The role of the terrestrial biosphere in the glacial CO2 problem: Implications for future carbon-climate feedback

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400 thousand years of Climate History

Strong correlation between CO₂ and temperature

Ice core from Vostok, Antarctica
...there is no consensus on what causes ice-age CO$_2$ changes. The sheer number of explanations for the 100,000-year cycle and for CO2 changes seem to have dulled the scientific community into a semi-permanent state of wariness about accepting any particular explanation. This places a great burden of proof on proponents of any particular theory.

T. Crowley (2002)
What caused lower glacial CO$_2$?

- Physical/chemical reorganization of the oceans
  - Temperature, salinity
  - Circulation
  - Sea ice in the southern oceans

- Carbonate chemistry
  - Deep ocean sediments
  - Coral reef

- Changes in biological productivity
  - The iron hypothesis
Land vs. Ocean in glacial-interglacial CO₂ change

Typical partitioning of deglacial CO2 change (Interglacial - Glacial):

• Atmosphere  +180 Gt   (increase)
• Land        +500 Gt   (increase)
• Ocean       -680 Gt   (decrease)

Traditional view: Land is an additional burden of about 30 ppmv that ocean carbon pool has to accommodate.

We suggest: Glacial land carbon storage was larger, not smaller than interglacial, so that land carbon contributes to the CO2 change, thus helping the ocean scenarios. This idea challenges all the three methods of estimating glacial land carbon.
Role of Land

Three Methods of estimating land carbon storage at LGM

1. Marine C13 inference (Shackleton 1977)

2. Paleoecological data, i.e., pollen (Adams et al., 1990)

3. Terrestrial carbon model forced by reconstructed climate (Prentice and Fung 1990)
An example of marine C13 inference:

Present values (approx):
\[ d^{13}C(\text{land}) = -24\% \]
\[ d^{13}C(\text{atmo}) = -6\% \]
\[ d^{13}C(\text{ocean}) = 0\% \]

A 500Gt transfer of land carbon to the ocean implies a lowering of \( d^{13}C(\text{ocean}) \) by 0.35\% at LGM.

Challenge: the dC13 change has alternative explanations (Spero et al., 1997, Lea et al., 2000)
Paleoecological reconstruction

Major differences at LGM:
1. Climate    drier/colder
2. CO2 level  lower
3. Ice sheets  23M km2
   => less carbon on land
4. Continental shelf  18M km2
   => more carbon on land

Overall, much less carbon on land

Challenges:
1. The ‘modern analog’ approach may underestimate soil carbon storage which would be high at lower temperature
2. Nothing under ice?
### Estimates of land carbon storage

