *ß* means that the fertilization effect is weakening and greening is slowed down. The explanation is that further growth of the vegetation is constrained by other factors. An important factor is nutrient limitation. Plant growth is limited by the nutrient that is most scarce, not by the abundance of others. Even if CO_2 is super-abundant, plants cannot grow indefinitely if they don't have enough other essential nutrients like nitrogen or phosphorus. Also, the availability of sufficient water can be a limiting factor that slows down the growth rate. Another element is plant acclimation. Plants can physiologically adjust to sustained high CO_2, if they cannot use all the extra carbon for growth due to nutrient or other limitations.

We can apply Mitscherlich's Law, also known as the Law of Diminishing Returns in Agriculture, to describe the relationship between the application of a single variable input (e.g., fertilizer, water) to a fixed area of land and the resulting crop yield. The law states that the increase in crop yield due to an additional unit of input diminishes as more of that input is applied, assuming other factors (e.g., soil quality, sunlight) remain constant. The application of Mitscherlich's Law has been demonstrated individual crop growth responses to rising atmospheric carbon dioxide, e.g. (Allen Jr., 2019).

3. Modelling Diminishing Returns

Here we have investigated the application of Mitscherlich's Law to describe not just individual crop yields, but the global GPP as a whole in response to increasing CO_2 levels. It posits that the response (e.g., crop yield or vegetation growth) to an input (in this case the actual CO_2 concentration) increases rapidly at low input levels but approaches a maximum as the input continues to rise. For Earth's greening it can be written as follows.

$$\beta = \frac{dp}{dc} = B \cdot (A - p) \tag{3}$$

This equation says that the rate of GPP increase related to the CO_2 concentration is proportional to the gap between the maximum GPP and the current GPP, where:

c is the input level, in this case the actual CO_2 concentration,
p is the yield at input level c, in this case the gross primary production (GPP),
A is the attainable yield, in this case the maximum GPP (with other factors constant),
B is a constant related to the efficiency of the input (CO_2),
ß or dp/dc represents the rate at which yield (GPP) increases with respect to input (CO_2).

To investigate whether Mitscherlich can be applied to describe the greening of the Earth based on the CO_2 concentration, we apply the results of a study by (Wang *et al.*, 2024). This study investigated the global trends in terrestrial Gross Primary Productivity (GPP) and their driving factors over the past four decades, utilizing eight different GPP datasets, including BEPS GPP, CCDAS GPP, EC-LUE GPP, GIMMS GPP, LRF GPP, GPPNIRv, P-model GPP, and TRENDY GPP. The findings indicate a notable decrease in global GPP trends, from 0.43 $PgCyr^{-2}$ in 1982–1999 to 0.17 $PgCyr^{-2}$ in 2000–2016, a phenomenon observed across more than 68% of the terrestrial surface. This decline due to a reduced CO_2 fertilization effect was particularly evident in satellite-derived GPP data.

After solving the differential equation Mitscherlich's Law for the greening of the Earth can be written as follows (with p_T as the terrestrial GPP).

$$p_T = A(1 - \exp(-B(c - C_0)) \quad (4)$$

Photosynthesis typically stops functioning at CO_2 concentrations below 150 ppm. So, this level can be regarded as a starting point in the equation, which is reflected in the value 318.6 PgC for C_0 (which is equal to 150 ppm). By matching the time series of the mean values of the 8 models with the actual concentration level in each year (Lan and Keeling, 2025), we were able to compare the (*c*, *p*)-values with Equation 4, as presented in Figure 1. Each blue dot represents a GPP value for the associated CO_2 value. With the use of the Non-linear Least Squares method we were able to find values for A and B that give the best fit for the given data. The red line shows the best fit line with an R^2 of 0.85.

