# NITROGEN REGULATION OF CARBON SEQUESTRATION IN TERRESTRIAL ECOSYSTEMS IN RESPONSE TO RISING ATMOSPHERIC $CO_2$ CONCENTRATION

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A highly controversial issue in global change research is the regulation of terrestrial carbon (C) sequestration by soil nitrogen (N) availability. The Third Assessment IPCC Report predicts rising atmospheric $CO_2$ alone could stimulate terrestrial carbon (C) sequestration by 350 – 980 Pg (=$10^{15}$ g) C in the 21st Century. Sequestering 350 – 980 Gt C in terrestrial ecosystems requires 7.7 – 37.5 Pg (N) based on a stoichiochemical relationship that approximately 0.005 g N is required for 1 g C stored in long-lived plant biomass (i.e., wood) and 0.067 g N for 1 g C sequestered in soil organic matter (SOM). Thus, to realistically predict future C sequestration in terrestrial ecosystems, we have to understand how closely C and N processes are coupled in response to rising $C_a$

In general, rising atmospheric $CO_2$ enhances photosynthesis and stimulates initial C sequestration in terrestrial ecosystems. Increased C influx at elevated $CO_2$ generally requires more N to support plant growth than is required at ambient $CO_2$ and, in turn, sequesters N into long-lived plant biomass and soil organic matter pools. This N sequestration can decrease soil N availability for plant uptake. However, increased plant N demand and/or sequestration could induce changes in N supply. When elevated $CO_2$ increases N use efficiency (NUE) and stimulates N transfer from the soil organic pools with narrow C:N ratios to plants with broad C:N ratios, N limitation may be delayed. If additional C input at elevated $CO_2$ stimulates capital gain of N through fixation, decreased losses, increased forage for soil N, or any combinations of them, N limitation may not occur. If it does, $CO_2$-induced C sequestration in ecosystems declines over time. In short, N will constrain C sequestration over time unless additional C input at elevated $CO_2$ stimulates N gain in ecosystems. Thus, the key parameters to indicate N limitation of C sequestration are C and N accumulations in plant and soil pools, and stoichiometrical flexibility in C/N ratios in various pools.

We conducted a meta-analysis of data on C and N processes in plant and soil in response to rising atmospheric $CO_2$ to reveal general patterns among different studies across ecosystems. The primary focus of this study is on C and N contents in various plant and soil pools and their stoichiometrial flexibility. These variables are presumably indicative of long-term dynamics of C and N interactions.

Averaged C pool sizes in shoot, root, and whole plant over the compiled database increase by 22.4, 31.6, and 23.0%, respectively, at elevated $CO_2$ in comparison with those at ambient $CO_2$. Averaged litter and soil C pool sizes are higher by 20.6 and 5.6% at elevated than ambient $CO_2$. We calculated averaged C contents from all the ground-area-based data in our database, which are higher by approximately 110, 70, and 200 g C $m^{-2}$ at elevated than ambient $CO_2$ in plant, litter, and soil pools, respectively. The duration of exposure of those experimental plots to elevated $CO_2$ varies from one to eight years and is used to calculate annual rates of C accumulation. The averaged rate of C accumulation in ecosystems is approximately 100 g C $m^{-2}$ $yr^{-1}$ more at elevated than ambient $CO_2$.

Averaged N pool sizes in shoot, root, and whole plant over the database are 4.6, 10.0, and 10.2%, respectively, higher at elevated than ambient $CO_2$. Averaged litter and soil N contents also increase by 25.4 and 11.2% at elevated $CO_2$ in comparison with those at ambient $CO_2$. We averaged area-based data to estimate N accumulations in plant and soil pools. Averaged N contents increase by 1.75, 3.17, and 1.87 g N $m^{-2}$ in plant, litter, and soil pools, respectively, at elevated $CO_2$ relative to those at ambient $CO_2$. Thus, the averaged increase in the whole ecosystem N content is 6.77 g N $m^{-2}$ and an averaged annual rate of ecosystem N accumulation is approximately 1.0 g N $m^{-2}$ $yr^{-1}$ more at elevated than ambient $CO_2$.

The $CO_2$-induced percent increases in C contents in plant pools are larger than the increases in plant N pools, resulting in significant increases in C/N ratios in all the plant pools. Averaged C/N ratios in shoot and root pools over the entire database increase by 11.6 and 10.8%, respectively, at elevated $CO_2$ in comparison to those at ambient $CO_2$. Averaged soil C/N ratio is also higher by 2.9% at elevated than ambient $CO_2$. In addition, $CO_2$-induced change in litter C/N ratio is not statistically significant. The averaged change in R/S ratio in response to elevated $CO_2$ is marginally significant, similar to results from other studies.

Accumulation of organic C in plants and soil may result from several processes, such as increased C input into ecosystems, decreased litter quality and decomposability, and enhanced physical protection through formation of either intra-aggregate or organomineral complexes. Ecosystems have a number of processes that can lead to net N accumulation under elevated $CO_2$. Those processes include biological N fixation, retention of atmospheric N deposition, reduced N loss in gaseous and liquid forms, and extended root growth to root-free zones for N uptake.

The significant net N accumulations revealed in our meta-analysis, at the minimum, suggest that complete downregulation of $CO_2$ stimulation of ecosystem C processes would not be pervasive across ecosystems. If the long-term C sequestration is indeed regulated primarily by N availability, the substantial N accumulations in all the plant, litter and soil pools at elevated $CO_2$ would support long-term C sequestration in terrestrial ecosystems in response to rising $C_a$. Adjustments in C/N ratios in the plant, litter and soil pools, redistribution of ecosystem N stocks among the pools, and increased rooting systems likely support short-term $CO_2$ stimulation of plant growth and C sequestration. Concomitant increases in C and N contents in plant and soil pools at elevated $CO_2$ point toward a long-term trend of terrestrial C sequestration in response to rising $C_a$

But the smaller percent increases in plant N pools than in plant C pools and the increased C/N ratios could suggest that rising $C_a$ primarily stimulates ecosystem C storage followed by N accumulation with time lags. Also, additional N fertilization in $CO_2$ experiments results in larger stimulation of C accumulations than no N addition treatments. Thus, three lines of evidence likely indicate that N at least partially constrains C accumulation in the $CO_2$ experiments. Nevertheless, N is less likely to constrain C accumulation in the real-world ecosystems, which are exposed to a gradual increase in $C_a$ and require much less N to balance additional C influx than in $CO_2$ experimental plots.

The large variability in $CO_2$-induced changes in C and N pool sizes among studies poses a great challenge to modelers on how to incorporate the diverse mechanisms of C and N interactions into regional and global predictions of future C sequestration. Toward that goal, a probabilistic approach might be only an effective one to account for stochastic nature of diverse N processes.