Decreasing efficiency and slowdown of the increase in terrestrial carbon-sink activity

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Summary

Anthropogenic fertilization of the Earth with increasing concentrations of atmospheric CO_2 and nitrogen inputs has enhanced plant photosynthesis and carbon sinks of terrestrial ecosystems. Several signals now suggest, however, that this carbon-sink activity is slowing its rate of increase because of limitations of nutrients, water, and heat, among other factors.

Current anthropogenic warming, as a result of greenhouse had emission, particularly carbon dioxide (CO_2), poses a very high risk to nature and human well-being. Up to now, this risk has been buffered by a key group of other species on the planet, the terrestrial plants, which have assimilated almost a third of emissions, helping us avoid a much stronger and faster degree of warming.. Terrestrial plants have been able to perform this task through the effects of fertilization from increasing concentrations of atmospheric CO_2 and anthropogenic inputs of nitrogen (N) that have enhanced their photosynthesis and growth. The question now is for how long will plants continue to rescue us? Several signals suggest that this carbon-sink activity might be decreasing its efficiency and slowing its rate of increase because of limitations of nutrients, water, heat, fires, pollution, and reduced vegetation carbon residence time. This likely deceleration in the rate of fixing C and mitigating climate change remains largely understudied and, if current models continue to ignore it, they may overestimate carbon sinks, and therefore underestimate climate warming and over-estimate mitigation potential.

Human Fertilization of the biosphere

Understanding the balance between CO_2 emissions from human activities and the uptake of CO_2 by oceans and land-based ecosystems is crucial for predicting future climate change. Terrestrial **carbon sinks**, including forests, grasslands, and wetlands, play a crucial role in mitigating climate change by removing CO_2 from the atmosphere. Recent estimates suggest that human activities emit around 40 billion tonnes of CO_2 each year, with approximately one third absorbed by land-based ecosystems, one half remaining in the atmosphere, and the rest absorbed by the oceans (Fig. 1).

We humans are **fertilizing the Earth**. We are adding increasing amounts of CO_2, which is the substrate of plant photosynthesis. We are also adding increasingly more N from the combustion of fossil fuel and the use of fertilizers and N-fixing plants to the point that we are adding more N than do all the other natural processes of biological N fixation [1]. We are moreover warming the climate, thus advancing the unfolding of spring leaves and mostly delaying leaf fall in autumn, and so lengthening the period of vegetation growth [2].

Multiple lines of evidence support **an increase in plant productivity and therefore an increase in C uptake as a result of this fertilization**, and longer growing period. Data from eddy-covariance towers, which measure the exchange of CO_2 between the earth's surface and the atmosphere, indicate an increase in net ecosystem production (NEP) of temperate and boreal forests by an average of 1% annually from 1995 to 2011, and this increase has been highest where N deposition is high [3]. Inverse modeling of atmospheric CO_2 concentrations and Earth system models confirm this increase in NEP [3]. Remotely sensed data further support this increase in C assimilation by a general greening of the planet (25-50 % greening area versus 4% browning area) of which 70%, 8%, 9%, and 4% has been attributed to CO_2, climate, N deposition, and land-cover changes, respectively [4].

With multiple factors conspiring against this continuous increase in NEP and carbon sinks, the next immediate question is **for how long?**

Nutrient Limiting Factors of Fertilization

Plant production **requires many more nutrients** than just C and N. Bio-elements such as phosphorus (P), potassium, calcium, magnesium, molybdenum, manganese, and zinc are needed for information and energy production and storage, functional control, catalytic power, physiological processes and cell homeostasis, i.e. for cell structure and function, and therefore for plant growth. The availability of carbon from rising atmospheric carbon dioxide levels, and of nitrogen from various human-induced inputs to ecosystems, is continuously increasing. However, these increases are not paralleled by a similar increase in all these other bio-elements. Fertilization with C and N and the longer growing period are increasing the demand of these elements while the supply is limited and uncertain. For example, the required additional P should come from i) ash and dust deposition, ii) free-up of inaccessible soil P, and iii) weathering of mineral P supply. While human activities are increasing P deposition, the increasing inputs of N increase the activity of phosphatases, enzymes that release the P from organic material and make it available for plant uptake, and plants release acids in their root exudates that decrease the pH and weather mineral P, the demand of P is, however, much higher than these additional inputs. Current projections report substantial P limitations for NEP, which when incorporated in Earth system models, translate into a 20% decrease in plant growth trajectories [5]. Additional evidence of this increasing nutrient limitation is provided by the clear signals of decreasing foliar concentrations of N, P, K, Mg, and S in Europe during the last thirty years [6]. This is likely linked to increased tree productivity, possibly resulting from high N deposition and from the global increase in atmospheric CO_2. This deterioration of tree mineral nutrition seems to result from an insufficient soil nutrient supply that cannot meet the demands of faster growing trees. Furthermore, decomposition and soil CO_2 emissions increase where the availability of soil nutrients increases because of warming, similar to the C-rich soils of the permafrost. Higher availabilities of nutrients prime microbial activity and therefore decomposition and CO_2 release.