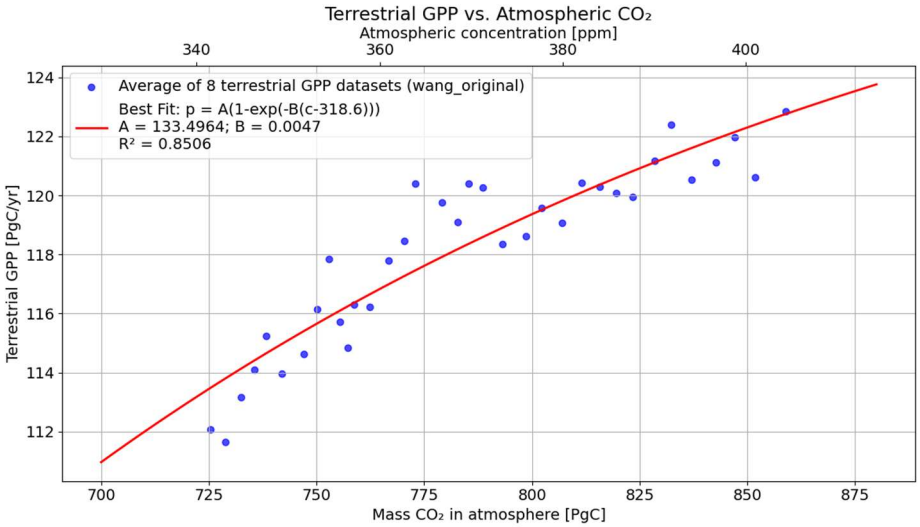

Figure 1: The mean terrestrial GPP values of 8 long term models as a function of the actual CO_2 concentration in the atmosphere (blue dots). The red line represents the best fit line according to Mitscherlich's Law as given by equation 4.

The available GPP data only relate to terrestrial absorptions, while we are interested in the total global GPP. We have, however, no reliable dataset for oceanic GPP changes in the past decades. Most studies on the fertilization effect are focused on terrestrial vegetation, supported by satellite observations. Global oceanic GPP trends are less straightforward than terrestrial trends and exhibit considerable regional and seasonal variability (Evans, Hales and Strutton, 2011).

Photosynthesis and respiration occur in water using dissolved CO_2, making it hard to distinguish biological processes from physio-chemical ones that interact with the atmosphere. Biological processes determine the dissolved CO_2 concentration and aquatic partial pressure (pCO_2), while the atmospheric exchange is driven by the difference in pCO_2 between the surface water and the atmosphere.

According to the 6th Assessment Report from the IPCC not just terrestrial, but also oceanic emissions have increased since pre-industrial times. Emissions from the oceans have increased from 54 $PgCyr^{-1}$ in 1750 (IPCC, 2021) up to 80 $PgCyr^{-1}$ (Friedlingstein *et al.*, 2023). The temperature dependence of physical-chemical processes (reduced solubility of CO_2 and temperature dependence of constants in the carbonate system) is 4 to 4.5% per degree Celsius, which is too small to explain this increase (Liu, Fukuda and Matsuda, 2006). This suggests that biological processes appear to cause changes to seawater pCO_2 that are more significant than the temperature effect on the solubility pump alone.

Although there is no direct measurement, a comparable fertilization effect may occur in marine environments due to the similar processes of carbon fixation involved. In Figure 2 we can see that we get a very good fit with the IPCC estimate for 1750 (IPCC, 2021) and the GCB figure (Friedlingstein *et al.*, 2023), if we assume an increase of oceanic photosynthesis that is proportional to the increase of terrestrial photosynthesis. Each blue dot in Figure 2 represents the sum of the terrestrial GPP value from the 8 models, and a proportional value for the oceanic GPP. The green squares are estimates from the IPCC and GCB of the down fluxes. The good fit with the red line based on Mitscherlich's Law confirms that the total GPP is close to the total down flux. Including the two extra data points in the dataset, results in a R^2 value of 0.94.

