Forest response to elevated CO$_2$ is conserved across a broad range of productivity

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Climate change predictions derived from coupled carbon-climate models are highly dependent on assumptions about feedbacks between the biosphere and atmosphere. One critical feedback occurs if C uptake by the biosphere increases in response to the fossil-fuel driven increase in atmospheric CO$_2$ (“CO$_2$ fertilization”), thereby slowing the rate of increase in atmospheric CO$_2$. Carbon exchanges between the terrestrial biosphere and atmosphere are often first represented in models as net primary productivity (NPP). However, the contribution of CO$_2$ fertilization to the future global C cycle has been uncertain, especially in forest ecosystems that dominate global NPP, and models that include a feedback between terrestrial biosphere metabolism and atmospheric CO$_2$ are poorly constrained by experimental evidence. We analyzed the response of NPP to elevated CO$_2$ (~550 ppm) in four free-air CO$_2$ enrichment experiments in forest stands. We show that the response of forest NPP to elevated CO$_2$ is highly conserved across a broad range of productivity, with a stimulation at the median of 23 ± 2%. At low leaf area indices, a large portion of the response was attributable to increased light absorption, but as leaf area indices increased, the response to elevated CO$_2$ was wholly caused by increased light-use efficiency. The surprising consistency of response across diverse sites provides a benchmark to evaluate predictions of ecosystem and global models and allows us now to focus on unresolved questions about carbon partitioning and retention, and spatial variation in NPP response caused by availability of other growth limiting resources.

Experimental data should provide useful guidance to models, thereby increasing our confidence in model predictions. Experiments have unequivocally shown that plants can grow faster and larger in a CO$_2$-enriched atmosphere (6–8), and the mechanisms of response are well understood (4). The relevance of this evidence to prediction of global C budgets over decadal time frames, however, may be limited. As spatial and temporal scales increase beyond what can be captured in experiments, modifying influences of resource availability and biogeochemical feedbacks within the ecosystem become increasingly important, and these tend to diminish the simple response to elevated CO$_2$ observed in small-scale experiments. The problem is especially severe with forests because of the inherent difficulty in conducting relevant experiments at appropriate spatial and temporal scales with large and long-lived organisms and complex ecosystems. Nevertheless, the potential responses of forests to rising CO$_2$ cannot be ignored in global C cycling analyses and predictions of climatic change because forest ecosystems contribute ~50% of global NPP and ~80% of terrestrial NPP (9). With the development of Free-Air CO$_2$ Enrichment (FACE) technology (10, 11), it is now possible to elevate atmospheric CO$_2$ in large plots in intact forest ecosystems without altering other microclimatic and biotic variables (12). Recognizing that the results from any single experiment may not be broadly representative, here we provide the an analysis of NPP data from the four FACE experiments operating in forest stands.

Materials and Methods

The forest stands examined in the FACE experiments (Table 1) represent a broad range of productivity, climatic and soil conditions.

Conflict of interest statement: No conflicts declared.

Abbreviations: APAR, absorbed photosynthetically active radiation; FACE, Free-Air CO$_2$ Enrichment; LAI, leaf area index; NPP, net primary productivity; NPPe, NPP in elevated CO$_2$; NPPc, NPP in current CO$_2$; NPPi, NPP in current CO$_2$.  

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Table 1. Characteristics of the four FACE experiments

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>DukeFACE</th>
<th>AspenFACE</th>
<th>ORNL-FACE</th>
<th>POP-EUROFACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Durham, NC</td>
<td>Rhinelander, WI</td>
<td>Oak Ridge, TN</td>
<td>Tuscania (Viterbo), Italy</td>
</tr>
<tr>
<td>Latitude, longitude</td>
<td>35°58’N, 79°0’5”W</td>
<td>45°40’N, 89°37’W</td>
<td>35°54’N, 84°20’W</td>
<td>42°22’ N, 11°48’E</td>
</tr>
<tr>
<td>Mean annual precipitation, mm</td>
<td>1,440</td>
<td>810</td>
<td>1,390</td>
<td>818*</td>
</tr>
<tr>
<td>Mean annual temperature, °C</td>
<td>15.5</td>
<td>4.9</td>
<td>14.2</td>
<td>14.1</td>
</tr>
<tr>
<td>Growing season,† days</td>
<td>200</td>
<td>150</td>
<td>190</td>
<td>247</td>
</tr>
<tr>
<td>Soil classification (U.S.)</td>
<td>Ulitic Hapludalf</td>
<td>Alfic Haploarthod</td>
<td>Aquic Haplustalf</td>
<td>Pachic Xerumbrept</td>
</tr>
<tr>
<td>Soil texture</td>
<td>Clay loam</td>
<td>Sandy loam</td>
<td>Silty clay loam</td>
<td>Loam and silt loam</td>
</tr>
<tr>
<td>Total soil N, kg m⁻¹</td>
<td>0.79</td>
<td>1.20</td>
<td>1.12</td>
<td>1.1–1.4</td>
</tr>
<tr>
<td>Peak leaf area index,‡ m²m⁻²</td>
<td>3.4</td>
<td>2.7–3.4</td>
<td>5.5</td>
<td>4.6–7.4</td>
</tr>
<tr>
<td>Year planted</td>
<td>1983</td>
<td>1997</td>
<td>1988</td>
<td>1999</td>
</tr>
</tbody>
</table>

