Carbon Cycling in Tropical and Boreal Forests

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Is the increase in global mean temperature a result of increases in Greenhouse gases (CO₂, CH₄, N₂O)?

From: IPCC, Third Assessment Report, 2000
The Global Carbon Budget: Terms we know well

GigaTons Carbon per year

<table>
<thead>
<tr>
<th>CO₂ Sources</th>
<th>CO₂ sinks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel emission</td>
<td>Increase in atmospheric CO₂</td>
</tr>
</tbody>
</table>

- Fossil fuel emission: 5 GigaTons Carbon per year
- Increase in atmospheric CO₂: 3 GigaTons Carbon per year
Fossil fuel emission

Increase in atmospheric CO₂

Uptake by oceans

GigaTons Carbon per year

The Global Carbon Budget: Terms we kind of know

CO₂ Sources

CO₂ sinks
The Global Carbon Budget: Terms we *don’t know well*

- **GigaTons Carbon per year**
  - Tropical deforestation
  - Fossil fuel emission
  - Uptake by Terrestrial Ecosystems
  - Uptake by oceans
  - Increase in atmospheric CO$_2$

**CO$_2$ Sources**

**CO$_2$ sinks**
Big, unanswered questions include:

What ecosystems are storing carbon?

Why are ecosystems storing carbon?

What determines how much carbon an ecosystem stores?

How much longer will ecosystems continue storing carbon?

Kyoto Protocol (1997) - carbon trading, credits for carbon sequestration
## Distribution of Carbon Pools

<table>
<thead>
<tr>
<th>Environment</th>
<th>Area ($10^{12}$ m$^2$)</th>
<th>Plant C (kg C m$^{-2}$)</th>
<th>Soil C (kg C m$^{-2}$)</th>
<th>Total C ($10^{15}$ gC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical forest</td>
<td>18.1</td>
<td>11.5</td>
<td>10.4</td>
<td>400</td>
</tr>
<tr>
<td>Temperate forest</td>
<td>9.2</td>
<td>8</td>
<td>11.8</td>
<td>170</td>
</tr>
<tr>
<td><strong>Boreal forest</strong></td>
<td><strong>15</strong></td>
<td><strong>9.5</strong></td>
<td><strong>14.9</strong></td>
<td><strong>370</strong></td>
</tr>
<tr>
<td>Desert</td>
<td>18.2</td>
<td>0.3</td>
<td>5.6</td>
<td>110</td>
</tr>
<tr>
<td>Tundra</td>
<td>11</td>
<td>0.8</td>
<td>21.6</td>
<td>250</td>
</tr>
<tr>
<td>Wetland</td>
<td>2.9</td>
<td>2.7</td>
<td>68.6</td>
<td>210</td>
</tr>
</tbody>
</table>

**Global** ~2000

Tropical and boreal forests account for about 50% of terrestrial carbon

Tropical forest carbon is in biomass, boreal is in soil.
Net Ecosystem Exchange (NEE)

\[ \text{NEE} = \text{Photosynthesis} - \text{Respiration} \]

- Sign: ??
  - (big negative #)
  - (big positive #)

Diagram of a tree with arrows indicating the exchange processes.
How to track the carbon balance?

Land use monitoring: satellite surveys

Study intact forests: biometry (takes a long time) <--

Study the CO$_2$ budget:

    small scale: chambers (1 m$^2$)

    tower scale: several km$^2$, turbulence method. <--

    region/synoptic scale: 1000’s km$^2$, budget methods.
Species Conservation Equation

ASSUMING 1-D forest-atmosphere coupling

\[
\text{NEE} = F_c + S
\]

Turbulent flux  \quad \text{Storage “flux”}

Control volume

\[ S = \frac{dC}{dt} \]
Eddy Covariance

• **Direct** measurement of turbulent flux, $F_c = \langle w'c' \rangle$

• High **Precision**

• Large **Footprint** (many km$^2$)
Example (2 days)

Fluxes are calculated each **30 minutes**.

Units of flux are **micromoles CO$_2$ m$^{-2}$ s$^{-1}$**

![Graph showing Sunlight, Nighttime Respiration, Daytime Photosynthesis over two days.]

- Sunlight flux varies significantly throughout the day, peaking during daylight hours.
- Nighttime respiration shows a decrease in CO$_2$ exchange.
- Daytime photosynthesis is evident with an increase in CO$_2$ exchange.

**Notes:**
- Fluxes are calculated every 30 minutes.
- Units for flux are micromoles CO$_2$ m$^{-2}$ s$^{-1}$.
- Graphs illustrate the diurnal cycle of CO$_2$ exchange in relation to sunlight availability.
How do we use eddy flux data?

1. Classical Approach: Parameterization / modeling

\[ \text{NEE} = f(\text{PAR}, T, \text{soil h2o}, \text{etc}) \]
How do we use eddy flux data?

2. Direct Approach: Integrate long (years), continuous flux data sets to calculate directly a site carbon budget

Requires accuracy of fluxes (difficult)!
How do we use eddy flux data?

