INSIGHTS

PERSPECTIVES

CLIMATE CHANGE

The limits of forest carbon sequestration

Current models may be overestimating the sequestration potential of forests

By **Julia K. Green**[1] and **Trevor F. Keenan**[1,2]

Although nations are grappling with reducing carbon emissions to minimize climate change risks, they actually need to remove carbon dioxide from the atmosphere if the goal is to keep warming to less than 1.5°C (*1*). Although there has been substantial investment in technologies focusing on carbon capture, there is also interest in natural solutions, such as planting trees (*2*, *3*). Trees remove CO_2 from the atmosphere through photosynthesis, and forests sequester CO_2 in the form of biomass and soil carbon. Though it seems logical that increased photosynthesis should lead to increased growth, multiple reports suggest that this is often not the case (*4*, *5*). The interaction between photosynthesis, tree growth, and carbon sequestration has large implications for future carbon uptake and is a topic that remains widely debated. On page 758 of this issue, Cabon *et al.* (*6*) contribute to this debate by examining global photosynthesis estimates and tree ring measurements as a measure of growth.

Carbon sequestration in land ecosystems has been gradually increasing since the 1970s (*7*). CO_2 is a necessary component for plant photosynthesis, and rising concentrations of atmospheric CO_2 from anthropogenic emissions have led to higher rates of carbon uptake by plants, a phenomenon known as carbon fertilization (*8*). Additionally, increases in greenhouse gases have lengthened the growing season indirectly through warming, leading to additional increases

Cabon *et al.* highlight the importance of considering processes other than photosynthesis to estimate how much carbon trees can sequester.

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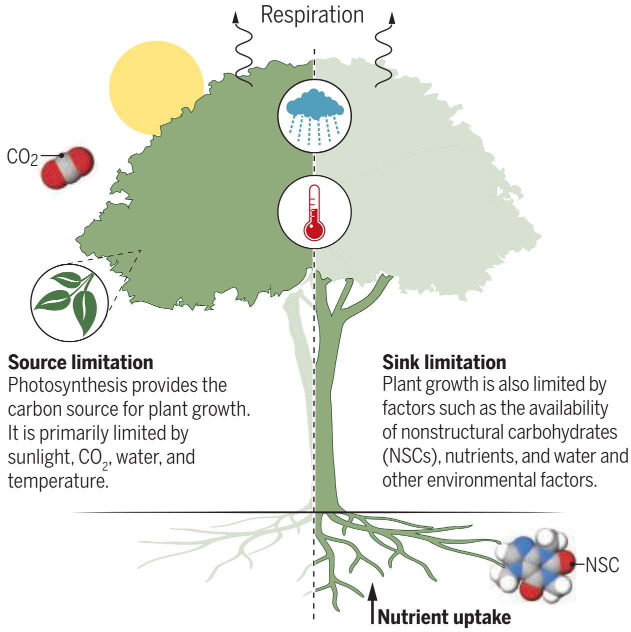
in ecosystem carbon uptake (*7*, *9*, *10*). These increases in response to rising atmospheric CO_2 concentration have led to claims that ecosystems are mostly limited by the amount of atmospheric CO_2. However, a large body of research has indicated that increases in atmospheric CO_2 do not necessarily translate to increased carbon sequestration because of other strong limitations on plant growth (*11–13*). Even if more carbon is available to vegetation, other factors are needed to help stoke growth from photosynthesis. Most notably, nutrient abundance and water content in the soil, as well as temperature, can limit growth (see the figure). This complication, best characterized as a dichotomy of whether forest carbon sequestration is carbon source limited (limited by how much carbon the plant can photosynthesize) or sink limited (limited by how much the plant can grow because of all environmental factors), has large implications for how much forests can sequester carbon.

Source and sink limitations on plant growth

Plant growth can be restricted by source and/or sink limitations. Although source and sink limitations share several controlling factors, the time scales on which they operate and their sensitivity to these factors often differ.



To understand the restrictions on plant growth related to source and sink limitations, Cabon *et al.* used gross primary production (GPP) estimates—which denote the amount of carbon taken up by plants during photosynthesis—and combined them with tree ring data from the International Tree-Ring Data Bank to perform a cross-biome correlation analysis. They compiled the most comprehensive tree ring dataset to date and identified source-sink relationships across the globe. They demonstrated that there is a strong decoupling between vegetation photosynthesis and the radial growth of a tree trunk, which shows substantial variation based on vegetation type (e.g., angiosperm versus gymnosperm), ecosystem traits (e.g., forest age and nutrient availability), and climate (e.g., more decoupling in cooler, more arid climates). These results emphasize that the relationship between photosynthesis and growth is not as simplistic as the current representation in models, which typically depict vegetation carbon sequestration as being closely related to GPP (*14*).

The results reported by Cabon *et al.* have implications for using natural ecosystems to sequester carbon and for the success of natural climate solutions, such as planting trees, in combating climate change. If less carbon than predicted will be stored in biomass in the coming years, the utility of this ecosystem service is greatly diminished. Additionally, the results emphasize caution when interpreting findings solely on the basis of GPP estimates that make generalizations about carbon storage. For example, a GPP increase in the springtime from plants producing their leaves earlier may not translate to an increased overall growth by the end of the year.

Nevertheless, the use of GPP estimates and tree ring data to understand the degree to which growth and carbon sequestration by trees are inherently sink limited does have some constraints. For example, related to the use of GPP data, a portion of the CO_2 absorbed during photosynthesis is released back into the atmosphere through plant respiration. Therefore, the amount of carbon available to plants for growth is actually not GPP, but the carbon gains during GPP minus the autotrophic respiration losses—i.e., the net primary production (NPP). Many studies examining the relationship between plant carbon uptake and growth have used NPP data, which are more directly linked to vegetation growth (*15*) and have a stronger relationship with biomass. GPP is therefore not necessarily a reliable proxy for the carbon source available for growth. For this reason, studies that measured NPP at some of the same sites as Cabon *et al.* have reported a stronger correlation between carbon source activity and tree ring widths, without a role of sink limitation (*15*). Also, related to the use of tree ring data to infer tree growth, plants allocate carbon not only to woody aboveground biomass, but also to their root systems, their leaves, and pools of nonstructural carbohydrates that are stored throughout the plant. Plants alter their carbon allocation depending on environmental changes, forest age, and the time of year. Therefore, there are uncertainties when one infers the amount of carbon sequestered based solely on tree ring measurements because woody growth is not synonymous with total carbon sequestered.

Despite these limitations, Cabon *et al.* show that carbon projections using the current modeling framework may be overestimating the carbon sequestration in forests. Their findings highlight the need for an in-depth assessment of the degree to which vegetation models effectively represent growth dynamics and the degree of carbon sink and source limitations. To do so will require a better understanding of these limitations, which should be possible with new methodologies of measuring autotrophic respiration and NPP directly at flux tower sites, as well as an increase in the number of collocated measurements related to carbon allocation and sequestration. ■

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10.1126/science.abo6547

Science

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Science, 376 (6594), • DOI: 10.1126/science.abo6547

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