*The POP-EUROFACE experiment used irrigation to avoid drought, so inferences regarding precipitation should be avoided for this site.
†For deciduous stands, the growing season is the duration that trees have leaves; for the evergreen system, it is the period of active stem growth.
‡Values of leaf area index are expressed as leaf area per ground area; the range in values describes portions of experimental plots occupied by different species after LAI was no longer increasing.

Experimental conditions, stand development history, and life history characteristics of the dominant species, although all four are young stands in the temperate zone. Two experiments were initiated in established monoculture plantations that had fully occupied the sites: an evergreen loblolly pine (Pinus taeda) stand at DukeFACE and a deciduous sweetgum (Liquidambar styaciflua) stand at ORNL-FACE. The other two experiments, AspenFACE and POP-EUROFACE, comprise simple multispecies assemblages dominated by Populus spp. that were initiated on previously bare ground.

Each experiment used FACE technology to control the CO₂ concentration in the atmosphere in replicated 25- to 30-m-diameter plots in the tree stands. The DukeFACE, ORNLFACE, and AspenFACE experiments used similar technology, whereby pure CO₂ was mixed with a turbulent air-stream in a plenum and released through vertical vent pipes at the up-wind side of each plot (10). In the POP-EUROFACE experiment, pure CO₂ was released at supersonic velocity directly into the atmosphere from pipes on the up-wind side of each plot (11).

The average atmospheric [CO₂] in current-CO₂ plots across all years of these experiments was 376 ppm, and the FACE systems (10, 11) provided additional CO₂ sufficient to maintain an average concentration (across all experiments) in the elevated-CO₂ plots of 550 ppm (13). These CO₂ treatments were chosen on the basis of current projections of atmospheric [CO₂] anticipated for 2050 (14). Detailed descriptions of the exposure systems and the CO₂ concentration dynamics are provided for DukeFACE (10), ORNL-FACE (15), AspenFACE (16, 17), and POP-EUROFACE (11).

Our analysis of NPP was based on all years and subplots for which data were available and canopy development was complete. Our goal was to understand the response of closed-canopy forests. We therefore excluded data from stands with an expanding canopy, which would not be informative of the response of the global forest (7). For ORNL-FACE and DukeFACE, the CO₂ treatments were initiated after canopy development was complete, and 5–6 years of data were used (1999–2003 and 1997–2002, respectively). The plots in the AspenFACE experiment were planted half with a monoculture of trembling aspen (Populus tremuloides), one fourth with an equal mixture of trembling aspen and paper birch (Betula papyrifera), and one fourth with a mixture of trembling aspen and sugar maple (Acer saccharum). On the basis of our canopy closure criterion, 1 year (2003) of data from the aspen stand and 3 years (2001–2003) from the aspen–birch stand were included in the analysis; the aspen–maple stand was not included because the canopy was still open. Six of the 12 plots in AspenFACE received elevated concentrations of ozone; these were not included in the analysis. The plots in the POP-EUROFACE were split into subplots, each occupied by a different Populus species; data from all subplots from 2000–2001 were used.

NPP, expressed as grams of C per square meter of land surface per year, was calculated as annual carbon increments (Iwood + Ileaf + Icoarse root + Ifine root), plus the major inputs to detritus, litterfall, and fine root turnover (Dlitterfall + Dfine root) (18), although different approaches were used in the four experiments. The annual increments of stem wood (Iwood) and coarse woody root (Icoarse root) were estimated by applying site-specific allometric equations to periodic measurements of the diameter of trees in current and elevated CO₂ plots. Harvest data from the POP-EUROFACE (19) and AspenFACE experiments (20); and the tree height–diameter relationship for trees at DukeFACE (21) indicate that exposure to elevated [CO₂] did not affect the allometric relationships between plant parts. The allometric equation used at ORNL-FACE incorporated basal area, height, taper, and wood density to reduce the possibility of the allometry being altered by elevated [CO₂] (15). In the pine forest at DukeFACE, Ileaf also was estimated from allometric regression (22) applied at different intervals (18); Ileaf = 0 for the deciduous forests. The production of leaf litter (Dlitterfall) was estimated from litter baskets at all sites (23–25). In most cases biomass measurements were converted to C units by using the measured C content of different tissues, which varied between 0.4 and 0.5 (26, 27); when measured values were not available, C content was assumed equal to 0.5.

