CO₂ fertilization and the global carbon cycle

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For over a millennium these old trees grew in an atmosphere with nearly unchanging \([\text{CO}_2]\) (~280 ppm)
The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.
IPCC’s Fourth Assessment Report documents changes in physical and biological systems that are more rapid than projected in the Third Assessment Report.

Observations of global GHG emissions show rates above even the most severe of the current projections.

New simulations with improved ecosystem processes show a potential for >1000 ppm even with optimistic emission scenarios.
Future Climate Simulations

Multi-Model Averages and Assessed Ranges for Surface Warming

Global surface warming (°C)

Year

Future Climate Simulations

about 2.5° C
The Global Carbon Cycle

About half the CO$_2$ released by humans is absorbed by oceans and land.

“Missing” carbon is hard to find among large natural fluxes.

Thanks to Scott Denning, CSU
Present Value of Carbon Sinks

- Terrestrial and marine exchanges currently remove more than 4 GtC per year from the atmosphere.
- This free service provided by the planet constitutes an effective 50% emissions reduction, worth $400 Billion per year at today’s price on the ECX! (27.43 Euros/ton CO$_2$)
- Carbon cycle science is currently unable to quantitatively account for
  - The locations at which these sinks operate
  - The mechanisms involved
  - How long the carbon will remain stored
  - How long the sinks will continue to operate
  - Whether there is anything we can do to make them work better or for a longer time
Where Has All the Carbon Gone?

• Into the **oceans**
  - **Solubility pump** (CO$_2$ very soluble in cold water, but rates are limited by slow physical mixing)
  - **Biological pump** (slow “rain” of organic debris)

• Into the **land**
  - **CO$_2$ Fertilization**
    (plants eat CO$_2$ ... is more better?)
  - **Nutrient fertilization**
    (N-deposition and fertilizers)
  - **Land-use change**
    (forest regrowth, fire suppression, woody encroachment ... but what about Wal-Marts?)
  - **Response to changing climate**
    (e.g., Boreal warming)
The Oceans
Components of the ocean C cycle

Diffusion into surface ocean

Carbonate chemistry dynamics

Ecosystem food web processes

Biological pump - export of “new” production

Thermo-haline dynamics - physical mixing, circulation

Sedimentation
Rapid Cycling

Respiration

Sinking flux to sediments

Dissolved Organics

CO₂ → Respiration → Dissolved Organics → Sinking flux to sediments
Ocean thermo-haline dynamics
The Land
Different processes are important at different time scales

- **CO2**
- **GPP**

**Plant respiration**
- **Short-term carbon uptake**
  - NPP 60 Pg/y

**Soil and litter respiration**
- **Medium-term carbon storage**
  - NEP 10 Pg/y

**Disturbance**
- **Long-term carbon storage**
  - NBP 1–2 Pg/y

Conversion of tropical forests to pasture
• Releases stored C
• Remove C sink
• Trades CO₂ for CH₄
Agricultural Development & Abandonment

• Land clearing in 18th and 19th centuries released large amounts of CO₂ to atmosphere

• Shift of agriculture to Midwest and California in 20th century

• Regrowing forests are a carbon sink

ED model result: Moorcroft et al (2001)
Ecosystem Succession

\[
\frac{dC}{dt} = NEP \approx NPP - R_h
\]

Woodwell and Whittaker, 1968
We know how trees respond to elevated CO$_2$

There is a wealth of data from many CO$_2$ enrichment studies demonstrating physiological responses of seedlings and young trees

- Elevated CO$_2$ stimulates photosynthesis
- Stomatal conductance often is lower
- Trees grow faster in elevated CO$_2$ and are bigger at the end of the experiment
The large size and long life of trees preclude direct assessment of CO$_2$ fertilization of intact, mature forests.

Scale: the big challenge

Are data from short-term experiments with young trees relevant to questions about the global C cycle?
Questions of scale dominate global change research

Trees and forests create particularly challenging experimental subjects
Extrapolation of experimental results from young trees and seedlings can lead to a false view of forest response.

Wide variation in response is difficult to explain or summarize.

Belowground productivity is too often ignored.

Current free-air CO₂ enrichment (FACE) studies help to resolve some of the uncertainty.
FACE experiments provide valuable data for projecting future global carbon cycling.

