FOREST ECOLOGY

Nutrients trigger carbon storage

Analysis of data from 92 forested sites across the globe indicates that nutrient availability is the dominant driver of carbon retention in forests.

Wim de Vries

Global carbon budgets indicate that approximately 27% of anthropogenic CO$_2$ emissions are stored in terrestrial ecosystems with a similar percentage stored in the oceans[1]. Of the terrestrial ecosystems, forests are by far the most important carbon sink, due to the long storage time of carbon in stem wood[2]. Declining global forest sinks could potentially increase the growth rate of atmospheric CO$_2$ concentration by 50%. Unfortunately, model predictions of the fate of carbon in forests over long timescales (the coming decades) are highly uncertain because of the many interacting drivers that affect forest carbon cycling. Apart from forest management, many field studies and model approaches suggest that atmospheric CO$_2$ concentration[3] and climate variables, including temperature changes and precipitation[4], play a key role in carbon cycling. However, in most cases data were collected in a restricted area or the datasets/models did not include all influencing drivers, such as nitrogen deposition, site nutrient availability and ozone exposure. Consequently, we do not yet know which factor(s) most strongly govern forest carbon storage. This leads to an uncertainty in any future prediction of atmospheric CO$_2$ increase and related temperature rise.

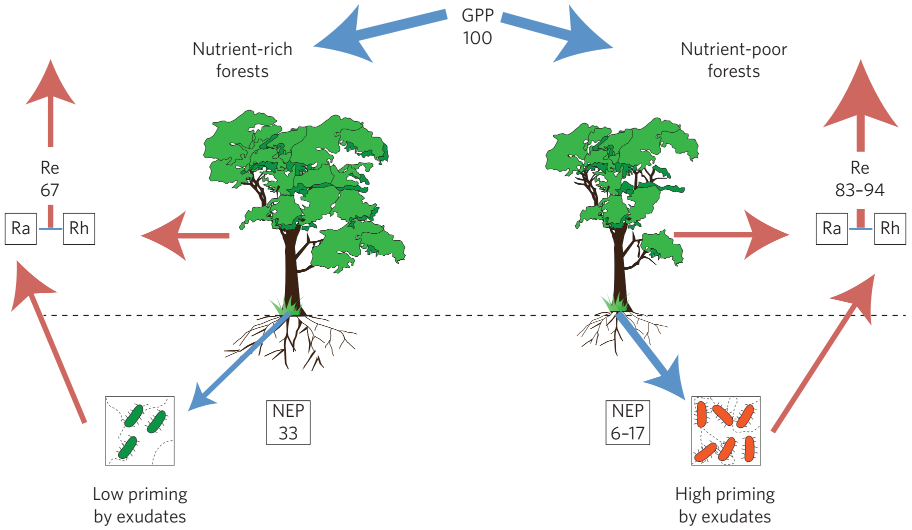

Figure 1 | Schematic illustration of the link between nutrient availability and carbon-use efficiency (CUE). The blue arrows indicate carbon flow due to photosynthesis (GPP) and below-ground root turnover and the red arrows indicate above- and below-ground respiration flows. The GPP rate of 100 has arbitrary units (for example, kilograms) and NEP is expressed in the same units. The analysis by Fernández-Martínez *et al.*[5] suggests that the CUE — equal to the ratio of NEP to GPP — in nutrient-rich forests is much larger (33%) than in nutrient-poor forests (6–17%). This is due to a much lower ecosystem respiration (Re), which is the sum of aboveground autotrophic respiration (Ra) and belowground heterotrophic respiration (Rh). The authors propose that this difference arises because limited nutrient availability decreases carbon allocation to woody tissues with long turnover times and increases carbon allocation to fungal root symbionts and exudates, stimulating soil carbon decomposition (priming effect).

In a study published in *Nature Climate Change*, Marcos Fernández-Martínez and colleagues[5] propose that the availability of important plant nutrients (such as nitrogen, phosphorus and potassium) is the chief determinant of the amount of carbon sequestration in forests (trees and soils) on a global scale. The team created a dataset of 92 forest stands — across a range of boreal, temperate, Mediterranean and tropical forests — consisting of observations of gross primary production (GPP), net ecosystem production (NEP) and ecosystem respiration (Re), combined with information on forest management and stand age. In this context, NEP (equal to the difference between GPP and Re) quantifies the forest carbon sink. Estimates of climate variables, including mean annual temperature, precipitation and water deficit, were assigned on the basis of climate interpolations and satellite-based observations. Finally, they assigned a nutrient availability status to each site using, among other features, soil characteristics and information on nitrogen and phosphorus concentrations in soil and foliage. Sites were classified as either nutrient-rich (with no apparent nutrient limitation) or nutrient-poor (with an apparent nutrient limitation). The dataset was then used to determine which variables best explain the variation in NEP and carbon-use efficiency at the ecosystem level (CUEe), defined as the ratio of NEP to GPP. Statistical models were applied to disentangle the effects of the explanatory variables (including GPP, management, stand age, climatic factors and nutrient availability) from their interactions.

