Amazon Tall Tower Observatory (ATTO)
SCIENTIFIC BRIEF

How long can Amazon forests store carbon?

Carbon dioxide removal activities must consider not only how much carbon is removed from the atmosphere, but also how long it can be retained and stored. The assessment of both the amount and the time that carbon is stored in ecosystems provides a robust approach to quantify climate benefits of forest carbon sinks.

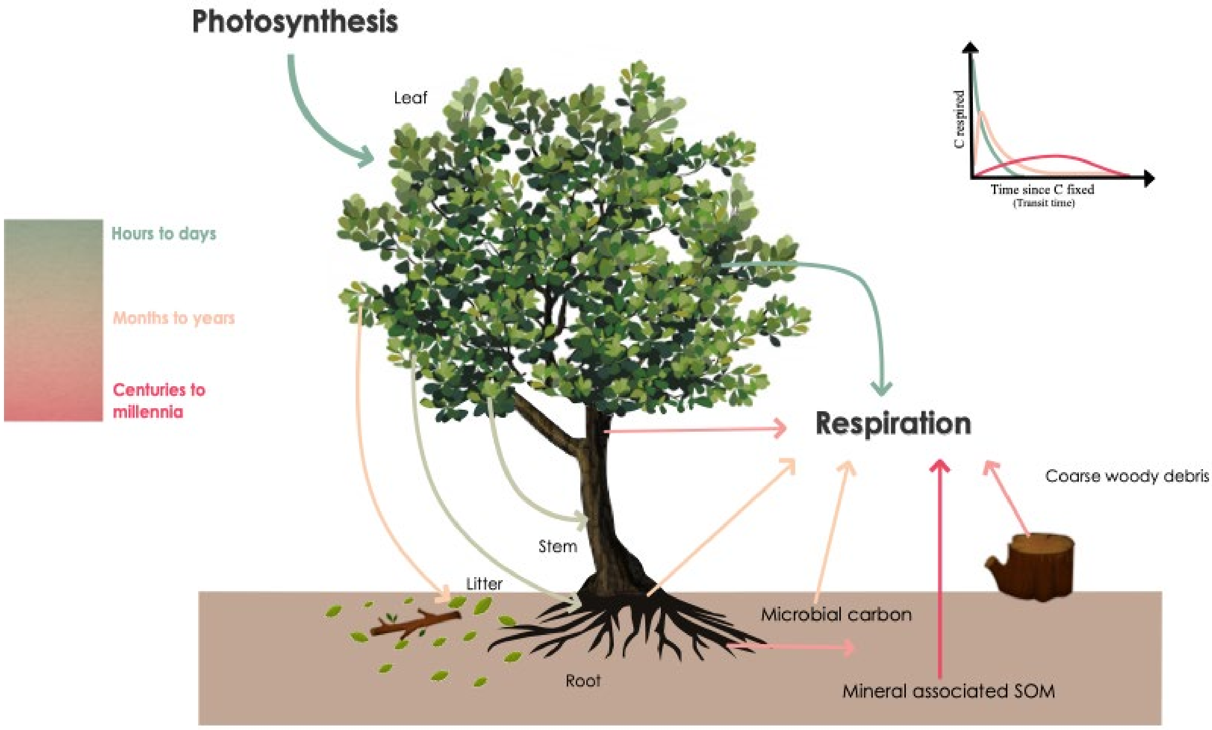

Figure 1. The transit time of carbon in ecosystems is the time that carbon atoms need to move through an ecosystem, from photosynthetic fixation until loss by respiration or decomposition from leaves, stems, roots, and dead organic matter. Because these ecosystem compartments store carbon for different amounts of time, the transit time expresses the proportion of carbon of different ages contributing to ecosystem respiration.

Preface

Carbon Dioxide Removal (CDR) is defined by the Intergovernmental Panel on Climate Change (IPCC) as anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. This definition of CDR implies that activities directed towards mitigating climate change through the management of the carbon cycle must consider both the amount of carbon dioxide removed from the atmosphere and the durability of its storage. While there are well-established methodologies to quantify the amount of carbon removed for particular activities, it is not trivial to quantify the duration of carbon storage. Most CDR activities involving Nature-based Solutions (NbS) are temporary in nature, and there is a need to develop methodologies that go beyond quantifying how much carbon inputs can be increased to determining how long that extra carbon can be stored before returning to the atmosphere.