Free-air CO₂ enrichment (FACE) experiments are the best source of data to inform models.
Oak Ridge Experiment on CO$_2$ Enrichment of Sweetgum
A FACE experiment in a deciduous forest

Goal

• To understand how the eastern deciduous forest will be affected by CO$_2$ enrichment of the atmosphere, and what are the feedbacks from the forest to the atmosphere

• This goal will be approached by measuring the integrated response of an intact forest ecosystem, with a focus on stand-level mechanisms

http://face.ornl.gov
Calculation of Net Primary Productivity

Stem
Allometry: $DM = f(BA, H, \text{taper, density})$

Coarse root
Allometry: $DM = f(BA)$

Fine root
Minirhizotrons and in-growth cores

Leaf
Litter traps

Understory
Harvest
Oak Ridge Experiment on CO₂ Enrichment of Sweetgum

Net primary productivity

CO₂ has stimulated NPP
Average increase is 23%
The response has been declining in the last several years

Graph showing net primary productivity (NPP) from 1997 to 2007. The graph compares ambient and elevated CO₂ conditions. The average increase in NPP is 23%. The response has been declining in the last several years.
Photosynthesis under prevailing conditions relative to canopy position

- Photosynthetic rates at the top of the canopy were generally 30-70% higher in elevated CO₂
- Photosynthetic enhancement occurred at all canopy positions
- Foliar N concentration is lower, but photosynthetic N use efficiency is higher
- Leaf area and light absorption are not increased, but light-use efficiency is
**Forest FACE Synthesis Project**

**Objectives:**

- Quantify CO₂ effect on NPP in a manner that will inform ecosystem and global models
- Quantify N uptake, N-use efficiency, and related expressions of C-N interaction
- Look for general patterns of response that apply across diverse sites

Four experiments in which forest stands exposed to ~550 ppm CO₂ for 3-8 years

**Closed-canopy**
- DukeFACE (NC) – loblolly pine
- ORNL-FACE (TN) – sweetgum

**Developing stands**
- AspenFACE (WI) – aspen/birch
- PopEuroFACE (Italy) – poplars
Good fellowship....

....good science
NPP increased in elevated CO$_2$ across a wide range of NPP

- Regression is significantly different from 1:1 line
- Regression defines a median response of 23% enhancement
- Response is robust across a wide range of NPP
- Provides a critical benchmark for ecosystem and global models
- But the data all are from temperate forests

Norby et al. (2005) PNAS 102: 1805
Congruence of model and data on NPP response adds confidence to subsequent model results that depend on the biosphere-atmosphere feedback

- Modeled increase in NPP is reduced when combined with climate change
- Prediction of NEP depends on accurate representation of NPP
- CO₂ fertilization allows for uptake of 35% of C emissions from 1991 to 2100, reduced to 23% when combined with climate change

But atmospheric CO₂ will continue to increase!

Experimental results provide a benchmark for global models

<table>
<thead>
<tr>
<th>NPP enhancement (%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FACE experiments</td>
<td>23 +/- 2</td>
</tr>
<tr>
<td>Global forests</td>
<td>24.5 +/- 0.06</td>
</tr>
<tr>
<td>Boreal forests</td>
<td>15.1 +/- 0.06</td>
</tr>
<tr>
<td>Temperate forests</td>
<td>25.7 +/- 0.14</td>
</tr>
<tr>
<td>Tropical forests</td>
<td>35.1 +/- 0.09</td>
</tr>
</tbody>
</table>

Fig. 2 Geographic pattern of the simulated NPP enhancement resulting from a step increase of CO₂ from ambient to 550 ppmv; NPP values averaged over 1996-2002.


Experiments in tropical and boreal ecosystems may be an important priority
This analysis does not resolve all issues about forests in a CO$_2$-rich world

- The median response masks spatial and temporal variability
- Interactions with other global change factors may be significant
- The analysis did not include tropical or boreal forests
- Will responses persist in more mature forests?
- C partitioning patterns may determine the ultimate fate of the additional C
- N feedbacks might limit response over the long term

It’s time to look below ground!
Calculation of N Uptake

**N uptake** = N content of current year wood
  + N content in live canopy – amount resorbed from previous year
  + amount used in fine-root production

**Peak N content** = amount in all wood
  + N content of canopy at peak mass
  + N content of fine roots at peak mass

**Data**
Concentration of N in green leaves, leaf litter, fine roots, and wood

[N] combined with biomass data to calculate N content

**NUE** = NPP / N uptake
**N productivity** = NPP / N content
**MRT** = N content / N uptake
**NUE = Nprod \times MRT**
Nitrogen-use efficiency describes the relationship between NPP and N uptake

• Within a site, both NPP and N uptake are generally higher in elevated CO₂.