Model results showed that commonly assumed controls, such as water availability and management, had an insignificant effect on NEP. The most important variable was nutrient availability, which alone explained 19% of the variance in NEP, whereas temperature alone explained only 9%. Most strikingly, the analysis suggests that nutrient-rich forests retain a much larger proportion (33%) of carbon, which is exchanged by photosynthesis GPP, than nutrient-poor forests (6–17%). In line with previous hypotheses[6], the authors propose various mechanisms that explain why increasing nutrient availability increases the NEP; the most important are summarized in Fig. 1.

It is important to note that the study by Fernández-Martínez *et al.*[5] is observational and allows for hypothesis testing, but it does not allow elucidation of underlying mechanism(s). The team use a global scale data set and an advanced statistical modelling approach to show that there is a strong relationship between nutrient availability and forest carbon sequestration, or NEP. Nevertheless, a range of experiments — with different combinations of variables such as nutrients, CO_2 levels and climate variables — are required to convincingly show that nutrient availability is the main driver of forest carbon storage. Systematic experimental assessments of all these variable combinations are rare. There is observational evidence that elevated forest carbon storage, in response to elevated atmospheric CO_2, is limited by nitrogen availability[7] and that nitrogen availability increases with elevated CO_2 and temperature[8]; but a full picture of the major drivers and their interactions, based on experiments, is lacking.

Furthermore, the analysis of large observational data sets can be subject to bias due to factors like the inclusion of outliers, unobserved variables (for example, climatic extremes), unaccounted correlations and assumed linearity in relationships. The authors were aware of these potential biases and tested the robustness of their analyses using alternative methods and restricted data sets. Nevertheless, an important bias could result from the fact that the GPP range for nutrient-poor forests was much larger than for nutrient-rich forests. Published data support the idea that CUEe decrease with an increase in GPP[9] and the data presented by Fernández-Martínez *et al.* also indicate this effect, suggesting a nonlinear relationship. The authors, however, included an analysis in which they restricted the comparison of nutrient-rich and nutrient-poor forests to a common range of GPP values where linearity seems more probable — this increased the average CUEe from 6% to 17% (Fig. 1). The larger CUEe value seems more probable than the reported 6%. The use of outliers, including three very young nutrient-rich forests with extremely high NEPs, may also have affected their result.

Despite potential shortcomings, the results presented by Fernández-Martínez and colleagues are a strong indication that the nutrient status of forests strongly controls carbon sequestration. Scientists use model projections to help policy makers design strategies to preserve carbon sinks. Historically, these models have been developed based on the idea that CO_2 and climate act as the drivers of photosynthesis and respiration — an understanding that contains serious flaws. Recently, a range of global terrestrial carbon cycle models have been further developed to include carbon–nitrogen interactions. However, even in the recent 5th Assessment report of the Intergovernmental Panel on Climate Change[10], only two of the eight Earth-system models used to make projections of the land CO_2 sink incorporated nitrogen limitations. Furthermore, very few global models include both nitrogen and phosphorus limitations[11] and the work of Fernández-Martínez and colleagues indicates that these are crucial. Nutrient availability, as classified in their study, is broader than nitrogen alone and also includes the availability of phosphorus and potentially other nutrients such as potassium, calcium and magnesium. The implied message is that Earth-system models must include carbon–nitrogen–phosphorus interactions to allow reliable predictions of the future global carbon sink on land. ❐

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Correction

In the News Feature 'A new climate for grazing livestock' (*Nature Climate Change* **4,** 321–323; 2014) Olimpo Montes's source of funding was incorrectly stated. He received a Payment of Environmental Services as compensation for changes he made as a participant in a project funded by the Global Environment Facility and administered by the World Bank. This has now been corrected in the HTML and PDF versions after print 8 May 2014.

Correction

In the News & Views 'Nutrients trigger carbon storage' (*Nature Climate Change* **4,** 425–426; 2014), the name of the author of the associated Letter was incorrectly stated and it should have read Marcos Fernández-Martínez. This has now been corrected in the online versions after print 29 May 2014.