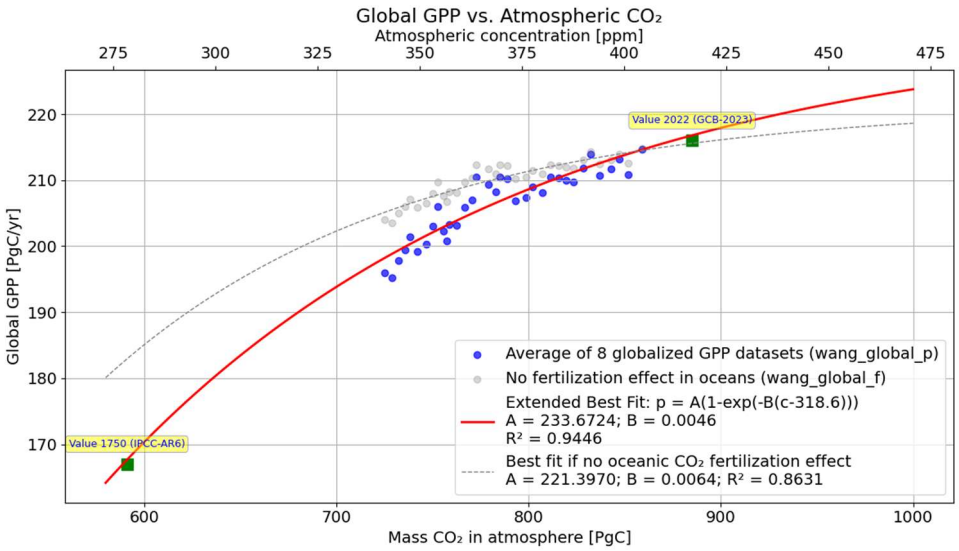

Figure 2: Similar to Figure 1 with extended axes and an assumed proportional GPP change in the oceans. The two added datapoints give a good fit to the best fit line:1. CO_2 mass and down flux in 1750, based on IPCC-AR6 estimate (IPCC, 2021), and 2. the CO_2 mass and down flux in 2022, based on the Global Carbon Budget 2023 (Friedlingstein et al.*, 2023). The gray dashed line and dots show the result if no CO_2 fertilization effect in the oceans is assumed.*

If we assume a smaller than proportional fertilization effect from the oceans, or even zero, we will get a best fit line that is more flat than the original one, but with a similar concave curve. In all cases the increase of the global down flux is slowing down compared to the increasing CO_2 concentration in the atmosphere. The gray dashed best fit line shows the most extreme case with no CO_2 fertilization effect in the oceans, so with a stable oceanic down flux, that does not change with CO_2 concentration.

Even though we only have terrestrial GPP data, we can easily show that in all cases an increasing terrestrial GPP leads to a larger global down flux (land + oceans) and a longer residence time, which together are consistent with a higher atmospheric CO_2 concentration.

The global down flux d_G can be written as the sum of the flux to land d_T and to the oceans d_O.

$$d_G = d_T + d_O = p_T + d_O \tag{5}$$

The terrestrial GPP (p_T) is almost equal to the terrestrial down flux (d_T). When p_T increases under the influence of more CO_2, the global down flux will also increase, as long as the down flux to the oceans (d_O) is not decreasing under the influence of more CO_2.

The slowing down of the greening under the influence of diminishing returns, represented by the concave curve in Figures 1 and 2 instead of a straight line, indicates a longer residence. It can also be seen if we express the residence time τ as a function of the terrestrial greening p_T.

$$\tau = \frac{c}{d_G} = \frac{C_0 - \frac{1}{B}\ln\left(1 - \frac{p_T}{A}\right)}{p_T + d_O} \tag{6}$$

Since in Mitscherlich's law the maximum GPP is limited by the value A, the residence time will increase sharply at higher values of the terrestrial GPP, which we can see in Figure 4 (red line). The gray line shows the average residence time as a function of the terrestrial GPP if there is no CO_2 fertilization effect in the oceans, in which case the oceanic down flux is assumed stable in relation to varying GPP-values. This results in an even faster increase of the residence time.