3. Response: to perturbation, e.g. logging, fire.

Requires precision, eddy covariance well suited!
Objective in Tropical Forest

• **Classic Approach:** understand factors controlling CO$_2$ exchange (Goulden et al, 2002).

• **Direct Approach:** integrate long term measurements - is undisturbed forest a carbon **source** or **sink**? (Miller et al, 2002).

• **Response:** How does **Selective-Logging** affect CO$_2$ cycling in tropical forest. Stay tuned...
Previous tower-based annual carbon budgets in primary tropical forest

<table>
<thead>
<tr>
<th>Site</th>
<th>Reference</th>
<th>NEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhondonia</td>
<td>Grace et al. 1996</td>
<td>-1</td>
</tr>
<tr>
<td><strong>Manaus</strong></td>
<td><strong>Malhi et al. 1998</strong></td>
<td><strong>-5.9</strong></td>
</tr>
<tr>
<td>Several Sites</td>
<td>Kabat 2000</td>
<td>-3 to -7</td>
</tr>
</tbody>
</table>

**Units:** Tons of Carbon per hectare per year \([\text{T C ha}^{-1} \text{ yr}^{-1}]\)

Recall, **unknown global terrestrial sink** is about **2 Gt C yr\(^{-1}\)**

Amazon Basin is about **6 million km\(^2\)**

Carbon sink of about **3-4 T C ha\(^{-1} \text{ yr}^{-1}\)** across the Amazon would account for the entire unknown **global** terrestrial sink!

**Question:** Are the tower-based annual sums **accurate**?
LBA-Ecology Sites

Santarem, Para

LBA = Large Scale Biosphere-Atmosphere Experiment in Amazonia
Experimental Plan

Logged Site

Tapajos River

Control Site

Wind dir

INDEX MAP
Sanatogen, PA

60 km

16 km
Tower Measurements

**METEOROLOGY**

PAR (up/down)
Radiation (short and long wave, up and down)
Rain

**PROFILES**

Wind (6 levels cups and 2D Sonics)
Temperature (6 levels)
CO$_2$/H$_2$O (12 levels)

**FLUXES (64 meters)**

Momentum/Heat
CO$_2$/H$_2$O

sonic anemometer
Infrared Gas Analyzer
Sonic anemometer looks **East**, the most common wind direction.
Elevator to raise and lower eddy flux sensors.
KM 83: JULY 2000-SEPT 2001

Data chart showing trends for Wind Spd, Wind Dir, Temp, Rnet, HS, HL, Fc, and SOIL H2O RAIN from July 2000 to September 2001.
We measure a large carbon sink, similar to previous reports. Sink of $-4$ across Amazonia will absorb entire global carbon budget deficit.
How confident can we be in this result?

Case 1: TRUE

Where is the Carbon going?

♦ Trees (Biometry)? (Malhi et al., 1998)
♦ Soil? (Malhi et al., 1999)
♦ Rivers? (Richey et al, 2002)

Case 2: FALSE

Is there a bias in the tower-based measurement?

• Hardware/software techniques?
• Meteorological bias?
Trees: Ground Based Inventories

Tree inventories (diameter, DBH>55cm) quantify carbon density

- 1984 Tree biomass 105 Tons Carbon per hectare
- 2000 Tree biomass 106

Over 16 years, carbon was essentially neutral (not a source or sink).

Soil: Isotopes

0 +/- 0.5 T C ha⁻¹ yr⁻¹ (Trumbore)

Biometric Summary

0 +/- 1.5 T C ha⁻¹ yr⁻¹

Tower --> 4 T C ha⁻¹ yr⁻¹
How confident can we be in this result?

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Case 2: FALSE

Is there a bias in the tower-based measurement?

• Hardware/software techniques?
• Meteorological bias?
Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO₂


School of Oceanography, University of Washington, Seattle, Washington 98195, USA
Institute for Computational Earth System Science, University of California, Santa Barbara, California 93106, USA
Centro de Energia Nuclear na Agricultura, Caixa Postal 96, Piracicaba SP, Brazil

How does carbon get to the river?

Malhi/Grace viewpoint

1.2 T C ha⁻¹ yr⁻¹
How confident can we be in this result?

Case 1: TRUE

Where is the Carbon going?

♦ Trees (Biometry)? (Malhi et al., 1998)
♦ Soil? (Malhi et al., 1999)
♦ Rivers? (Richey et al., 2002)

Case 2: FALSE

Is there a bias in the tower-based measurement?

• Hardware/software techniques?
• Meteorological bias?
Hardware and Software techniques have a small effect...

Rotations, averaging time, open/closed path systems, high frequency corrections, density corrections

Envelope for 6 “defensible” hardware/software combinations

1 YEAR
And there remains a large gap between tower and biometric estimates of carbon exchange.
How confident can we be in this result?

Case 1: TRUE

Where is the Carbon going?

- Trees (Biometry)? (Malhi et al., 1998)
- Soil? (Malhi et al., 1999)
- Rivers? (Richey et al., 2002)

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Is there a bias in the tower-based measurement?