The contribution of fine roots (Dfine root) to NPP typically was low in these forests (~3% in AspenFACE, 6% in DukeFACE, 7% in POP-EUROFACE, and 16% in ORNL-FACE) and was estimated differently among sites. At ORNLFACE (28) and PopFACE (29), fine-root production was measured directly by using minirhizotrons and in-growth cores. The DukeFACE experiment used a compartment flow model for estimating fine-root production (30); AspenFACE calculated fine-root turnover from published rates of aspen fine-root production and mortality (31) that were then applied to allo- metrically determined peak standing fine-root biomass (20). Other components of NPP (e.g., losses to herbivory and root exudation) were not included in our analysis because data were not available. The combined contribution of herbivory and dissolved organic C in the DukeFACE experiment was only 3%
of NPP (18), so it is unlikely that their exclusion would alter our results.

Absorbed photosynthetically active radiation (APAR, or the light energy in megajoules absorbed by the canopy) was estimated from the difference between quantum sensor measurements of down-welling radiation (400–700 nm) and the amount reaching the forest floor (POP-EUROFACE and ORNL-FACE) (19, 25) or by applying a Beer's Law approximation to measurements of leaf area index (LAI) (21). Values of APAR were integrated over the growing season.

Results

The relationship between NPP in elevated [CO₂] (NPPₑ) and NPP in current [CO₂] (NPPᶜ) (Fig. 1A) was remarkably consistent across a broad range of productivity. Although many important forest types are missing in this analysis (e.g., boreal and tropical forests, in which FACE experiments have not been conducted), the range in NPP comprises much of the range observed among forests globally (9) and represented in models (32). The linear relationship between NPPₑ and NPPᶜ is different from the 1:1 line (P < 0.0001), indicating a significant effect of [CO₂] on NPP. The positive intercept implies that as NPP increases, the CO₂ response declines, but this response was defined primarily by a single experimental forest stand, and the intercept is not significantly different from zero. Rearranging the regression equation gives the CO₂ response ratio as NPPₑ/NPPᶜ = 1.18 ± 0.05, with NPPᶜ expressed as g of C per m² yr⁻¹. At the median of the range of NPP in our data set, the CO₂ response ratio as predicted by the regression was 1.23 ± 0.02.

LAI in high LAI stands was generally similar in current and elevated [CO₂] (data not shown), so APAR in these stands also was similar (Fig. 1B). If APAR did not increase, then the response of NPP derived not from increased energy capture but primarily from higher efficiency by which light energy is converted to organic matter (light-use efficiency, Ý). We assessed this by calculating the fraction of the normalized gain in NPP attributable to a gain in APAR (Fig. 2). In the lower LAI stands, 60–90% of the gain in NPP with CO₂ fertilization was associated with increased APAR, whereas in high LAI stands there was little gain in APAR even when CO₂ enrichment caused higher LAI.

Discussion

Our analysis indicates a 23% increase in forest NPP as atmospheric [CO₂] increases to 550 ppm over the next few decades. The logarithmic biotic growth factor (β-factor) formulation, which expresses the response as a function of the relative [CO₂] increase (8, 33), calculated from these data are 0.60. A 23% enrichment response is less than that of previous syntheses of tree growth (not NPP) responses, which ranged from 29% in an analysis dominated by short-term seedling studies (6) to 55% (median value) for field-grown trees (7). However, these older analyses considered higher CO₂ concentrations, generally 300 ppm higher than ambient, and often only aboveground biomass increment, so the results are not directly comparable. The wide variation among these older values has resulted in substantial uncertainty as to the true response, and they could not be used with confidence because, in experiments with individual, fast-growing seedlings and saplings, growth responses are confounded with ontogeny (7).
A useful analytical tool for interpreting plant responses that are confounded with ontogenetic or stand development has been to separate the response into structural and functional components (25), which also is an important analytical framework used in ecosystem models (34) and remote sensing analysis (32). Here, the structural component is leaf area by which light is absorbed, and the functional component is the conversion of light energy to organic matter. Our analysis suggested that at low LAI, elevated [CO$_2$] was causing structural changes and increased APAR even after LAI in current [CO$_2$] had reached a maximum. At higher LAI, there was no additional gain in light absorption even if elevated [CO$_2$] increased LAI (a consequence of Beer’s Law), and increased NPP in elevated [CO$_2$] was primarily or wholly attributable to increased $e$.