<table>
<thead>
<tr>
<th>Source</th>
<th>Method</th>
<th>Land carbon difference</th>
</tr>
</thead>
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<tr>
<td>Shackleton, 1977</td>
<td>ocean δ^{13}C, 0.7 o/oo</td>
<td>1000</td>
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<tr>
<td>Duplessy et al., 1984</td>
<td>ocean δ^{13}C, 0.15 o/oo</td>
<td>220</td>
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<td>Berger and Vincent, 1986</td>
<td>ocean δ^{13}C, 0.40 o/oo</td>
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<td>Curry et al., 1988</td>
<td>ocean δ^{13}C, 0.46 o/oo</td>
<td>650</td>
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<td>Duplessy et al., 1988</td>
<td>ocean δ^{13}C, 0.32 o/oo</td>
<td>450</td>
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<tr>
<td>Broecker and Peng, 1993</td>
<td>ocean δ^{13}C, 0.35 o/oo</td>
<td>425</td>
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<tr>
<td>Bird et al., 1994</td>
<td>ocean δ^{13}C</td>
<td>270-720</td>
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<tr>
<td>Maslin et al., 1995</td>
<td>ocean δ^{13}C 0.40+0.14 o/oo</td>
<td>400-1000 (700)</td>
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<tr>
<td>Beerling, 1999</td>
<td>13C inventory</td>
<td>550-680</td>
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<td>Adams et al., 1990</td>
<td>palaeoecological data</td>
<td>1350</td>
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<tr>
<td>van Campo et al., 1993</td>
<td>palaeoecological data</td>
<td>430-930 (713)</td>
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<td>Crowley et al., 1995</td>
<td>palaeoecological data</td>
<td>750-1050</td>
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<tr>
<td>Adams and Faure, 1998</td>
<td>palaeoecological data</td>
<td>900-1900 (1500)</td>
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<td>Prentice and Fung, 1990</td>
<td>GISS, Holdridge/Carbon Density</td>
<td>-30 to 50</td>
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<td>Sellers, SLAVE</td>
<td>300</td>
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<tr>
<td>Prentice et al., 1993</td>
<td>ECMWF T21, BIOME</td>
<td>300-700</td>
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<tr>
<td>Esser &amp; Lauten, 1994</td>
<td>ECHAM, HRBM</td>
<td>-213 to 460</td>
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<tr>
<td>Friedlingstein et al., 1995</td>
<td>GISS/Sellers, SLAVE</td>
<td>507-717 (612)</td>
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<td>Peng et al., 1995</td>
<td>Pollen Recon., OBM</td>
<td>470-1014</td>
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<td>Francois et al., 1998</td>
<td>ECHAM2, CARAIB</td>
<td>134-606</td>
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<td>Beerling, 1999</td>
<td>UGAMP/NCAR, SDGVM</td>
<td>535-801 (668)</td>
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<td>Otto et al., 2002</td>
<td>4 PMIP models, CARAIB</td>
<td>828-1106</td>
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<td>Kaplan et al., 2002</td>
<td>UM, LPJ</td>
<td>821</td>
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<tr>
<td>This study</td>
<td>CCM1, VEGAS</td>
<td>-407 to -749 (-547)</td>
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</tbody>
</table>

- Marine C13
- Pollen
- Model

270-1000 Gt
430-1900 Gt
-213 to 1106 Gt
Climate effects: Temperature, precipitation and CO2 fertilization

- **Temperature**: Lower decomposition rate leads to higher soil storage, especially soil
- **Precipitation**: Slightly drier with regional difference; overall effect small
- **CO2 fertilization**: High sensitivity; without CO2 fertilization effect, models tend to produce a higher storage at LGM (Kaplan et al. 2002; Otto et al. 2002)

Challenge: How good are model parameterizations?
Summary of estimates of land carbon change
LGM-Holocene

Zeng (2003, 2007)

Ciais et al. 2010
The development of these huge ice sheets must have led to the destruction of all organic life at the Earth's surface. The ground of Europe, previously covered with tropical vegetation and inhabited by herds of great elephants, enormous hippopotomi, and gigantic carnivora became suddenly buried under a vast expanse of ice covering plains, ... The silence of death followed...

Louis Agassiz (circa 1837)
What happens to boreal carbon during glaciation?

**Bulldozer vs. Freezer**

- **The Bulldozer hypothesis**
- **The glacial burial hypothesis**
Can buried carbon be preserved? GBH II

Pine needle or grass blade under the Greenland icesheet

Woody debris, Malaspina Glacier, Alaska

Oetzi the iceman, 5300yrs old, The Alps, Italian-Austrian border
Atmospheric CO2

Physical Climate
Semi-empirical

Land

Carbon Cycle
Mechanistic

Ocean Carbon

Sea Level

SST + others

Ice cover ($w_l$)
Ice volume ($w_h$)

Glacial burial carbon

Vege
Soil

$w = 0.5 w_c + 0.3(1-w_l) + 0.2(1-w_h)$

Mixing

CO2 ($w_c$)
500 ky simulation from the coupled carbon-climate model

Model:
semi-empirical physical climate and icesheet; state-of-the-art carbon cycle

Initialization: interglacial equilibrium
First 26ky: an artificial CO2 sink of 0.015GtC/y (390GtC)
After 26ky: no external forcing;
After 150ky: settled to quasi-100ky cycles, ΔT=6 °C

No orbital forcing
Difference in carbon pools
Glacial max – Interglacial

Major changes:
Glacial burial carbon
Continental shelves
Active biosphere
due to lowered temperature
Why do our results on terrestrial carbon change differ from others?

