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Satellite based estimates underestimate the effect of CO₂ fertilization on net primary productivity

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To the Editor

The recent study by Smith *et al.*¹ (hereafter S15) concludes that Earth system models (ESMs) overestimate the effect of CO₂ fertilization on net primary productivity (NPP). Whilst this finding is possible², here we highlight that the satellite derived NPP estimates used are likely to underestimate the CO₂ fertilization effect because they do not account for the primary effect of CO₂ on photosynthesis. Additionally the calculation of NPP sensitivity to atmospheric CO₂ is misleading, invalidating the comparison with free air CO₂ enrichment (FACE) data.

Satellite derived NPP estimates have often been treated as observations³, however they are not⁴. S15 uses three independent satellite based proxies for NPP: a light use efficiency (LUE) model, a model tree ensemble⁵ (MTE) constrained by ecosystem carbon flux measurements, and remotely sensed vegetation optical depth⁶ (VOD). The LUE and MTE models assume that CO₂ affects NPP solely through changes in the observed fraction of absorbed photosynthetically active radiation (fAPAR), which is closely related to leaf area. However, the primary biochemical effect of rising CO₂, which both these models ignore, is an increase in photosynthesis due to increased LUE⁷.

At the two longest-running forest FACE sites, we calculated the change in LUE due to CO₂ using NPP, growing season photosynthetically active radiation, and the Beer-Lambert law, relating annual maximum leaf area index to fAPAR. We found a large increase in LUE due to CO₂ across all years: mean = 17.4% (range = 8.9–32.6%) and 24.3% (8.0–35.9%), at Oak Ridge (1998–2008) and Duke (1996–2007), respectively. By contrast, the indirect change due to CO₂ (that is, via changes in fAPAR), which is accounted for in the satellite models, is small across all years: 0.3% (1.3–2.0%) and 2.9% (–0.3–6.0%), at Oak Ridge and Duke, respectively. Other, more open, canopies may experience larger changes in fAPAR due to CO₂ fertilization, but will still experience the large direct effect of CO₂ on LUE that is incorrectly ignored by the LUE and the MTE models used by S15.

The third proxy for global NPP used by S15 is based on VOD, which is closely related to above-ground biomass (AGB). However, AGB (a state) is not the same thing as NPP (a flux). Standing biomass, particularly in long-lived forest stands, will not fully reflect increases in NPP until many years after the rise in CO₂. In addition, AGB excludes below-ground allocation⁸, which contributes to total NPP. As a result, VOD will systematically underestimate the effect of CO₂ on whole-ecosystem NPP.

The conclusions of S15 are bolstered by comparing model results with data from FACE experiments. S15 defines β as the percentage enhancement of NPP per 100 ppm CO₂ increase, and their values of β appear to be consistent with those estimated from FACE experiments. However, this definition of β ignores the saturating response to CO₂ (ref. 9), which means that values of β estimated from a low CO₂ concentration range (such as the range for the satellite record, which is ~350–400 ppm) should be higher than values estimated over a higher CO₂ concentration range (such as the range for the FACE experiments, which typically increase CO₂ from ~370 ppm to ~550 ppm) (Fig. 1). Furthermore, S15's synthesis of FACE data is incomplete as it omits several years of published data^{10,11}, and incorrectly estimates an overall effect size by taking the median across experiments, species and years, rather than calculating a more appropriate response ratio¹².

Figure 1 | Illustration of the effect of different measurements of atmospheric CO₂ concentration (C_a) ranges on estimation of β , defined as the relative change in net primary productivity (NPP) for a 100-ppm change in C_a . We assume there is a universal, saturating response of NPP to C_a (green line; here illustrated as the response of RuBP-regeneration-limited photosynthesis to C_a , taken from ref. 12). The red point extrapolates the straight line joining 360 and 400 ppm to 460 ppm ($360 + 100$), thus indicating the value of β that would be estimated from measurements over the C_a range 360–400 ppm (corresponding to satellite measurements). Similarly, the blue point interpolates the straight line joining 360 ppm and 600 ppm to 460 ppm, thus indicating the value of β that would be estimated from measurements over the C_a range 360–600 ppm (corresponding to FACE experiments).

S15 concludes that CESM1-BGC, the ESM most consistent with the satellite NPP estimates, is an improvement over other ESMs, likely due to its inclusion of explicit carbon-nitrogen interactions. We agree that the inclusion of such interactions in ESMs is a desirable objective, and that neglect of these in 'carbon only' ESMs risks overestimating long-term CO₂ effects on NPP². However, it is premature to reach this conclusion given the inability of CESM1-BGC to capture the magnitude of recent CO₂ uptake¹³ or even (uniquely among models tested) the 'sign' of the relationship between tropical land temperatures and CO₂ uptake¹⁴. In addition, the land surface model (CLM4) in CESM1-BGC underestimates the measured NPP response to elevated CO₂ from the two longest-running FACE experiments — predicting a smaller response than ten other ecosystem models that included nutrient limitations on NPP¹⁵.

In summary the comparison of satellite and FACE estimates of CO₂ fertilization is invalid, and the discussion of nitrogen limitations is based on a single model that poorly represents the response of NPP to CO₂.

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