Global Carbon Trends

Pep Canadell
Global Carbon Project
CSIRO Marine and Atmospheric Research
Canberra, Australia
1. Recent Trends
2. Perturbation Budget
3. Sink Efficiency
4. Attribution
5. Processes
6. Future
1. Recent Trends
Carbon Emissions from Net Deforestation

Tropical deforestation

13 Million hectares each year

Trees are worth more dead than alive

2000-2005

Tropical Americas  0.6 Pg C y\(^{-1}\)
Tropical Asia  0.6 Pg C y\(^{-1}\)
Tropical Africa  0.3 Pg C y\(^{-1}\)

1.5 Pg C y\(^{-1}\)
Historical C Emissions from Net Deforestation

Carbon Emissions from Tropical Deforestation

2000-2006
1.5 Pg C yr⁻¹
(18% total emissions)

Pg C yr⁻¹


Africa
Latin America
S. & SE Asia
SUM

Houghton, unpublished; Canadell et al. 2007, PNAS
Carbon Emissions from Fossil Fuel

2006 Fossil Fuel: 8.4 Pg C

[Total Anthrop. Emis.: 8.4 + 1.5 = 9.9 Pg]

1990 - 1999: 1.3% y⁻¹

2000 - 2006: 3.3% y⁻¹

Raupach et al. 2007, PNAS; Canadell et al 2007, PNAS
Global Fossil Fuel Emissions

Raupach et al. 2007, PNAS

CO₂ Emissions (GtC y⁻¹)

Actual emissions: CDIAC
Actual emissions: EIA
450ppm stabilisation
650ppm stabilisation

A1FI
A1B
A1T
A2
B1
B2

SRES (2000) growth rates in % y⁻¹ for 2000-2010:
A1B: 2.42
A1FI: 2.71
A1T: 1.63
A2: 2.13
B1: 1.79
B2: 1.61

Observed 2000-2006 3.3%

Raupach et al. 2007, PNAS
Drivers of Anthropogenic CO$_2$

Factor (relative to 1990)

- Emissions
- Population
- Wealth = per capita GDP
- Carbon intensity of GDP

World

Raupach et al 2007, PNAS
Regional Pathways

C emissions
Population
Wealth pc
C Intensity

USA
EU
Japan
D1 Developed Countries (-)
FSU
China
India
D2 Developing Countries
D3 Least Developed Countries

Raupach et al 2007, PNAS
Regional Pathways

Raupach et al 2007, PNAS
Regional Pathways

- USA: C emissions, Population, Wealth pc, C Intensity
- EU: Graphs showing changes over time
- Japan: Graphs showing changes over time
- D1 Developed Countries (-)
- FSU: Graphs showing changes over time

Raupach et al 2007, PNAS
Regional Pathways

Raupach et al 2007, PNAS

Regional Pathways

USA

Population

Wealth pc

C emissions

C Intensity

Developed Countries (-)

Developing Countries Least Developed Countries

Wealth pc

Population

C emissions

C Intensity

Developed Countries (-)

FSU

China

India

Regional Pathways

Raupach et al 2007, PNAS
Year 2007
Atmospheric CO₂ concentration: 382.6 ppm
35% above pre-industrial

1970 – 1979: 1.3 ppm y⁻¹
1980 – 1989: 1.6 ppm y⁻¹
1990 – 1999: 1.5 ppm y⁻¹
2000 - 2006: 1.9 ppm y⁻¹

NOAA 2007; Canadell et al. 2007, PNAS
2. Perturbation Budget
Anthropogenic Perturbation of the Carbon Budget

Le Quere unpublished; Canadell et al. 2007, PNAS
Anthropogenic Perturbation of the Carbon Budget

Le Quere unpublished; Canadell et al. 2007, PNAS
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Le Quere unpublished; Canadell et al. 2007, PNAS

CO₂ flux (Pg C y⁻¹)

Sink Source

fossil fuel emissions
deforestation
atmospheric CO₂

Time (y)

1850 1900 1950 2000

2000-2006

7.6
1.5
4.1
Anthropogenic Perturbation of the Carbon Budget

<table>
<thead>
<tr>
<th>Time (y)</th>
<th>Sink Source</th>
<th>CO₂ flux (Pg C y⁻¹)</th>
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<td>2000-2006</td>
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Le Quere unpublished; Canadell et al. 2007, PNAS
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</tr>
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Le Quere unpublished; Canadell et al. 2007, PNAS
Fate of Anthropogenic CO₂ Emissions (2000-2006)

- Atmosphere: 45%
- Land: 30%
- Oceans: 25%

Canadell et al. 2007, PNAS
Natural CO$_2$ sinks are a service provided by the planet which constitutes an effective 55% emissions reduction NOW worth US$300 Billions per year if we had to provide it through mitigation measurements (assuming $20/ton CO$_2$-equivalents).
3. Sink Efficiency
Increase in the fraction of anthropogenic emissions that stays in the atmosphere.

