Large divergence of satellite and Earth system model estimates of global terrestrial CO₂ fertilization

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**Supplementary Table 1. CMIP5 model centers, identification numbers, and names.**

<table>
<thead>
<tr>
<th>Modelling Center</th>
<th>Institute ID</th>
<th>Model Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing Climate Center, China Meteorological Administration</td>
<td>BCC</td>
<td>BCC-CSM1-1</td>
</tr>
<tr>
<td>Community Earth System Model Contributors</td>
<td>NSF-DOE-NCAR</td>
<td>CESM1-BGC</td>
</tr>
<tr>
<td>Met Office Hadley Centre</td>
<td>MOHC</td>
<td>Had-GEM2-ES</td>
</tr>
<tr>
<td>Institut Pierre-Simon Laplace</td>
<td>IPSL</td>
<td>IPSL-CM5A-MR</td>
</tr>
<tr>
<td>NOAA Geophysical Fluid Dynamics Laboratory</td>
<td>NOAA GFDL</td>
<td>GFDL-ESM2M</td>
</tr>
</tbody>
</table>
Supplementary Table 2. Characteristics of the Free-Air CO₂ Enrichment (FACE) experimental sites.

<table>
<thead>
<tr>
<th></th>
<th>Latitude Longitude</th>
<th>MAT (°C)</th>
<th>MAP (mm)</th>
<th>Available NPP data</th>
<th>Elevated CO₂ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspen¹</td>
<td>45°40’N 89°37’W</td>
<td>4.9</td>
<td>810</td>
<td>2001-2003</td>
<td>580</td>
</tr>
<tr>
<td>Duke¹</td>
<td>35°58’N 79°05’W</td>
<td>15.5</td>
<td>1140</td>
<td>1996-2007</td>
<td>580</td>
</tr>
<tr>
<td>ORNL¹</td>
<td>35°54’N 84°20’W</td>
<td>14.2</td>
<td>1390</td>
<td>1998-2008</td>
<td>550</td>
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<tr>
<td>Pop-Euro¹</td>
<td>42°22’N 11°48’E</td>
<td>14.1</td>
<td>818</td>
<td>2000-2001</td>
<td>550</td>
</tr>
<tr>
<td>BioCON²</td>
<td>45°N 93°W</td>
<td>10.3</td>
<td>660</td>
<td>1998-1999</td>
<td>560</td>
</tr>
<tr>
<td>PHACE²</td>
<td>41°11’N 104°54’W</td>
<td>7.5</td>
<td>384</td>
<td>2006-2009</td>
<td>600</td>
</tr>
</tbody>
</table>

¹Forest FACE sites (see ref. 12 and ref. 14); ²Non-forest Face sites (see ref. 13 and ref. 15)
Supplementary Figure 1. Temporal changes in NPP for each CMIP5 model considered. 

a. CMIP5\textsubscript{CO2+CLIM} NPP. b. CMIP5\textsubscript{CLIM} NPP. The change in NPP (1960-2011) for individual CMIP5 models (light lines) and the ensemble mean (heavy line) are shown. The CMIP5 model that considered nutrient constraints (CESM1-BGC) is shown with a dashed line.

Supplementary Figure 2. Terrestrial net primary productivity (NPP) trends across climatic zones.

- Climate zones boundaries defined according to Köppen-Geiger climate classification.
- The NPP anomaly across tropical, temperate, cold, and arid climate zones. Lines represent linear trends while shading indicates uncertainty (± 1σ) due to among-model variability for CMIP5 and model parameterization for satellite estimates. Box and whisker plots (right panels) show the distribution of estimates for the full time period. For comparison, the CMIP5 model that considered nutrient constraints (dashed green line; green circle), Flux MTE (dashed red line; red diamond), satellite FPAR (dashed cyan line; cyan circle), and satellite VOD (dashed purple line; purple square) are shown separately. Letters indicate statistically significant differences in distributions at $\alpha = 0.05$. 

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The NPP anomaly across b. tropical, c. temperate, d. cold, and e. arid climate zones. Lines 
represent linear trends while shading indicates uncertainty (± 1σ) due to among-model variability 
for CMIP5 and model parameterization for satellite estimates. Box and whisker plots (right 
panels) show the distribution of estimates for the full time period. For comparison, the CMIP5 
model that considered nutrient constraints (dashed green line; green circle), Flux MTE (dashed 
red line; red diamond), satellite FPAR (dashed cyan line; cyan circle), and satellite VOD (dashed 
purple line; purple square) are shown separately. Letters indicate statistically significant 
differences in distributions at α = 0.05.
**Supplementary Figure 3. Terrestrial net primary productivity (NPP) trends by biome type.**