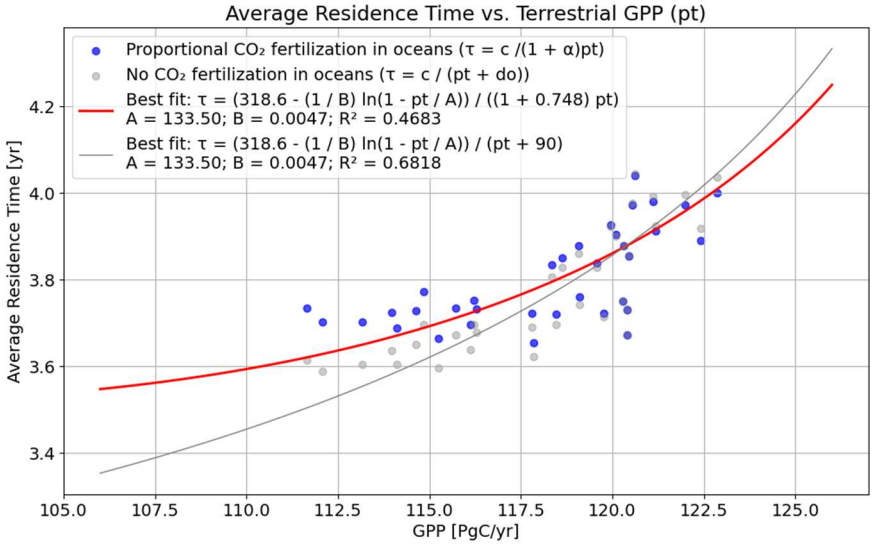

Figure 4: The calculated average residence time of the original dataset as a function of the terrestrial GPP (blue dots). The red line represents the best fit line according to Equation 6. The gray line and dots assume no fertilization effect in the oceans.

Constraining factors such as nutrient and water diminish the return of vegetation associated with rising CO_2. This effect translates into a longer residence time. Figure 4 shows that as a result of the diminished return, the average residence time of CO_2 in the atmosphere increases with higher GPP values. As the CO_2 mass in the atmosphere is proportional to both the down flux and the residence time, it is clear that a green Earth with a large GPP is inextricably linked to a high CO_2 concentration in the atmosphere. Around 10,000 years ago, forest cover was 50% greater than today (Ritchie, 2021). The land use change since that period as a result of human deforestation and agriculture, is illustrated in Figure 5. With a mean GPP of 2.0 $kgCm^{-2}yr^{-1}$ forests represent the most productive land cover, while grasslands and croplands on average reach 1.5 and 1.8

$kgCm^{-2}yr^{-1}$, respectively. When these GPP estimates are combined with the historical land use change, it follows that the global terrestrial GPP was 4.4% larger in that period than today (Krause *et al.*, 2022).

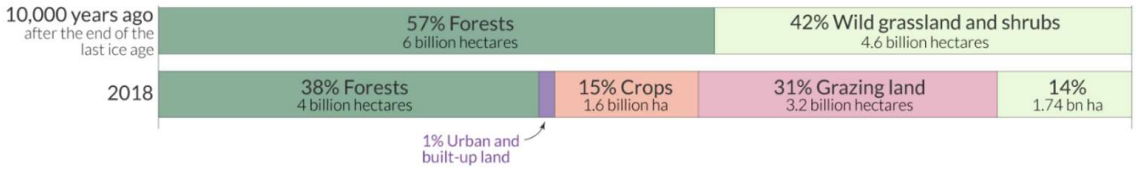

Figure 5: Land use change over the past 10,000 years. Based on the average GPP values per square meter for forest, grassland and cropland, we can conclude that the total GPP 10,000 years ago was approximitly 4.4% larger than today. Image adapted from Our World in Data (Ritchie, 2021).

Following Equation 6 and Figure 4, the residence time will increase relatively faster than the GPP, which implies that in that period the average residence time was at least as high as the current residence time of approximately 4.1 years, and thus also the amount of CO_2 in the atmosphere. We have no reason to believe that nature's response in terms of GPP to the actual CO_2 level was very different from today, so a shorter residence time is very unlikely. We can therefore conclude that global GPP 10,000 years ago was at least as high as today.

4. Discussion

It is obvious that the application of Mitscherlich's Law is a simplification of the complex processes that define the Earth's vegetation. The diminishing return is confirmed for individual plant species, where the application for the total GPP might raise new complexities, like global variability with different growth rates for the many ecosystems, nonlinear interactions and long-term effects (e.g. changes in the species composition) complicating the model. The available data from the 8 models show nevertheless a good fit, explaining that constraining factors like nutrient and water availability can be responsible for a slowdown of the greening. Apparently, the behavior of the sum of all vegetation does not fundamentally differ from that of individual plant species in this respect. It makes it evident that large GPP values lead to longer atmospheric residence times.

In a period without human disturbance and with the same or higher GPP as today, a CO_2 concentration of approximately 280 ppm would imply a residence time of approximately 2.7 years (590 PgC / 216 $PgCyr^{-1}$) or less. This would only be possible if nature's response to the CO_2 level were fundamentally different from what we observe today. CO_2 is one of the constraining factors that define the growth rate of vegetation. A larger GPP at low CO_2 levels would only be possible if other factors like sunshine, nutrient and water availability, were significantly more favorable than today. Especially in our example of 10,000 years ago, this is very unlikely. The deforestation and expanding agricultural land since that period is primarily the result of human activities (Ritchie, 2021). There is no indication that the other limiting factors have significantly changed.

