CARBON CYCLE

Fertilizing change

Carbon cycle–climate feedbacks are expected to diminish the size of the terrestrial carbon sink over the next century. Model simulations suggest that nitrogen availability is likely to play a key role in mediating this response.

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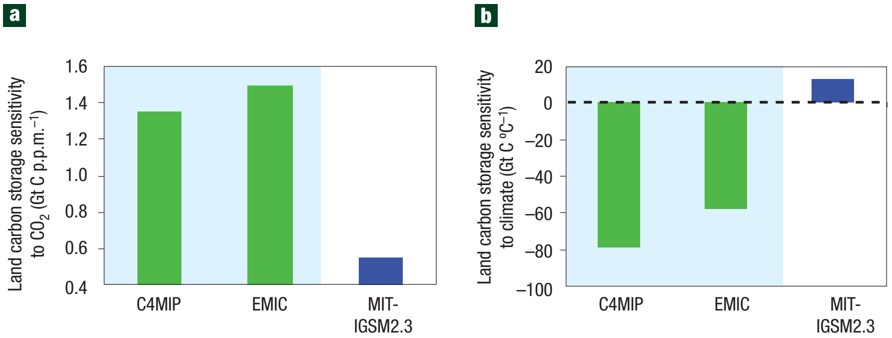

Figure 1 Carbon cycle–climate feedbacks in response to increasing atmospheric CO_2 and warming, with and without nitrogen. Data represent the mean response of eleven C4MIP models[2] (coupled climate–carbon cycle model intercomparison project) and five EMIC models[12] (Earth system models of intermediate complexity), which do not consider carbon–nitrogen interactions, and the results for the MIT–IGSM Earth system model of intermediate complexity, which includes nitrogen. **a**, CO_2-induced increases in terrestrial carbon storage are substantially higher in the carbon-only simulations owing to the absence of nitrogen limitations. **b**, Whereas the carbon-only models predict a decrease in terrestrial carbon storage in response to warming, the carbon–nitrogen model predicts an increase in terrestrial carbon storage, as increased nitrogen availability stimulates plant growth.

Undisturbed terrestrial ecosystems soak up 2.8 Gt of carbon per year, equivalent to 30% of total anthropogenic CO_2 emissions[1]. However, this carbon sink is expected to weaken with global warming: climate simulations that incorporate carbon cycle–climate feedbacks predict significant decreases in the terrestrial uptake of atmospheric carbon dioxide over the next century, and thus a positive feedback between the carbon cycle and climate[2]. Importantly, however, these coupled carbon cycle–climate models have ignored the impacts of nitrogen on the terrestrial carbon sink. In a recent article published in the *Journal of Climate*, Sokolov and co-workers[3] use a climate model to show that carbon–nitrogen interactions significantly reduce net terrestrial carbon uptake, even though, at least for small to moderate climate warming, enhanced nitrogen availability stimulates plant growth and changes the sign of the carbon cycle–climate feedback. This suggests that atmospheric CO_2 may increase more rapidly in the future than carbon-only models predict.

The strength of the terrestrial carbon sink is governed by the balance between photosynthetic CO_2 uptake and respiratory CO_2 release. In a comparison of eleven coupled carbon cycle–climate models[2], increases in carbon dioxide and temperature have opposite effects on the carbon sink: increases in atmospheric carbon dioxide stimulate photosynthetic uptake of CO_2 in a 'CO_2 fertilization' effect that dampens anthropogenic-induced increases in atmospheric CO_2, and increases terrestrial carbon storage by 1.35 Gt of carbon per p.p.m. increase in atmospheric CO_2 (Fig. 1a). By contrast, warming stimulates plant and soil respiration, leading to an overall decline in terrestrial carbon storage equivalent to 79 Gt of carbon per degree Celsius (Fig. 1b). When both effects are considered together, CO_2 fertilization loses out. Warming-induced increases in terrestrial respiration consistently outweigh CO_2-induced increases in photosynthesis. Or, expressed differently, the feedbacks between climate and the carbon cycle are predicted to increase atmospheric CO_2 concentrations by the end of this century.

The importance of incorporating carbon cycle feedbacks into climate simulations is apparent. However, the models continue to overlook the role that nitrogen may play in changing the balance between CO_2 fertilization and warming-induced increases in respiration. The primary effect of nitrogen lies in the limitation it imposes on CO_2 fertilization: many ecosystems lack the nitrogen needed to sustain the CO_2-induced increases in plant biomass that are predicted by climate models[4,5]. However, soil warming, by stimulating decomposition and freeing up the nitrogen locked up in organic material, could help to ease these limitations[6]. Ecologists have long included such carbon–nitrogen interactions in ecosystem models[7–10].

Sokolov and co-workers used the Massachusetts Institute of Technology Integrated Global System Model (MIT-IGSM), an Earth system model of intermediate complexity, to investigate the influence of carbon–nitrogen interactions on the response of terrestrial ecosystems to climate change. Consideration of carbon–nitrogen interactions affects CO_2 fertilization: nitrogen limitation means that only about half of the fertilization effect seen in carbon-only models is realized (Fig. 1a). The terrestrial carbon sink is therefore much smaller when carbon–nitrogen interactions are accounted for. However, warming leads to opposing effects in carbon-only and carbon-nitrogen models. Warmer soils release more carbon to the atmosphere, further increasing atmospheric CO_2 concentrations. But if the nitrogen cycle is included, warmer soils also release more organically bound nitrogen, which relaxes nitrogen limitations on plant growth. Thus carbon uptake during plant growth exceeds carbon loss from soils, and terrestrial carbon accumulates with warming (Fig. 1b). In contrast, carbon-only models predict a decrease in terrestrial carbon with warming. Overall, although net terrestrial carbon sequestration is reduced when nitrogen is accounted for, climate warming increases carbon sequestration in a negative, rather than a positive feedback. However, with strong warming, respiratory losses win out and terrestrial ecosystems become a source of carbon despite the beneficial effects of nitrogen.