Climate Change Slowing Carbon Sinks

The limitations for increasing carbon sinks do not end with nutrients; many other limitations are linked to climate change itself, which raises temperatures above the optimum and drives aridification of many regions. First, in some calid regions of the world **air temperature is reaching values above optimum** for vegetation productivity so there should be a slow decline of productivity [7]. Second, the increase of normalized difference vegetation index NDVI, a proxy of green biomass, observed in the northern latitudes is **negatively sensitive to rising nocturnal temperatures**, since there is no photosynthesis and only respiration during the night [8]. Third, the sensitivity of the advancement of the date of leaf unfolding to temperature has decreased around 50%, i.e. while in 1980s leaf unfolding started 4 days earlier per degree of warming, nowadays the advancement is only 2 days per degree of warming, and means that the increased carbon sink due to advanced foliar unfolding per degree of warming has been reduced to half. This **reduction in sensitivity to warming** is likely to be partly attributable to reduced chilling, and other possible involved mechanisms such as 'photoperiod limitation' or even plant acclimation, so the predicted strong winter warming in the future may further reduce sensitivity and therefore result in a slowdown in the advance of tree spring phenology [9]. Fourth, the decreasing trends in greening in recent studies have gone in parallel to the decreasing trends in water availability [10]. Fifth, the advanced spring also has **drying effects**: earlier evapotranspiration produces drier summers with less precipitation, less evapotranspiration, and less soil water content which decreases plant productivity [11]. Sixth, **Longer and more severe heat waves** are thereafter generated [11]. These heat waves can even convert an entire continent such as Europe into a source rather than a sink of CO_2 (e.g. Europe behaved as a source of 0.5 Pg C y^{-1} in the heatwave of 2003 [12]), and have already increased about four-five times in frequency and intensity relative to 1900 [7]

Other Disturbing Factors For Carbon Sinks

In addition to nutrients, heat, and water, other disturbing factors such as **deforestation and fires** are conspiring against the increase in the assimilation of carbon [13]. For example, the factors of fire associated with increasing temperatures in the Artic have increased in recent decades in a near-exponential relationship with annual burned area. These large fires in the Arctic are likely to recur with climatic warming before mid-century, because the temperature trend is reaching a threshold in which small increases in temperature are associated with exponential increases in the area burned with huge amounts of CO_2 (%). Our estimates of the corresponding carbon emissions from this regional burning alone were 55.3 and 90.4 Tg C for 2019 and 2020 [14], which is similar to the annual emissions of CO_2 of an entire country such as Spain.

We moreover need to also consider another key component of carbon sinks: **the residence time of the carbon assimilated by plants**. Despite recent increases in forest growth, forest carbon sinks are likely to be constrained by an acceleration in plant mortality and the corresponding release of CO_2 [15].

With all these conspiring factors, we can thus expect **the pace of current carbon sinks to slow** because of decreased efficiency. Figure 1 details the various mechanisms that contribute to the declining rate. We have first signals of this slowdown now. First, when we focus on instantaneous instead of accumulated NDVI trends since 1982, we realize that in fact the rate of increasing greening [4] has declined in recent years, mostly in parallel with the availability of soil water [10]. Second, a decline in the efficiency of global CO_2 fertilization from *ca* 25 in 1982 to the current *ca* 10% 100 ppm^{-1} has also been reported with the maximum decrease in the trend of CO_2 fertilization efficiency occurring at the lowest foliar N and P concentrations and lowest water soil contents [16]. Third, the terrestrial carbon sink is still increasing, but at slower pace than in the last century and tending towards lower ratio of land sink to total anthropogenic emissions (Fig. 1). The land CO_2 sink increased mostly during the last decades of 20th century (the rate of increase of the land uptake was about 0.045 GtC y^{-2}), albeit with large interannual variability, but during this century there is a decreasing rate of the increase (it is now only about 0.02 GtC y^{-2}). Regarding the land-borne fraction, the ratio of land sink to total anthropogenic emissions, although considered as constant over the last 60 years [13], presents a slight decreasing trend since the 1970s if analyzed using a piecewise regression approach, indicating a slight decrease in the efficiency of land to remove anthropogenic CO_2 emissions. Forth, further evidence is provided by the report of both increasing temperature and temperature variability as the most important drivers of the declining rate of increase of NBP and an increase in its variability. These temperature changes and, by extension NBP changes, are mostly attributed to climate change and point to a destabilization of the coupled carbon–climate system [17].