• Exception: N uptake was not increased in the irrigated, fast-growing Euro-PopFACE experiment.

• Within a site, data generally align along a constant NUE isopleth.

• NUE is greater in the older stands.
Nitrogen uptake is the first point of interaction between soil N and plant N

- N uptake increased significantly in elevated CO₂
- Increased uptake was not associated with any measured effect on microbial N metabolism
- Increased root exploration is indicated
Nitrogen-use efficiency is often assumed to increase in elevated CO$_2$ -- *not supported by our data*

- There was no response of NUE to elevated CO$_2$
- Understanding and predicting N uptake should be a key objective for modeling NPP response to elevated CO$_2$
The Atmosphere
Coupled simulations of climate and the carbon cycle

Given nearly identical human emissions, different models project dramatically different futures!
Responses vary across the land surface

Responses to climate change due to vegetation change
# Coupled Carbon Cycle Climate Model Intercomparison Project (C^4MIP) used in IPCC AR4

<table>
<thead>
<tr>
<th>Model</th>
<th>Sensitivity of Vegetation NPP to CO_2: % change for a CO_2 doubling</th>
<th>Sensitivity of Vegetation NPP to Climate: % change for a 1°C increase</th>
<th>Sensitivity of Specific Heterotrophic Respiration Rate to Climate: % change for a 1°C increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. HadCM3LC</td>
<td>57</td>
<td>-5.8</td>
<td>10.2</td>
</tr>
<tr>
<td>B. IPSL-CM2C</td>
<td>50</td>
<td>-4.5</td>
<td>2.3</td>
</tr>
<tr>
<td>C. MPI-M</td>
<td>76</td>
<td>-4.0</td>
<td>2.8</td>
</tr>
<tr>
<td>D. LLNL</td>
<td>73</td>
<td>-0.4</td>
<td>7.0</td>
</tr>
<tr>
<td>E. NCAR CSM-1</td>
<td>34</td>
<td>0.8</td>
<td>6.2</td>
</tr>
<tr>
<td>F. FRCGC</td>
<td>21</td>
<td>1.2</td>
<td>7.2</td>
</tr>
<tr>
<td>G. UVic-2.7</td>
<td>47</td>
<td>-2.3</td>
<td>6.5</td>
</tr>
<tr>
<td>H. UMC</td>
<td>12</td>
<td>-1.6</td>
<td>4.8</td>
</tr>
<tr>
<td>I. BERN-CC</td>
<td>46</td>
<td>1.2</td>
<td>8.7</td>
</tr>
<tr>
<td>J. CLIMBER2-LPJ</td>
<td>44</td>
<td>1.9</td>
<td>9.4</td>
</tr>
<tr>
<td>K. IPSL-CM4-LOOP</td>
<td>64</td>
<td>-0.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Mean</td>
<td>48</td>
<td>-1.3</td>
<td>6.2</td>
</tr>
<tr>
<td>Std Dev</td>
<td>±20</td>
<td>±2.6</td>
<td>±2.7</td>
</tr>
</tbody>
</table>
Figure 7.14. Uncertainties in carbon cycle feedbacks estimated from analysis of the results from the CMIP models. Each effect is given in terms of its impact on the mean airborne fraction over the simulation period (typically 1860 to 2100), with bars showing the uncertainty range based on the ranges of effective sensitivity parameters given in Tables 7.4 and 7.5. The lower three bars are the direct response to increasing atmospheric CO₂ (see Section 7.3.5 for details), the middle four bars show the impacts of climate change on the carbon cycle, and the top black bar shows the range of climate-carbon cycle feedbacks given by the CMIP models.
The first-generation C4MIP models excluded the effects of forest fires and prior land use change
- forest regrowth may account for a large part of the land carbon sink in some regions
- combustion of vegetation and SOM may be responsible for a significant fraction of the interannual variability in CO₂

Modeling of other processes is even less straightforward and was not included
- N cycling on the land
- impacts of increasing ozone concentrations on plants

There must be a continued dialogue between experiments and models
Summary

• Emissions of CO₂ by global industry are part of a much bigger biogeochemical cycle of carbon

• About half of anthropogenic CO₂ emissions are removed from the atmosphere by perturbations to natural biogeochemistry that are not completely understood

• Uncertainties in future human emissions and in the response of global biogeochemistry to changing climate are among the leading sources of uncertainty in predictions of 21st century climate