a. Biome classifications defined according to the MODIS collection 5 global land-cover classification and the Köppen-Geiger climate classification. The NPP anomaly across b. northern hemisphere evergreen forest, c. northern hemisphere deciduous forest, d. temperate grassland, e. arid grassland, f. temperate shrubland, and g. arid shrubland biomes. Lines represent linear trends while shading indicates uncertainty (± 1σ) due to among-model variability for CMIP5 and model parameterization for satellite estimates. Box and whisker plots (right panels), show the distribution of estimates for the full time period. For comparison, the CMIP5 model that considered nutrient constraints (dashed green line; green circle), Flux MTE (dashed red line; red diamond), satellite FPAR (dashed cyan line; cyan circle), and satellite VOD (dashed purple line; purple square) are shown separately. Letters indicate statistically significant differences in distributions at $\alpha = 0.05$. 

![Supplementary Figure 3](image-url)
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- e. temperate shrubland, and
- g. arid shrubland biomes. Lines represent linear trends while shading indicates uncertainty (± 1σ) due to among-model variability for CMIP5 and model parameterization for satellite estimates. Box and whisker plots (right panels), show the distribution of estimates for the full time period. For comparison, the CMIP5 model that considered nutrient constraints (dashed green line; green circle) is shown separately. Letters indicate statistically significant differences in distributions at $\alpha = 0.05$.

Supplementary Figure 4. Vapor pressure deficit (VPD) and minimum temperature (TMIN) trends across long-term climate zones. The TMIN (a.-d.) and VPD (e.-h.) anomaly across tropical, temperate, cold, and arid climate zones. Lines represent linear trends while shading indicates uncertainty (± 1σ) due to among-model variability for CMIP5 and model parameterization for satellite estimates. Box and whisker plots (right panels), show the distribution of estimates for the full time period. For comparison, the CMIP5 model that considered nutrient constraints (dashed green line; green circle) is shown separately. Letters indicate statistically significant differences in distributions at $\alpha = 0.05$. 

Year
Supplementary Figure 5. Spatial and latitudinal correlation between terrestrial net primary productivity (NPP) and minimum temperature (TMIN) from 1982 to 2011. a. CMIP5\textsubscript{CO2+CLIM}, b. CMIP5\textsubscript{CLIM}, and c. satellite estimates. In the latitudinal plots (right panels), shading indicates uncertainty (± 1σ) due to among-model variability for CMIP5 and model parameterization for satellite estimates. For comparison, the CMIP5 model that considered nutrient constraints (CESM1-BGC; top panel, dashed line), satellite VOD (bottom panel, dotted line), and satellite FPAR (bottom panel, dashed line) are shown separately.
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Supplementary Figure 6. Spatial and latitudinal correlation between terrestrial net primary productivity (NPP) and vapor pressure deficit (VPD) from 1982 to 2011 a. CMIP5CO2+CLIM, b. CMIP5CLIM, and c. satellite estimates. In the latitudinal plots (right panels), shading indicates uncertainty (± 1σ) due to among-model variability for CMIP5 and model parameterization for satellite estimates. For comparison, the CMIP5 model that considered nutrient constraints (CESM1-BGC; top panel, dashed line), satellite VOD (bottom panel, dotted line), and satellite FPAR (bottom panel, dashed line) are shown separately.
Supplementary Figure 7. Change in the sensitivity of CMIP5 terrestrial net primary productivity (NPP) to vapor pressure deficit (VPD) and change in the variance of NPP and VPD from 1982 to 2011. a.-c. Tropical, d.-f. temperate, g.-i. cold, and j.-l. arid climatic zones. The change in the sensitivity of NPP to VPD was calculated as the unit change in NPP per unit change in VPD using a 10-year sliding window. The change in the variance of NPP and VPD was also calculated using a 10-year sliding window. Lines represent linear trends while shading indicates uncertainty (± 1σ) due to among-model variability.
Supplementary Figure 8. Change in the sensitivity of satellite-derived terrestrial net primary productivity (NPP) to vapor pressure deficit (VPD) and change in the variance of NPP and VPD across climate zones from 1982 to 2011. a.-c. Tropical, d.-f. temperate, g.-i. cold, and j.-l. arid climatic zones. The change in the sensitivity of NPP to VPD was calculated as the unit change in NPP per unit change in VPD using a 10-year sliding window. The change in the variance of NPP and VPD was also calculated using a 10-year sliding window. Lines represent linear trends while shading indicates uncertainty (±1σ) due to among-model variability. For comparison, the change in sensitivity of FPAR to VPD (cyan lines) is shown separately.