Satellite based estimates underestimate the effect of CO₂ fertilisation on NPP

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Smith et al.¹ (hereafter S15) compared global estimates of net primary production (NPP) derived from satellites and earth system models (ESMs). They concluded that ESMs over-estimate the effect of CO₂ fertilisation on NPP. An overestimation by ESMs is possible², but here we draw attention to the fact that the satellite-derived NPP estimates used in S15 are likely to underestimate the CO₂ fertilisation effect because they do not account for the primary effect of CO₂ on the biochemistry of photosynthesis. We also show that the calculation in S15 of the sensitivity of NPP to atmospheric CO₂ is misleading, invalidating the comparison with Free Air CO₂ Enrichment (FACE) data.

Global NPP cannot be measured; however, by exploiting the observed linear relationship between NPP and absorbed photosynthetically active radiation (APAR)³, light use efficiency (LUE) models use satellite data to estimate NPP on a pixel basis. Although satellite-derived NPP estimates have often been treated as observations⁴, they are not⁵. S15 used three independent satellite-based proxies for NPP: a LUE model, a model tree ensemble (MTE⁶) constrained by ecosystem carbon flux measurements, and remotely sensed vegetation optical depth (VOD⁷). The LUE and MTE models assume that CO₂ affects NPP solely through changes in the observed fraction of absorbed radiation (fAPAR), which is closely related to leaf area. However, the primary biochemical effect of CO₂, which both these models ignore, is an increase in photosynthesis with rising CO₂ due to increased LUE⁸ (although alternative LUE models account for this effect⁹,¹⁰). 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 LAI 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 % (range = 8.0 – 35.9 %), at Oak Ridge (1998–2008) and Duke (1996–2007), respectively. By contrast, we found the indirect change due to CO₂ (i.e. via changes in fAPAR), which is accounted for in the satellite models, to be small across all years: mean = 0.3 % (range = −1.3 – 2.0 %) and 2.9 % (range = −0.3 – 6.0 %), at Oak Ridge and Duke, respectively. Whilst it is true that other, more open, canopies may experience larger changes in fAPAR due to CO₂ fertilisation, such open canopies 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. Consequently, theses approaches are unsuitable for studying the effect of elevated CO₂ on NPP.

The third remote-sensing based proxy for global NPP used in S15 was based on VOD, which is closely related to above-ground biomass. However, above-ground biomass (a state) is not the same thing as NPP (a flux). Biomass is the result of the long-term allocation of NPP and the turnover of plant tissues. Standing biomass, particularly in long-lived forest stands, will not fully reflect increases in NPP until many years after the rise in CO₂ causing stimulation. In addition, above-ground biomass excludes below-ground allocation, which contributes to total NPP; and it has commonly been observed that plants increase below-ground allocation under elevated CO₂. As a result, VOD will systematically under-estimate the effect of CO₂ on whole-ecosystem NPP.

The conclusions of S15 were bolstered by comparing model results with data from FACE experiments. S15 defined β as the percentage enhancement of NPP per 100 ppm increase in CO₂. Values of β estimated from FACE experiments appeared to be consistent with the modelled NPP estimates derived from satellite data. However, this definition of β ignores the fact that there is a saturating response to CO₂. This saturating response means that values of β estimated from a low CO₂ concentration range (e.g. the range for the satellite record, which is ~350 to 400 ppm) should be higher than values estimated over a higher CO₂ concentration range (e.g. the range for
the FACE experiments, which typically increase CO$_2$ from ~370 to ~550 ppm) (Figure 1). Furthermore, S15’s synthesis of FACE data is incomplete as it omits several years of published data$^{13,14}$, and incorrectly estimates an overall effect size by taking the median across experiments, species and years, rather than calculating a more appropriate response ratio$^{15}$.

S15 conclude that CESM1-BGC, the ESM most consistent with the satellite NPP estimates, represents 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 interactions in “carbon only” ESMs risks over-estimating long-term CO$_2$ effects on NPP by neglect of nutrient limitations on plant growth$^2$. However, it is premature to conclude that CESM1-BGC represents an improvement on previous models, given its inability to capture the magnitude of recent CO$_2$ uptake$^{16}$ or even (uniquely among models tested) the sign of the relationship between tropical land temperatures and CO$_2$ uptake$^{17}$. The land surface model (CLM4) in CESM1-BGC also under-estimated the measured NPP response to elevated CO$_2$ from the two longest-running FACE experiments, and predicted a smaller response than ten other ecosystem models that included nutrient limitations on NPP$^{18}$.

In summary, the remote-sensing based proxies for NPP used in S15 are not appropriate to examine the effect of CO$_2$ fertilisation on global NPP. They do not account for the direct effect of CO$_2$ on photosynthesis, nor the commonly observed increase in belowground allocation of NPP under elevated CO$_2$$^{11}$. The comparison of satellite and FACE estimates of CO$_2$ fertilisation is invalid, and the discussion of nitrogen limitations is based on a single model that poorly represents the response of NPP to CO$_2$. 
Figure 1: Illustration of the effect of different measurement \( C_a \) ranges on estimation of \( \beta \), defined as the relative change in net primary productivity (NPP) for a 100-ppm change in \( C_a \). The overall response to \( C_a \) is a saturating function (green line; here illustrated as the response of RuBP-regeneration-limited photosynthesis to \( C_a \), taken from Franks et al.\textsuperscript{12}). The red point indicates the value of \( \beta \) that would be estimated from measurements over the \( C_a \) range 360 – 400 ppm (corresponding to satellite measurements, indicated with solid red line). The blue point indicates the value of \( \beta \) that would be estimated from measurements over the \( C_a \) range 360 – 600 ppm (corresponding to FACE experiments, indicated with solid blue line).
References


