The Carbon Cycle as a Grand Challenge

Chris Jones
Research fellow, Met Office Hadley Centre

Forest Dynamics in the Anthropocene, AGCI Workshop.
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Overview

• Why is the carbon cycle a Grand Challenge?
  • “Why do we care?”

• How do carbon sinks help us set/achieve climate targets?
  • “natural” carbon sinks & the remaining carbon budget

• How can we use carbon sinks to mitigate climate change?
  • “managed” carbon sinks & land-based mitigation
  • “nature based solutions” / “natural climate solutions”
  • how do carbon sinks respond to reducing CO2?

• Where are the uncertainties and research priorities?
The carbon cycle as a Grand Challenge

“Climate research must sharpen its view”

- Human activity is changing Earth's climate. ... this has been acknowledged and accepted in international negotiations ...

- <we need to> ... cast the challenges ahead into a few simple yet powerful guiding questions:
  - first, where does the carbon go?
• WCRP Grand Challenge on Carbon Feedbacks in the Climate System

• What ... processes ... control land and ocean carbon sinks?

• Can ... climate-carbon feedbacks amplify climate changes ...?

• How will ... land and ocean carbon reservoirs respond to ... changes?

https://www.wcrp-climate.org/grand-challenges/gc-carbon-feedbacks
Total CO$_2$ emissions are strongly linked to total warming

- A key message from last IPCC report (AR5: 2013/14)
- Long-term warming is linearly related to total emissions of CO$_2$.
- For a given warming target, higher emissions now imply lower emissions later.

TCRE: Transient Climate Response to cumulative carbon Emissions

- Allows us to quantify exactly what we must do to meet targets
- Carbon “budget” we can spend
- Quantifying this drew together ALL of climate science into a single straight line!
Total CO$_2$ emissions are strongly linked to total warming

BUT: substantial uncertainty in this relationship...
• “2 degree” budget ranges from 1000 to 2000 GtCO$_2$
  • (plus or minus a few hundred)
  • perhaps
Why we care #1: carbon cycle controls much of the uncertainty in remaining budget

\[ \text{TCRE} = \text{TCR} \times \text{AF} \]

Climate sensitivity – clouds and stuff

**Airborne fraction** (a.k.a. where does the carbon go?)

- Circa 50% historically
- Very scenario-dependent in future
- Large uncertainty
- Largely determined by land biosphere response to CO2 (so-called “beta” in carbon cycle feedback)

*IPCC WG1, AR5, 2013*
Why we care #2:
If warming linked to emissions, then to stop warming we must stop emissions...
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To reach net zero – CDR required to offset hard-to-abate emissions
- If we exceed in near-term, need global net-negative in long term
- “natural” (AFOLU) CDR vs technological CDR
  - “Natural climate solutions”
The global tree restoration potential

Jean-François Bastin¹, Yeledra Finegold², Claude García³, Danilo Mollicone⁴, Marcelo Rezende⁵, Devin Routhe⁶, Constantin M. Zohner⁷, Thomas W. Crowther⁸

• 1 billion hectares of trees?
• 200 PgC uptake?

'Fake trees' could fight climate change

Forests of "fake trees" should be planted across the country to reduce the impact of climate change, according to a study.

https://science.sciencemag.org/content/365/6448/76
Some sort of land-based mitigation is required to achieve net-zero and/or net-negative emissions

- What is the capacity?
- How quickly can these act?
- How will carbon sinks respond to decreasing CO2?

1 billion hectares of trees?
200 PgC uptake?

https://science.sciencemag.org/content/365/6448/76
Why we care #3:
carbon sinks respond to CO2 removal

What we care about – stabilising climate – depends on the balance of natural and anthropogenic sources and sinks

These are interconnected...
Historical carbon cycle was easy(ish)

We put some in...

...nature took some out

• in approx constant fraction

Here we use CMIP5 simulations to show how the balance of inputs and removals depends on scenario and changes dynamically over coming decades/centuries

\[
\begin{align*}
\text{Fossil fuel & land use} & : +257 \\
\text{Land sink} & : -75 \\
\text{Ocean sink} & : 397 \text{ ppm}
\end{align*}
\]

Negative emissions – or carbon dioxide removal

\[
\begin{align*}
\text{Atmosphere in 1870} & : 288 \text{ ppm} \\
\text{Atmosphere in 2014} & : +109 \text{ ppm}
\end{align*}
\]

Jones et al., ERL, 2016
Fossil fuel / LU

Land / Ocean sink

CO2

RCP8.5
(high emissions)

RCP2.6
(strong mitigation scenario)

Jones et al., ERL, 2016
• So RCP2.6 relative to 8.5:
  • Lower fossil fuel emissions
  • More NETs
  • Perhaps not widely appreciated – much smaller land/ocean sinks (in absolute terms, but they’re bigger fraction of the emissions)

*Jones et al., ERL, 2016*
RCP2.6 second half of 21st century

RCP2.6 50-year moving window

Jones et al., ERL, 2016
RCP2.6
second half of 21st century

RCP2.6
50-year moving window

Jones et al., ERL, 2016
• Human input: positive
• Natural input: negative
• CO₂ decreases because of natural sinks

Jones et al., ERL, 2016
Modelling priorities:
a word on fluxes vs stores

Are we actually making progress in the modelling?
Where do we need development and evaluation effort?
What we’d like...

...what we’ve got

Jones et al., J. Clim., 2013

Anav et al., J. Clim., 2013
Global GPP within ±20-30%
Model spread in biomass

N. Hemi model spread: factor 4

Tropics model spread: factor 2

Anav et al., J. Clim., 2013
Modelling priorities:

a word on fluxes vs stores

- Model evaluation must move beyond fluxes (flux towers are great, but not the whole story...)
- Residence time, carbon stores are what we care about
- “change in store” ≠ “integrated flux”?  
  - different mindset
• The Carbon cycle is a Grand Challenge:

1. “Where does the carbon go?”
   • controlling question which determines carbon budgets

2. Natural climate solutions will rely on land-based mitigation
   • a crucial part of carbon dioxide removal
   • required for reaching net-zero

3. natural and anthropogenic sources and sinks interact
   • Need to quantitatively understand their dynamics and interplay
   • This requires Earth System Models

• Modelling needs care beyond fluxes
  • We care about the stores
  • … and how they respond to environmental changes
• Anav et al., 2013, J. Clim, https://journals.ametsoc.org/view/journals/clim/26/18/jcli-d-12-00417.1.xml
• Bastin et al., 2019, Science, https://science.sciencemag.org/content/365/6448/76
• Jones et al., 2013, J. Clim, https://journals.ametsoc.org/view/journals/clim/26/13/jcli-d-12-00554.1.xml
• Marotzke et al., 2017, Nature Climate Change, https://www.nature.com/articles/nclimate3206
• Pan et al., 2011, Science, https://science.sciencemag.org/content/333/6045/988

• IPCC, AR5, WG1, SPM: http://www.climatechange2013.org/report/full-report/
• IPCC SR15, Ch.2: https://www.ipcc.ch/sr15/chapter/chapter-2/