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Species Conservation Equation

**ASSUMING 1-D forest-atmosphere coupling**

\[
\text{NEE} = F_c + S
\]

- Turbulent flux
- Storage “flux”

\[
S = \frac{dC}{dt}
\]

Control volume
Nighttime above the forest is **very stable**, and mixing is not necessarily turbulent (Fitzjarrald et al. 1998)
Species Conservation Equation

ASSUMING 1-D forest-atmosphere coupling

\[ \text{NEE} = F_c + S \]

Turbulent flux \hspace{1cm} Storage “flux”

Control volume

\[ S = dC/dt \]
Species Conservation Equation

ASSUMING 1-D forest-atmosphere coupling

$$\text{NEE} = F_c + S + ???$$

Turbulent flux  Storage “flux”

Control volume

$$S = \frac{dC}{dt}$$
Can we trust the towers?

**u*** correction

**Assumption:** nighttime respiration and turbulent mixing above the forest are **independent**

**Procedure:** **reject** flux data during **calm nights**

**Difficulty:** **Most** nights are **very calm**. What cutoff **u*** to use?
Using this “filter” dramatically changes the annual sum!
Our best estimate (corrected tower, plus biometry)

$\sim 0 \text{ T C ha}^{-1} \text{ yr}^{-1}$ (approximately carbon neutral)

but, because of the poorly understood nighttime exchange. we assign a very large uncertainty, with limits of

-5.2 to +1

Uncertainty spans 6 T C ha$^{-1}$ yr$^{-1}$, compared to only 0.5 T C ha$^{-1}$ yr$^{-1}$ in boreal forests.

Why is the uncertainty so large?
Tower-based Annual sums in Tropical forest are less certain than other forest types because:

*high productivity, long growing season, calm nights*
Can we trust the towers?

**u* correction**

Assumption: nighttime respiration and turbulent mixing above the forest u* are **independent**

Procedure: **reject** flux data during **calm nights**

Difficulty: **Most** nights are **very calm**. What cutoff u* to use?
In addition, the tropical nighttime correction is more sensitive to the subjective choice of turbulence threshold.
What next?

Continue data analysis, including logging effects

Continue ground based surveys

Targeted additional carbon cycle measurements

Additional micrometeorological measurements
Dendrometers measure short term wood increment
What next?

Continue data analysis, including logging effects
Continue ground based surveys
Targeted additional carbon cycle measurements
Additional micrometeorological measurements
Soil respiration (presumably decomposition) strongly affected by rain (presumably litter moisture)

Autochamber measurements of soil respiration

Heavy rains interrupt 2001 dry season
We can make high-resolution soundings with elevator
Sub Canopy Micrometeorology

Above canopy wind easterly, night and day

Night-time low level (1.3 m) wind not aligned with above canopy wind.
Tethered balloon study of CO2 and water vapor accumulation in the stable boundary layer. July 2001 (2nd phase October 2001)

Balloon profiling done by the UFSM team.

L. to R: Otávio Acevedo, Rodrigo da Silva, and Osvaldo Moraes

Original inhabitants of field visit Acevedo.
Conclusions

• July 2000-July 2001 - forest appeared to be carbon neutral.

• Annual CO2 Budget is from towers is difficult.

• Eddy flux (towers) alone is not enough.
Thanks: Marcy Litvak, Fernando Alves Leão, Roberto Cardoso, Antonio Oviedo, Dan Hodkinson, Lisa Zweede and Bethany Reed, IBAMA, NASA and INPE.
Fire plays an integral role in boreal forest ecosystems

Lightning-induced fire in a stand of black spruce between BOREAS NSA and Churchill in 1994

Dominant disturbance in many regions

Fire returns every 50 to 200 years

Maintains boreal landscape as spatial mosaic of forest patches in different successional stages
BOREAS-Northern Study Area Fire history- TM July 25, 1990
Objectives in Boreal Forest

• **Classic Approach**: understand factors controlling CO$_2$ exchange (done in BOREAS).

• **Direct Approach**: integrate long term measurements - a carbon source or sink (done in BOREAS)?

• **Response**: How does forest CO$_2$ cycle recover after fire?
Hypothesis: Recovery from Fire

![Diagram showing the recovery process from fire with carbon source and sink phases labeled.]
BOREAS NSA-Chronosequence Study
1989 burn:
11 years after fire
1981 burn:
19 years after fire
1963 burn: 37 years after fire
1930 burn:
~70 years after fire
1850 burn:
~150 years after fire
Experimental design: 7 identical, solar powered, automated towers running year round

Temperatures are -40 C in winter, +40 C in summer
Logistical challenges

Solar power

**Sunlight**
Summer - ~20 hours
Winter - ~4 hours
Logistical challenges

Sites are several km from nearest road
Logistical challenges

Access to sites during 6 months of winter is limited.

Data is transmitted via GOES satellite link, every 3 hours.
Logistical challenges

Equipment box is buried beneath soil, and covered by snow during winter.

Box temperature remains about 20 C when ambient temp is -40 C.
Comparison of Summer Diurnal CO$_2$ fluxes

Time of day (hour)

Mean CO$_2$ flux (µmol m$^{-2}$ s$^{-1}$)

1989
1981
1964
1930
1850