1. The inclusion of about 500Gt carbon buried under the ice sheets (the glacial burial hypothesis); Not considered in the past

2. The delayed regrowth (soil/nutrient development) in the formerly ice covered regions (the importance of transient consideration, together with the multiple time scales in the ocean and sediments); Not considered before

3. More carbon storage at Gm in non-ice covered regions due to the reduced decomposition rate of soil carbon at lowered temperature, which outcompetes the more modest effects of reduced precipitation and CO2 fertilization (colder but not too much drier, weaker CO2 fertilization)

Uncertainty
CO2 $\Delta$CO2 from climate feedback

Enhanced global warming from carbon-climate interaction: the C4MIP results

But with large uncertainty: 100-200ppm 0.5-1ºC

Major differences in land response: Using variability as a testbed; understanding processes and mechanisms for better future projection

Friedlingstein et al., 2006
Climate effects: Temperature, precipitation and CO2 fertilization in the future

- **Temperature**: Lower $\rightarrow$ Higher decomposition rate leads to higher lower storage.
- **Precipitation**: Slightly drier wetter with regional difference; overall effect small.
- **CO2 fertilization**: High sensitivity; without (or weaker) CO2 fertilization effect, models tend to produce a higher storage at LGM (Kaplan et al. 2002; Otto et al. 2002) will lose carbon (land will switch to a carbon source).
Internally generated quasi-100ky GI cycles due to carbon-climate-icesheet interaction

Late glaciation

Glacial Inception

Glacial max and early deglaciation

Glacial burial carbon release

Icesheet growth

Ejection at base

Uptake due to regrowth

'Relaxation' due to Carbonate compensation

Shelf carbon

Late deglaciation

Late deglaciation

Glacial Inception
Summary of Implications/Predictions

- Drop-rise in $^{13}\text{C}$
- Drop in $^{14}\text{C}$
- River sediment
- Carbon in IRDs
- Ancient carbon under ice
- CO$_2$ trigger?
Conclusion: CO$_2$ change

- Contrary to a traditional view, land contributes to deglacial atmospheric CO2 increase. Three main reasons for this difference:
  1. Glacial burial and continental shelf carbon;
  2. Delayed regrowth;
  3. Cold glacial climate increases storage, out-competing lower CO2 fertilization

- Such a sign reversal from -30 ppm to +30 ppm enables the known ocean mechanisms to explain comfortably the rest of the 80-100 ppm change
Conclusion: Triggering Mechanism

• Carbon-climate-icesheet interaction can (but not necessarily) lead to self-sustaining glacial-interglacial cycles. Key triggering mechanisms:
  
  • **Glacial inception**: CO2 ‘rebound’ as burial CO2 is slowly absorbed into ocean/sediment, and regrowth uptake
  
  • **Deglaciation**: glacial burial carbon is ejected out of a main icesheet when grows long and large enough, triggering increase in CO2 and temperature, leading to a series of feedbacks.

• **Interaction with orbital forcing** to produce the complexity of observed G-I cycles

• **We should not be disappointed by such complexity, but rather be open-minded**
130ky change in carbon pools: Ontario (glaciated)

- Glacial Max
- Interglacial Max

kgC m$^{-2}$

Active Biospheric Carbon
Total Carbon
Glacial Burial Carbon
Shelf Carbon

Interglacial Max
Glacial Max
130ky simulation for various places

- Glaciated (Ontario)
- Non-ice/non-shelf: temperate (Maryland)
- Non-ice/non-shelf: tropical (Amazon)
- Shelf (Old Guinea)

Time from a Glacial Maximum (kyr)
Land carbon change by type

During deglaciation, land loses, not gains, carbon by 500-600 GtC, with contribution from:

1. Glaciated area (Canada, Scandinavia, etc.): 100GtC
2. Continental shelf area: 200GtC
3. The rest, non-ice/nonshelf area: 200GtC

But they are transient!
The ‘perpetual’ mystery of the glacial-interglacial cycles — a way out?

- The Milankovitch orbital theory has enjoyed great success as the pacemaker in explaining the glacial-interglacial cycles.