Temporary carbon storage is an important issue in the quantification of the climate benefits of protecting natural ecosystems such as tropical forests. There are important scientific and policy debates on the relevance of promoting carbon sequestration in tropical forests, not only because these ecosystems respire large quantities of carbon dioxide to the atmosphere, but also because they are prone to carbon losses through

deforestation and disturbances such as fires and diseases.

However, during the time that carbon is stored in the biomass of a tropical forest, it is removed from the atmosphere and does not contribute to atmospheric warming. For this reason, it is relevant to assign a value to the contribution of temporary carbon storage in policy instruments for climate change mitigation. The transit time can also provide an important constraint for the capacity to store carbon added as increased productivity, for example by CO_2 fertilization.

The Paris Agreement Crediting Mechanism (PACM) is currently working to establish the rules and accounting methodologies to include different forms of CDR activities into a global system of emission trading. The quantification of permanence in CDR activities, particularly for NbS, thus requires a clear methodology to assess the durability of carbon storage in natural systems that would facilitate the quantification of credits for the preservation of natural ecosystems such as tropical forests.

The transit time of carbon

The transit time of carbon is a key concept to understand the temporary nature of carbon removals from the atmosphere. It quantifies the amount of time that carbon atoms need to pass through an ecosystem, from fixation of atmospheric CO_2 via photosynthesis until loss of carbon, mostly via respiration by plants and microorganisms, but also by methane emissions, and by leaching as dissolved inorganic or organic matter.

However, not all carbon atoms take the same amount of time to pass through an ecosystem. Some atoms pass very quickly and have a short transit time, for example, when they are part of sugars that are metabolized quickly in trees. Other atoms spend a much longer time stored in the ecosystem, for example, when they are part of wood and are later transferred to the soils, where the decomposition process slowly releases those atoms back to the atmosphere after decades or even centuries. For this reason, the transit time of carbon is not one single number, but a probability function that tells us what proportions of carbon atoms pass quickly through the ecosystem, and what proportion of atoms are respired after a longer time (Figure 1).

The transit time of carbon is also different for different ecosystems and for different CDR activities. Not all activities that can remove carbon from the atmosphere would keep it stored for the same amount of time. In some ecosystems, carbon may remain stored only for a few years or maybe decades, and in other ecosystems it may remain stored for centuries to millennia. As the IPCC requires that CDR activities store carbon durably in specific reservoirs, the transit time of carbon provides the key metric to demonstrate the level of this durability. Thus, transit times of carbon should be quantified for any form of CDR activity, particularly for NbS, where temporary carbon storage is often considered an issue in the development of climate policies.

Relevance of ATTO observations

At the Amazon Tall Tower Observatory (ATTO), we are investigating the timescales of carbon storage in tropical forests. We are interested in determining the time it takes for carbon to transit this ecosystem: the time elapsed between fixation of carbon dioxide by photosynthesis until the release of carbon dioxide back to the atmosphere by plant respiration and decomposition of dead organic matter in litter and soil. For this purpose, we measure radiocarbon in air, plants, and soils, and we use these measurements to estimate the distribution of the transit time of carbon. We integrate this information into a mathematical model that provides estimates of the transit time of carbon for these mature tropical forests.

Our results show that most of the carbon that is respired from plants and soils in ATTO is very young (Figure 2). About 50% of the respired carbon only stays stored for half a year because it is used to fuel the metabolic activity of living cells. But the other 50% requires years or decades to pass through the ecosystem and appear in the respiration flux. Some of the carbon respired by roots and woody biomass is years or even decades old. Soils can respire very old carbon, but the contribution of this very old carbon to the total respiration flux is relatively small. On average, the transit time of carbon we obtained for these forests is between one to two decades (Chanca et al. 2025).