As the present level of greenness is not exceptional in the history of the Earth, our results indicate that variations in atmospheric CO_2 concentrations up to levels comparable to or exceeding those observed today are possible. The view that human emissions are the only cause of rising atmospheric CO_2 levels is based on the assumption that, over decades or centuries, natural carbon fluxes tend to remain relatively balanced without significant human influence. The ocean and terrestrial carbon sinks are often defined by their capacity 'to absorb a part of the human caused CO_2 emissions'. Without these human emissions, the natural yearly fluxes would cancel each other out, maintaining a stable atmospheric concentration at a level of typically 280 ppm (IPCC, 2021; Friedlingstein *et al.*, 2023).

A precise balance between natural upward and downward fluxes is however unlikely. For plant respiration, you can argue that it is in some way related to the absorption of CO_2 by those same

plants. But decomposition, the degeneration of carbon compounds that are stored in large quantities in the soil and the oceans, has only a delayed and indirect connection to current photosynthesis. There are different drivers for the most important fluxes to and from the atmosphere. For photosynthesis (down flux), the CO_2 concentration in the atmosphere is the most important driver. But for respiration (up flux), temperature is the most important driver, as long as enough organic carbon compounds are available. Bacterial processes responsible for the breakdown of organic material on and in the soil are exponentially related to temperature, with Q_{10}-values for soil respiration ranging from around 1.7 (approximately 5.4% per °C) to over 6 (approximately 20% per °C)(Luan *et al.*, 2013). Apart from the biological processes, the temperature dependence of physical-chemical processes in the seawater also causes additional emissions at higher temperatures (Liu, Fukuda and Matsuda, 2006; Takahashi *et al.*, 2009).

A period of rising temperatures can lead to more respiration from the large carbon buffers in the soil and oceans and thus a higher CO_2 concentration in the atmosphere and greening of the Earth. In a period of falling temperatures, the opposite effect can occur. As concluded by (Koutsoyiannis, 2024b): *"During cool periods, degradation slows more than photosynthesis, and this traps CO_2 into soil. During warm periods, carbon trapped in soils is released faster than photosynthesis can absorb it, and atmospheric CO_2 increases"*. The total carbon mass remains conserved within the Earth system, as substantial carbon reservoirs on land and in the oceans effectively buffer changes in carbon distribution. The changes in the buffers are very small compared to the total amount of 41,000 PgC (of which 3,100 PgC in the soil), a fortiori as the process of greening is relatively slow: 30% over a period of 120 years equals on average 0.2% per year.

More vegetation corresponds to higher CO_2 levels. This may appear contradictory, as plants absorb CO_2. However, greening is not the cause of the higher concentration but rather its result. The probable causality is summarized in Diagram 1.

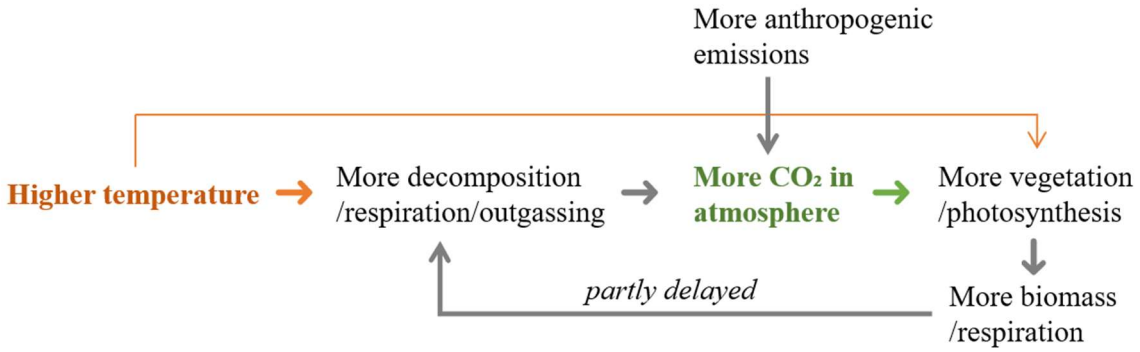

Diagram 1: Simplified causality diagram that illustrates that the CO_2 concentration can change naturally, due to different drivers for the up flux and down flux. Global warming is the main driver (in orange) for more respiration and oceanic outgassing and has a (smaller) positive effect on global greening. The increased atmospheric concentration is the main driver (in green) for more photosynthesis and global greening, which results in more biomass and respiration. Increasing anthropogenic emissions can accelerate this process.