Our experimental evidence provides a standard to evaluate models that generate predictions of a NPP response to CO$_2$ fertilization as an intermediate step in predicting a C cycle feedback between the biosphere and atmosphere. Six dynamic global vegetation models predicted increasing global NPP in response to rising [CO$_2$], with the forcing defined by the IS92a emissions scenario (14) and the response based on a standard photosynthesis model (5). The increase in NPP between 1999 and 2049 (the years corresponding to the current and elevated [CO$_2$] in our dataset) ranged from 15% to 32%, indicating some substantial discrepancies between models and data. Nevertheless, the average of the six models was 22%, in close agreement with the mean response of 23% reported here. A coupled carbon-climate model (1), which prescribes the CO$_2$ fertilization response using a $\beta$-factor formulation (35), used a $\beta$ of 0.65 as the “control” value, also in good agreement with our experimental results. Although there are other assumptions involved in the subsequent calculations of net ecosystem production and in the interactions between [CO$_2$] effects and climate change influences, the congruence of the NPP predictions with the experimental evidence we present here should add confidence in overall model results.

The concurrence across sites in the NPP response does not resolve all issues attending CO$_2$ fertilization. The mean response, while appropriate for global analyses, masks several sources of significant variation that could be especially important in determining how a specific site will respond to rising [CO$_2$]. At the DukeFACE, a wide range of response to CO$_2$ enrichment across replicate plots correlated with differences in soil N availability. Under low N availability, CO$_2$ enrichment increased NPP by 19%, whereas under intermediate and high N availability the percent CO$_2$ stimulation was 27% (36). Where soils are poor or prolonged water limitation occurs, represented only through within-site variation in our dataset, forests may have limited capacity to support any response to CO$_2$ enrichment (37). Concurrent increases in tropospheric ozone could negate the productivity increases from elevated [CO$_2$] (17, 20). In addition to controlling spatial variability in response, N availability may also be a factor in determining whether the responses observed here can be sustained for decades (38, 39). The data in our analysis all come from fast-growing, early successional stands, and there has been no evidence to date for a negative feedback on NPP through N availability in these stands (20, 40, 41).

NPP represents the amount of organic C entering an ecosystem; it does not address the fate of that C. Model comparisons demonstrate that whether additional C storage occurs in vegetation or in soil is crucial to understanding the future C cycle and its control of the climate system (2). Experimental results demonstrate that the partitioning of C between plant organs with different turnover rates determines the potential of an ecosystem to store additional C and whether the storage occurs in plant biomass or in soil. At DukeFACE, increased NPP was associated with C sequestration in stem wood (18, 42), whereas at ORNL-FACE increased NPP was partitioned to production of fine roots (28). Fine roots decompose rapidly and add C to soil, where most is respired by microbes, but a fraction may be sequestered into soil organic matter pools (28). Although the two forests have a similar NPP response to CO$_2$ enrichment, and over the short term their net ecosystem production response was similar (42), the longer-term trajectory of C cycling will differ. In our four-site dataset, the percentage of NPP gain partitioned to wood varied from 11% to 93%, and there was no discernible pattern between forest types. Global productivity models vary nearly as much in the fraction of C stored in vegetation vs. soil: from 35% to 85% (2). Results from some of the DukeFACE plots showed that the enhancement in wood production under CO$_2$ enrichment was not sustained at levels observed during the first 3 years of the experiment, but the initial enhancement was reestablished in half a plot that was supplied with nitrogen (37). Imposing additional treatments on existing FACE experiments or designing experiments that account for multiple constraints will remove some of the uncertainty in the controls over partitioning. With the response of NPP to CO$_2$ fertilization better resolved, it becomes especially important to understand the controls on C partitioning as a priority challenge in relating NPP to C cycling and storage in forest ecosystems.

The effect of CO$_2$ fertilization on forest NPP is now firmly established, at least for young stands in the temperate zone. Recent observations of older and larger deciduous trees in a mature Swiss forest (43) demonstrated that physiological responses (e.g., photosynthesis, foliar N and nonstructural carbohydrate concentrations) were similar to those of younger trees, thereby increasing our confidence that our results are more generally relevant. NPP and stand-level growth responses could not be measured in the Swiss study, but stem basal area increment was not significantly stimulated by elevated CO$_2$. Although interpreted as an indication of C saturation (43), this conclusion was based on the stem growth response of only 10 CO$_2$-enriched trees with high variance, and it is not at odds with our conclusion about the response of NPP. While the ongoing FACE experiments will continue to provide data relevant to questions about the fate of additional C in CO$_2$-enriched forests, there is not a compelling reason for new, single-factor FACE experiments in young, temperate-zone forests. Rather, the limitations of our current data show the need for new experiments in mature forests and in unexplored biomes, particularly tropical forests that contribute much to global NPP.

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