**Dynamics of the Airborne Fraction**

- **Emissions** 1 tCO₂
  - 440 Kg stay
  - 450 Kg stay

**A) Atmosphere**

Canadell et al. 2007, PNAS
Dynamics of the Airborne Fraction

Historical vs. C4MIP Modelled Airborne Fraction

% Change AF

Friedlingstein et al. 2007, unpublished
Efficiency of Natural Sinks

Land Fraction

Ocean Fraction

Canadell et al. 2007, PNAS
4. Attribution
Attribution of Recent Acceleration of Atmospheric CO$_2$

- 1970 – 1979: 1.3 ppm y$^{-1}$
- 1980 – 1989: 1.6 ppm y$^{-1}$
- 1990 – 1999: 1.5 ppm y$^{-1}$
- 2000 - 2006: 1.9 ppm y$^{-1}$

65% - Increased activity of the global economy

17% - Deterioration of the carbon intensity of the global economy

18% - Decreased efficiency of natural sinks
5. Processes
Factors Affecting the Airborne Fraction

1. The rate of CO$_2$ emissions.

2. The rate of CO$_2$ uptake and ultimately the total amount of C that can be stored by land and oceans:
   - **Land:**
     - (-) CO$_2$ fertilization effect, forest regrowth (woody encroachment N deposition fertilization, ...)
     - (+) soil respiration, fire, ...
   - **Oceans:**
     - (-) CO$_2$ solubility (temperature, salinity), ...
     - (+,-) ocean currents, stratification, winds, biological activity, acidification, ...
Half of the decline is attributed to up to a 30% decrease in the efficiency of the Southern Ocean sink over the last 20 years.

It is attributed to the strengthening of the winds around Antarctica which enhances ventilation of natural carbon-rich deep waters.

The strengthening of the winds is attributed to global warming and the ozone hole.
Effects of Drought and Warmer $T^a$ on Carbon Sinks

Major droughts in mid-latitudes, particularly summer
Warmer temperatures, particularly in autumn.

**Summer 1982-1991**

**Summer 1994-2002/04**

NDVI Anomaly 1982-2004
[Normalized Difference Vegetation Index]

Angert et al. 2005, PNAS; Buermann et al. 2007, PNAS; Ciais et al. 2005, Science
6. Future
Vulnerability of Carbon Pools in the 21st Century

Hot Spots of the Carbon-Climate System

Many of these Pools and Processes are not included in Earth System models.
Permafrost

200-400 Pg C - frozen soils vulnerable to warming

Many Pools and Processes not included in Earth System models
Pool Size of Frozen Carbon (C Pg)

Soil or deposit type

<table>
<thead>
<tr>
<th></th>
<th>Soils 0–300 cm</th>
<th>Yedoma sediments</th>
<th>Deltaic deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1024</td>
<td>407</td>
<td>241</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1672</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Permafrost zones

<table>
<thead>
<tr>
<th></th>
<th>0-30 cm</th>
<th>0-100 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>110.38</td>
<td>298.75</td>
</tr>
<tr>
<td>Discontinuous</td>
<td>25.5</td>
<td>67.44</td>
</tr>
<tr>
<td>Sporadic</td>
<td>26.36</td>
<td>63.13</td>
</tr>
<tr>
<td>Isolated Patches</td>
<td>29.05</td>
<td>67.10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>191.29</strong></td>
<td><strong>496.42</strong></td>
</tr>
</tbody>
</table>

Tarnocai et al, in preparation
Peatlands

400 Pg C – cold peatlands vulnerable to climate change

100 Pg C – tropical peatlands vulnerable to land use and climate change
ENSO-Drought x Land Use x Fire

Atmospheric CO$_2$ Growth Rate

Oct 1998 - Sept 1999

Flux Anomalies La Niña (g C m$^2$ yr$^{-1}$)

Rodenbeck et al. 2003; Rodenbeck et al. 2004
Drought x Land Use x Disturbances

Hot Spots of the Carbon-Climate System

>200 Pg C vegetation and soils vulnerable to drought x land use x fire

Many Pools and Processes not included in Earth System models

Field and Raupach 2004
Canadell et al. 2007
Increased Fire Emissions of Carbon

Mouillot et al. 2006

Increased Fire Emissions of Carbon

Mouillot et al. 2006

Increased Fire Emissions of Carbon

Mouillot et al. 2006
Annual Net C balance of Canada’s Managed Forests

Kurz et al. 2008, PNAS
Methane Hydrates
7. Conclusions
Since 2000:

• The growth of carbon emissions from fossil fuels has tripled compared to the 1990s and is exceeding the predictions of the highest IPCC emission scenarios.

• Atmospheric CO$_2$ is growing at 1.9 ppm per year (compared to about 1.5 ppm during the previous 30 years)

• The carbon intensity of the world’s economy has ceased to improve (after 100 years of doing so).
Conclusions (ii)

- The efficiency of natural sinks has decreased by 5% over the last 50 years (and will continue to do so in the future), implying that the longer it takes us to reduce emissions, the larger the cuts needed to stabilize atmospheric CO$_2$.

- Uncertainties on the stability of large Earth carbon pools shows the real potential for significant carbon-climate feedbacks not currently account in climate models.