Both higher temperatures and increasing anthropogenic emissions can lead to more CO_2 in the atmosphere, resulting in more photosynthesis and thus more vegetation. The effect is amplified, as more vegetation leads to more plant respiration and after some time biodegradation of the extra biomass. Increased temperatures also have a positive impact on the CO_2 outgassing of the oceans. Another element is the direct impact of temperature on global greening. Climate warming can enhance plant growth and extend the growing season in moderate and colder regions, but in tropical regions heat stress can reduce productivity. While less significant than CO_2 fertilization, the recent temperature increase resulted in a net positive contribution to global greening (Zhu *et al.*, 2016).

The important role of temperature in natural CO_2 fluctuations is supported by the proven unidirectional causal relationship between temperature and CO_2 (Koutsoyiannis *et al.*, 2023), and the developed mathematical framework that results in excellent agreement of the recent global warming with accurately measured CO_2 changes (Koutsoyiannis, 2024a). It also explains the abundance of vegetation 10,000 years ago, in the Holocene Thermal Maximum with relatively high temperatures.

In addition to global warming, human emissions have contributed to the greening process and so to the recent CO_2 rise. However, there is no need to assume a problematic ad hoc behavior for anthropogenic CO_2. According to the IPCC human emitted CO_2 accumulates and remains much longer in the atmosphere than natural CO_2, up to more than 100,000 years, which cannot be explained in the uncompartimented and well mixed atmosphere. Not the emissions, but the atmospheric concentration is the dominant driver for the uptake of CO_2 in the biosphere and through the oceans, which cannot differentiate based on the source of the CO_2 molecules.

5. Conclusions

Based on the relationship of the CO_2 concentration and the actual GPP values of 8 long term models, we showed that the global GPP response to increasing CO_2 follows Mitscherlich's Law, demonstrating diminishing returns. While CO_2 initially drives greening, its fertilization effect is slowing down due to limitations from other factors like nutrient availability and water. This implies that continued atmospheric CO_2 increases will lead to relatively smaller gains in GPP, and thus an increasingly longer CO_2 residence time. The global GPP is by far the most important component of the down flux to land and oceans. As the CO_2 concentration is proportional to the down flux and the residence time, a 'green Earth' is inextricably linked to high atmospheric CO_2 concentrations.

The current level of Earth's greenness is not extraordinary, suggesting that the present atmospheric CO_2 concentration is also not exceptional. This indicates that there have been natural variations in both GPP and CO_2 levels over time. These fluctuations are likely to occur, due to a combination of different drivers for the up and down flux and the large reservoirs of organic carbon in the soil and oceans. Rising temperatures increase the up flux to the atmosphere due to more terrestrial and oceanic respiration and more outgassing from oceans, leading to a higher atmospheric CO_2 level. This CO_2 level is the main driver for more greening and thus the down flux.

Human emissions have accelerated the greening process, but even if we assume that human emissions are the dominant cause for the recent CO_2 rise, it is still unlikely that historical CO_2 levels were as low as generally accepted. All assumptions discussed herein relate exclusively to how nature responds to changes in CO_2 levels, and do not address the underlying causes of increased CO_2 levels. A low CO_2 level of 590 PgC (280 ppm) combined with a similar high level of greenness would only be possible if nature's response to CO_2 were fundamentally different from what we observe today.

This conclusion contradicts the assumed low CO_2 concentrations in the past 800,000 years, based on the ice core records from Antarctica. In this context, we refrain from delving into the specifics of these records. However, it is important to acknowledge that ice core records are not direct measurements, but serve as proxies for historical CO_2 concentrations, which need correct interpretation and calibration, and which involve significant uncertainties. Several studies have raised serious questions regarding the accuracy and reliability of ice core data, especially with respect to the dissolvement of CO_2 in melting water the many years before the air bubbles in the ice are fully closed (Jaworowski, Segalstad and Ono, 1992; Jaworowski, Segelstad and Hisdsal, 1992; Harde, 2017).

