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# Elevated $CO_2$ indirectly stimulates $N_2$-fixation via its impact on legume biomass: a Bayesian meta-analysis

Kiona Ogle (1,2), Aimee Classen (3), Kristine Dyrnum (4), Sarah E. Hobbie (5), Tali Lee (6), Anders Michelsen (4), Paul Newton (7), Rich Norby (8), Craig W. Osenberg (9), Anders Priemé (4), Reich Peter (10,11), César Terrer (12), Kees Jan van Groenigen (2,13), and Bruce Hungate (2)

(1) School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, Arizona, USA, (2) Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, Arizona, USA, (3) Rubenstein School of Environment & Natural Resources, University of Vermont, Burlington, Vermont, USA, (4) Department of Biology, University of Copenhagen, Copenhagen, Denmark, (5) Department of Ecology, Evolution, and Behavior, University of Minnesota, St. Paul, Minnesota, USA, (6) Biology Department, University of Wisconsin, Eau Claire, Wisconsin, USA, (7) AgResearch, Palmerston North, New Zealand, (8) Environmental Sciences Division and Climate Change Science Institute, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA, (9) Odum School of Ecology, University of Georgia, Athens, Georgia, USA, (10) Department of Forest Resources, University of Minnesota, St. Paul, Minnesota, USA, (11) Hawkesbury Institute for the Environment, Western Sydney University, Penrith, New South Wales, Australia, (12) Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, Barcelona, Spain, (13) College of Life and Environmental Sciences, University of Exeter, Exeter, Devon, UK

The impact of rising atmospheric $CO_2$ on terrestrial carbon (C) accumulation depends in part on nitrogen (N) availability, an important source of which is biological $N_2$-fixation. Higher rates of $N_2$-fixation with rising $CO_2$ could provide the necessary N for maintaining the future land C sink. Yet, experimental results show mixed support for this hypothesis. We extracted data from 77 studies reporting experimental results of the effect of elevated $CO_2$ ($eCO_2$) on $N_2$-fixation. For all (468) records, we extracted the mean $N_2$-fixation rate for the control and $eCO_2$ treatments, and, when available, the corresponding standard deviation (SD). We also extracted information on other factors that might influence the response to $eCO_2$, including non-symbiotic vs symbiotic associations, inside vs outside experiments, monocultures vs mixed communities, phosphorus added vs not, intact vs disturbed soil, and the reported biomass (mean and SD) of $N_2$-fixing plants. For each record, we computed the log response ratio (LRR) and its corresponding SD, for both $N_2$-fixation and plant biomass. To accommodate the complexity of the compiled data, and to estimate key quantities of interest, we conducted a hierarchical Bayesian meta-analysis of the LRR data. The LRRs and SDs for $N_2$-fixation and plant biomass were simultaneously analyzed, allowing us to impute missing biomass LRRs, and to model $N_2$-fixation LRR as a function of the corresponding biomass LRR (observed or imputed), important experimental factors, and within and among study random effects. We estimated the global LRR of $N_2$-fixation across all studies and experimental factors, and for five scenarios describing a gradient from "most natural" (i.e., outside, intact soil, mixed community, no P addition) to "most artificial" (inside, disturbed soil, P added). The Bayesian model revealed that the $N_2$-fixation response was governed by the biomass response; $eCO_2$ generally stimulated production of $N_2$-fixing plants, which in turn lead to higher rates of $N_2$-fixation under $eCO_2$. Both plant biomass and $N_2$-fixation were most strongly stimulated by $eCO_2$ under more artificial conditions, and neither were significantly affected by $eCO_2$ under more natural settings. However, the $N_2$-fixation and plant biomass responses to $eCO_2$ were most strongly coupled under the most natural (undisturbed, outside) and most artificial (inside) settings, whereas they were only weakly coupled under disturbed, outside conditions. Additionally, non-symbiotic $N_2$-fixation generally did not respond to $eCO_2$, whereas there was a clear trend for symbiotic $N_2$-fixation to respond positively to $eCO_2$, but again, only under artificial conditions. In summary, the Bayesian meta-analysis (1) provided little support for direct effects of $eCO_2$ on $N_2$-fixation, and instead indicated an indirect response mediate through the direct effects of $eCO_2$ on biomass production of $N_2$-fixing plants, and (2) showed that neither $N_2$-fixation nor plant biomass responded to $eCO_2$ in natural, intact ecosystems; it was only under more artificial conditions that $eCO_2$ led to increased plant biomass and $N_2$-fixation. These results argue against the hypothesis that rising $CO_2$ will stimulate $N_2$-fixation in terrestrial ecosystems, and caution against building that expectation into models of the future land C sink.