Mosaic Solutions

The slowing pace of increasing carbon sinks and their destabilization in several regions calls for a reconsideration of IPCC climate projections towards **a possible reduction in the mitigation capacity of the terrestrial biosphere** even **warmer conditions than currently projected and stronger impacts.**

To keep the pace of terrestrial carbon sinks or even increase it and thus mitigate climate warming and avoid this disruptive scenario, **planting trees in afforestation and reforestation practices is often proposed**. But the laws of life, basically simple principles of restrictions [18], remind us that the availability of global annual solar radiation substantially decreases with latitude and that climatic and ecological factors, such as the length of the growing season, maximum leaf area index, annual precipitation, nutrient limitations and deficits of soil water content, combine to reduce an ecosystem's ability to receive sunlight and convert its energy into the chemical energy stored in carbon compounds. There are, moreover, large respiratory costs to support carbon-assimilating infrastructure, such as stems, roots, and leaves. Direct measurements of carbon exchange with eddy covariance indicate that over 80% of the assimilated carbon is respired and returned to the atmosphere. Planting forests, besides, has many unintended consequences. Their lower albedo than unforested areas can warm the air layer overhead, they use more water than the vegetation they are intended to replace, they may be consumed by fire, and they may deplete the groundwater in semi-arid regions [19]. Forests thus interact with their environment in complex and multifaceted ways that must be considered for a balanced assessment of their capacity to mitigating climate change. Many countries have already included tree planting campaigns in their NDCs (Nationally determined contributions), recognizing the vital role that terrestrial carbon sinks play in achieving net-zero emissions, but tree plantings may thus be beneficial or detrimental for mitigating climate-change depending on these many factors that differ among regions and local conditions. Appropriate assessments have to be made based on soil, radiation and water availabilities.

Given the potential for unintended consequences and the relatively low efficiency of converting solar energy to stored carbon, our efforts and resources should be more aimed toward very quickly reducing and soon eliminating carbon emissions, which is still the most critical step towards mitigating climate change. It is, however, important to acknowledge that relying solely on emissions reductions is not sufficient. Countries should focus on implementing a comprehensive multifactorial approach that includes emissions reductions, well-applied nature-based solutions such as reforestation, afforestation, and restoration of lands where the above-mentioned environmental conditions make them beneficial, and also clean energy technologies and the development and deployment of carbon removal technologies, such as direct air capture, bioenergy with carbon capture and storage, and enhanced weathering. Moreover, countries must work together to develop global policies that incentivize the adoption of these technologies, promote research and development, and provide financial support for **climate change mitigation actions** and their effectiveness in developing countries.

Climate change is unfortunately already here and may become stronger if mitigation actions do not fully succeed, so countries should also aim to develop better **adaptation strategies.** Currently, adaptation strategies are largely fragmented, local, and incremental, with limited evidence of transformational adaptation and negligible evidence of risk reduction outcomes [20]. Ultimately, global adaptation has thus substantial room for improvement.,

Historically, we have relied on terrestrial vegetation to limit the impacts of climate change, and now, we increasingly rely on it for climate mitigation and adaptation, yet our very actions are undermining its resilience and carbon sink capacity. As we shift from a fertilization-dominated to a warming-dominated biosphere [21], we need to diversify our approaches and take action to healing harms already inflicted and avoid worse future ones.

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Conflict of interest statement

The authors declare no competing interests.

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Figure caption

Figure 1. Schematic of the slowing pace of increase of the land-based C sink driven by anthropogenic fertilization of the Earth and the factors driving this slowing pace. Data from [13]. Carbon cycling per year expressed in GtC under or above arrows. Stocks also expressed as GtC.