The likelihood of higher CO_2 levels in the history of the Earth supports other studies that have identified temperature as a primary driver of the increase of the atmospheric CO_2 concentration (Harde, 2019; Berry, 2021; Koutsoyiannis, 2024a). The temperature dependence of the main

fluxes to the atmosphere makes it unnecessary to assume an ad hoc behavior for human CO_2 in the atmosphere, with a deviant (much longer) residence time than other CO_2.

Competing interests

The author declares that he has no conflict of interest.

Data availability

This research uses no new data. The data sets used have been retrieved from the sources described in detail in the paper. All the calculations and charts are available in a Jupyter Notebook format, via GitHub, at https://github.com/fsch0203/historical_co2.

Chief-Editor: H. Harde, **Reviewers**: anonymous.

References

Allen Jr., L.H., 2019: *Simplifying Crop Growth Response to Rising CO2 and Elevated Temperature*, Agricultural & Environmental Letters, 4(1), p. 190021. https://doi.org/10.2134/ael2019.06.0021.

Bereiter, B. *et al.*, 2015: *Revision of the EPICA Dome C CO2 record from 800 to 600 kyr before present*, Geophysical Research Letters, 42(2), pp. 542–549. https://doi.org/10.1002/2014GL061957.

Berry, E., 2021: *The impact of human CO2 on atmospheric CO2*, Science of Climate Change, 1.2, pp. 213–249. https://doi.org/10.53234/scc202112/13 (Accessed: 1 February 2023).

Chen, C. *et al.*, 2022: *CO2 fertilization of terrestrial photosynthesis inferred from site to global scales*, Proceedings of the National Academy of Sciences of the United States of America, 119(10), p. e2115627119. https://doi.org/10.1073/pnas.2115627119.

Evans, W., Hales, B. and Strutton, P.G., 2011: *Seasonal cycle of surface ocean pCO2 on the Oregon shelf*, Journal of Geophysical Research: Oceans, 116(C5). https://doi.org/10.1029/2010JC006625.

Friedlingstein, P. *et al.*, 2023: *Global Carbon Budget 2023*, Earth System Science Data, 15(12), pp. 5301–5369. https://doi.org/10.5194/essd-15-5301-2023.

Harde, H., 2017: *Reply to Comment on 'Scrutinizing the carbon cycle and CO2 residence time in the atmosphere'*. http://hharde.de/index_htm_files/Reply%202017-06-30.pdf (Accessed: 6 January 2023).

Harde, H., 2019: *What Humans Contribute to Atmospheric CO2: Comparison of Carbon Cycle Models with Observations*, Earth Sciences, 8(3), p. 139. https://doi.org/10.11648/j.earth.20190803.13.

Haverd, V. *et al.*, 2020: *Higher than expected CO2 fertilization inferred from leaf to global observations*, Global Change Biology, 26(4), pp. 2390–2402. https://doi.org/10.1111/gcb.14950.

Huang, Y. *et al.*, 2021: *Global Estimates of Marine Gross Primary Production Based on Machine Learning Upscaling of Field Observations*, Global Biogeochemical Cycles, 35(3), p. e2020GB006718. https://doi.org/10.1029/2020GB006718.

IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157896.

Jaworowski, Z., Segalstad, T.V. and Ono, N., 1992: *Do glaciers tell a true atmospheric CO2 story?*, Science of The Total Environment, 114, pp. 227–284. https://doi.org/10.1016/0048-9697(92)90428-U.

Jaworowski, Z., Segelstad, T.V. and Hisdsal, V., 1992: *Atmospheric CO2 and global warming: a critical review*. 2. rev. ed. Oslo: Norsk Polarinstitutt (Meddelelser / Norsk Polarinstitutt, 119). https://www.researchgate.net/publication/307215789_Atmospheric_CO2_and_global_warming_a_critical_review_2nd_edition.

Koutsoyiannis, D. *et al.*, 2023: *On Hens, Eggs, Temperatures and CO2: Causal Links in Earth's Atmosphere*, Sci, 5(3), p. 35. https://doi.org/10.3390/sci5030035.