The results of Sokolov and co-workers not only raise doubts about the reliability of carbon cycle–climate models that do not simulate the nitrogen cycle, but raise new uncertainties regarding the influence of additional atmospheric pollutants and ecological processes on the size of the terrestrial carbon sink. For example, anthropogenic nitrogen deposition, which is not considered in their model, could further stimulate plant growth[11], although progressive nitrogen limitations as nitrogen becomes increasingly bound up in larger biomass pools may diminish productivity[5]. Furthermore, biological nitrogen fixation, reallocation of nitrogen between vegetation and soils, and between labile and recalcitrant pools, together with redistribution of plant species in response to disturbance or climate change, must be considered.

The current generation of carbon cycle–climate models are based on the premise that CO$_2$-induced increases in plant productivity are offset by warming-induced increases in carbon loss[2,12]. The results of Sokolov and co- workers will undoubtedly motivate modellers to expand their biogeochemistry to include the nitrogen cycle, as well as other elements. Phosphorus, for example, is an important plant macronutrient, and nitrogen–phosphorus interactions influence ecosystem functioning[13].

However, better understanding of the carbon cycle–climate feedback will ultimately require a more comprehensive shift in model capabilities. Land–atmosphere interactions in climate models have expanded from their initial biogeophysical focus on energy and water to include biogeochemical cycles[14]. The models must now be expanded to include biogeographical processes such as land use, fire and post- disturbance vegetation succession, which greatly affect carbon fluxes. Interactions among biogeophysical, biogeochemical, and biogeographical processes, especially in response to human modification of the landscape, will probably produce a rich array of climate forcings and feedbacks.

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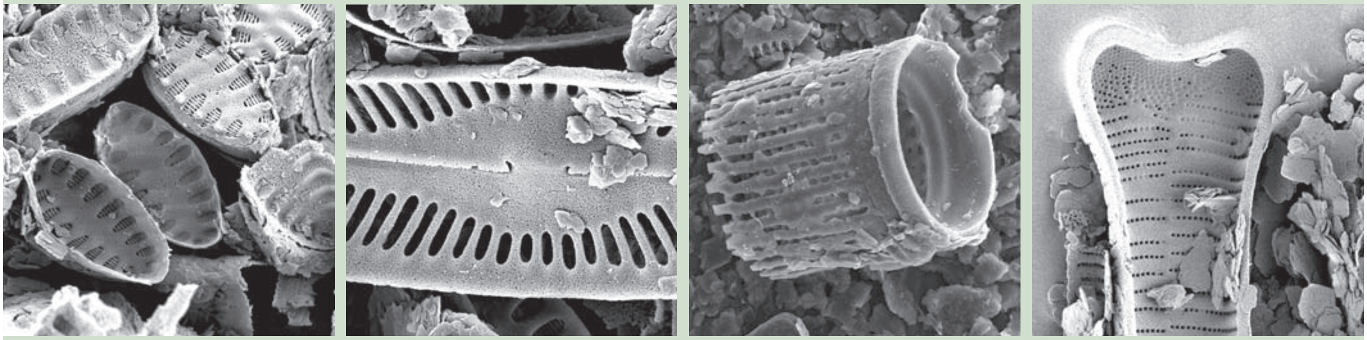
PALAEONTOLOGY

A long-lost tundra



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Hidden deep beneath vast ice sheets and in foreboding desert valleys lie the remnants of Antarctica's warmer past. Before the dawn of the southern ice sheets, Antarctica was covered by plants, lakes and rivers — a landscape that would be quite unfamiliar to the penguins and seals that call the continent their home today.

Beginning about 50 million years ago, the Earth's climate started to cool, and by 34 million years ago ice sheets slowly marched across the southernmost continent. Although this cooling marked the end of the reign of many temperature-sensitive plants, little is known about the survival of the more rugged shrub tundra community. Now Adam Lewis of Boston University and colleagues have discovered a wealth of fossils in the McMurdo Dry Valleys that chronicle the final demise of the tundra (*Proc. Natl Acad. Sci. USA* **105,** 10676–1068; 2008).

The team found spectacularly preserved fossils among the sediments of ancient alpine lakes from about 14 million years ago. The deposits revealed a number of diatoms and ostracods that colonized the lake surface and the bottom sediments. The researchers also found a number of semi-aquatic mosses from the lake shore and other mosses blown or carried in from further away. In addition, the sediments were rife with pollen from a number of plants, including beech trees, as well as the occasional beetle.

This fossil assemblage suggests that the lakes in question were permanent, and largely free of ice throughout the year. However, the lakes of that area, and their denizens, were gone 200,000 years later. The team used glacier modelling to conclude that air temperatures rapidly decreased by 8 °C from 14 to 13.8 million years ago. The overlying sediments suggest that the temperatures, and the tundra, never recovered.

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