- However, major puzzles remain; for instance:
  - The glacial CO2 problem
  - The role of carbon-climate interaction
  - Timing of events (‘causality problem’)

- New attempts: Paillard and Parrenin (2004), Toggweiler et. al (2006), both involving southern ocean carbon-climate interaction as trigger; and this proposal:
  - A carbon-climate-icesheet interaction theory involving the burial and release of organic carbon under the icesheets that may be the missing link.

Details described in Zeng (2003), Zeng (2007)
Deglaciation and Glacial Inception

Land vs. ocean contribution to CO2

- Positive land
- Land
- Land + Ocean
- Ocean
- SST

CO2 (ppmv)

Thousands of model years

20 thousand years
Timing of events at a termination

Initiation (subglacial transport becomes significant)

Atmospheric CO2 begins to increase

Temperature begins to increase

(If CO2 triggers termination)

Temperature lags CO2 by 50-100 years

→ near synchronous in paleo record?
Prediction I: \( \Delta C_{13} \) drops initially at deglaciation due to land carbon release followed by a rise in response to oceanic warming and regrowth on land.

Modeled atmospheric C\(_{13}\)

Air trapped in ice core at Taylor Dome, Antarctica

Smith et al. (1999)
Prediction II: Ocean C13 and Atmospheric C14

• Surface ocean $\delta^{13}C$ would also show a drop-rise transition at deglaciation because of the fast exchange with the atmosphere, except where the influence of thermohaline circulation change is large.

• Deep ocean $\delta^{13}C$? (contradicts traditional marine C13 interpretation)
  – Alternative explanations: (1) Carbonate ion effect (Spero et al., 1997); (2) Increased stratification (Toggweiler et al., 2006)

• Input of $^{14}C$-dead organic carbon from Eemian may drive down atmospheric $\Delta^{14}C$ by 100-200‰ at the deglaciation after LGM.
Deglacial C13 minima (Spero and Lea, 2002)

Oxygen 17 max: another indicator of deglacial land carbon release?

Blunier et al. (2002)
Termination II: a candidate for CO2 triggering?

Barbados sea level rise before insolation (Gallup et al. 2002)

Devil’s Hole calcite (Winograd et al., 1992)
Which terminations might have been triggered by CO2?

- The terminations triggered by glacial burial CO2 ejection are likely those preceded by long-lasting and cold glaciation during which icesheets can grow to large size: Termination II is a good candidate.

![Graph showing CO2 levels over time]
Mississippi River sediments
High Arctic islands
Ancient (Eemian) organic carbon of glacial burial origin?
Ice Rafted Debris
Mississippi River sediments
King George Island, Antarctica

Ancient organic carbon of glacial burial origin?

King George Island, Antarctica
Thank You

Paleoclimate study gives us insight about future climate change. Can it also inform us about climate change mitigation/adaptation?

If interested, I have one more slide…
Carbon sequestration via wood harvest and storage

Photosynthesis
60

Decomposition
60

Atmospheric CO$_2$

Fossil fuel

Biomass
Bioenergy Reserve

Low cost carbon sequestration

Wood harvest and storage

Future
Alternative use

Above-ground, below ground
Aerobic water
Role of Land

Typical partitioning of deglacial CO2 change (Holocene – LGM):

- Atmosphere: +180 Gt (90 ppm increase)
- Land: +500 Gt (increase)
- Ocean: -680 Gt (decrease)

Land is an additional 30ppm burden that ocean carbon pool has to accommodate, i.e., ocean needs to explain 120ppm increase in atmospheric CO2.

Why glacial land carbon pool is smaller?

The colder/drier glacial climate and lower CO2 are less favorable for vegetation growth, so less carbon stored on land.
Consequences to deglacial CO2

A release of 500 Gt land carbon would lead to an atmospheric CO2 increase by:

1. 240 ppmv if release is instantaneous
2. 120 ppmv in 10 years (upper ocean)
3. 45 ppmv in 1000 years (deep ocean uptake)
4. 15 ppmv in 10000 years (sediment dissolution)