Koutsoyiannis, D., 2024a: *Refined Reservoir Routing (RRR) and Its Application to Atmospheric Carbon Dioxide Balance*, Water, 16(17), p. 2402. https://doi.org/10.3390/w16172402.

Koutsoyiannis, D., 2024b: *Stochastic assessment of temperature–CO_2 causal relationship in climate from the Phanerozoic through modern times*, Mathematical Biosciences and Engineering, 21(7), pp. 6560–6602. https://doi.org/10.3934/mbe.2024287.

Krause, A. *et al.*, 2022: *Quantifying the impacts of land cover change on gross primary productivity globally*, Scientific Reports, 12(1), p. 18398. https://doi.org/10.1038/s41598-022-23120-0.

Lai, J. *et al.*, 2024: *Terrestrial photosynthesis inferred from plant carbonyl sulfide uptake*, Nature, 634(8035), pp. 855–861. https://doi.org/10.1038/s41586-024-08050-3.

Lan, X. and Keeling, R.F., 2025: *Trends in CO2 - NOAA Global Monitoring Laboratory*. https://gml.noaa.gov/ccgg/trends/data.html (Accessed: 11 July 2025).

Liu, Q., Fukuda, K. and Matsuda, T., 2006: *Study of Solution Process of Carbon Dioxide in Seawater*, Journal of The Japan Institute of Marine Engineering, 41, pp. 144–149. https://doi.org/10.5988/jime.41.SI_144.

Luan, J. *et al.*, 2013: *Factors Affecting Spatial Variation of Annual Apparent Q10 of Soil Respiration in Two Warm Temperate Forests*, PLoS ONE. Edited by B. Bond-Lamberty, 8(5), p. e64167. https://doi.org/10.1371/journal.pone.0064167.

Lüthi, D. *et al.*, 2008: *High-resolution carbon dioxide concentration record 650,000–800,000 years before present*, Nature, 453, pp. 379–382. https://doi.org/10.1038/nature06949.

Reich, P.B. and Hobbie, S.E., 2013: *Decade-long soil nitrogen constraint on the CO2 fertilization of plant biomass*, Nature Climate Change, 3(3), pp. 278–282. https://doi.org/10.1038/nclimate1694.

Riebesell, U. *et al.*, 2007: *Enhanced biological carbon consumption in a high CO2 ocean*, Nature, 450(7169), pp. 545–548. https://doi.org/10.1038/nature06267.

Ritchie, H., 2021: *The world has lost one-third of its forest, but an end of deforestation is possible*, Our World in Data. https://ourworldindata.org/world-lost-one-third-forests (Accessed: 23 June 2025).

Schrijver, F.J., 2024: *Impact of global greening on the natural atmospheric CO_2 level*, Science of Climate Change, 4(2), pp. 79–88. https://doi.org/10.53234/scc202411/02.

Takahashi, T. *et al.*, 2009: *Climatological mean and decadal change in surface ocean pCO2, and net sea–air CO2 flux over the global oceans*, Deep Sea Research Part II: Topical Studies in Oceanography, 56, pp. 554–577. https://doi.org/10.1016/j.dsr2.2008.12.009.

Terrer, C. *et al.*, 2019: *Nitrogen and phosphorus constrain the CO2 fertilization of global plant biomass*, Nature Climate Change, 9(9), pp. 684–689. https://doi.org/10.1038/s41558-019-0545-2.

Wang, S. *et al.*, 2020: *Recent global decline of CO2 fertilization effects on vegetation photosynthesis*, Science, 370(6522), pp. 1295–1300. https://doi.org/10.1126/science.abb7772.

Wang, Z. *et al.*, 2024: *Evolution of Global Terrestrial Gross Primary Productivity Trend*, Ecosystem Health and Sustainability, 10, p. 0278. https://doi.org/10.34133/ehs.0278.

Winkler, A.J. *et al.*, 2021: *Slowdown of the greening trend in natural vegetation with further rise in atmospheric CO_2*, Biogeosciences, 18(17), pp. 4985–5010. https://doi.org/10.5194/bg-18-4985-2021.

Zhu, Z. *et al.*, 2016: *Greening of the Earth and its drivers*, Nature Climate Change, 6, pp. 791–795. https://doi.org/10.1038/nclimate3004.