The transit time of carbon for tropical forests

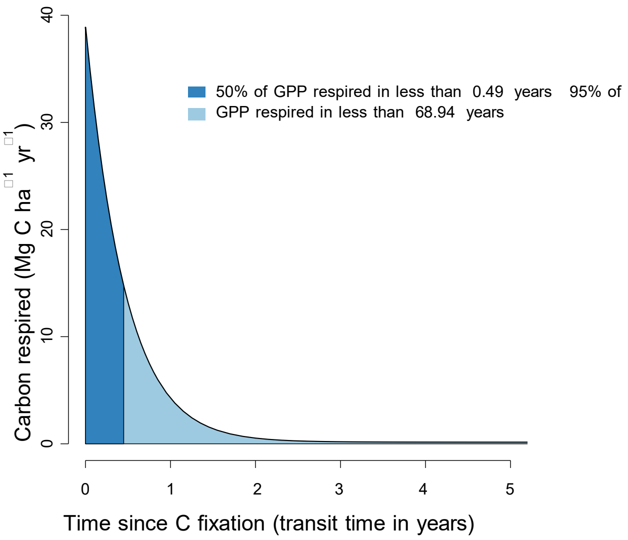

Figure 2. The transit time distribution of carbon was obtained for tropical forests based on observations from the Amazon Tall Tower Observatory and other forests. This distribution shows that most carbon is respired back to the atmosphere shortly after fixation via photosynthesis (also called gross primary production, GPP). Half of the carbon fixed at any given time is respired in half a year (median of the distribution), while 95% of the carbon is respired 69 years after fixation.

Integrating time in definitions of carbon removals under the PACM

To avoid ambiguities in the definition of carbon removals under the PACM and accurately quantify the climate benefits of carbon sequestration, we recommend the adoption of metrics that can quantify both the amount and the duration of carbon storage in CDR activities. The amount of carbon removed can be quantified by traditional metrics of mass of carbon removed per unit time. The duration of carbon storage should be quantified by the transit time of carbon.

The integration of both metrics provides an accurate estimate of the effectiveness of CDR activities in keeping carbon out of the atmosphere. However, the transit time of carbon is difficult and expensive to quantify, and very few countries or project developers have access to the technical laboratories required to measure radiocarbon.

Despite these technical challenges, it is possible to integrate the amount and the durability of carbon storage into one single metric, and it is not necessary to directly measure the transit time of carbon. A newly proposed methodology based on the concept of integrated carbon storage can combine both amount and duration into an easy-to-compute metric (Sierra 2025).

Under the newly proposed methodology, the amount of carbon that is stored over time is accumulated in the form of a mathematical integral; i.e., the area under the curve of carbon storage over time. This area under the curve has the property that is composed of two axes; one axis captures the amount of carbon stored in the ecosystem, and the other axis captures the time it has been stored.

We call the area under the curve of carbon storage, the Carbon Sequestration (CS) of the ecosystem, because it quantifies how much and for how long carbon is retained in an ecosystem and it is kept out of the atmosphere. CS is measured in units of mass multiplied by time, and it is reminiscent of the so-called tonne-year accounting methods, but it differs substantially from these previous methods because CS does not quantify an equivalence between emissions and removals. It simply quantifies the amount and the durability of carbon dioxide removals from the atmosphere.

At ATTO, we are developing state-of-the-art methods for quantifying the climate benefits of carbon removals in tropical forests. We aim to help in the development of climate policies that contribute to the preservation of these ecosystems while objectively measuring how much and for how long tropical forests keep carbon out of the atmosphere.

Recommendations

The durability of CDR activities must be quantified and integrated in metrics that assess the benefits of carbon sequestration and storage in NbS, such as the conservation of tropical forests. The transit time of carbon is a robust metric to quantify the durability of CDR activities, and it can be obtained with measurements of radiocarbon in air, vegetation, and soils. We recommend the quantification of the transit time of carbon in CDR activities to accurately quantify the permanence of carbon storage. However, we recognize that radiocarbon measurements are difficult and expensive to obtain and can only be used in certain specific cases where uncertainties related to permanence justify the measurement of transit times.

An alternative approach to obtain estimates of the durability of CDR in NbS is through the quantification of CS, a metric that integrates how much and for how long carbon can be kept out of the atmosphere. CS can be obtained as the area under the curve of carbon storage over time and provides an unambiguous method to quantify the permanence of carbon removals and reversals. We recommend the adoption of CS in accounting methodologies for CDR activities, particularly for new methodologies under the Paris Agreement Crediting Mechanism.

References

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