Nested Inversion of the North America Carbon Flux with Forest Stand Age and $^{13}$C Constraints

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Outline

- **Bottom-up**
  - Forest age and carbon cycle in Canada
  - Forest age and carbon cycle in USA
  - Continent-wide forest age map and age factor map

- **Top-down**
  - Comparison of inversion results with Carbon Tracker
  - Inversion with and without the age factor map
  - Comparison with bottom-up results in Canada

- **Tightening the top constraint with $^{13}\text{C}$**
  - Data and model preparations
Bottom-up
Variation of NPP with Forest Stand Age

Black spruce, Ontario

\[ NPP = 156 \times [1 + (2.0 \times \left(\frac{age}{25}\right)^{1.9} - 1)] / e^{\frac{age}{25}} \]

Ref.: Chen et al. (2002); Chen et al. (2003)
NPP varies much more than Rh, causing large NEP variations with age.
Measured and Modeled NEP at CCP Tower Sites Against Forest Stand Age

Data sources: Andy Black, Harry McCaughey, Paul Jarvis, Alan Barr, Brian Amiro, Hank Margolis
Spatial Distribution Patterns of Net Biome Productivity (NBP) and Forest Age

Simulation period 1901-2003
Including disturbance and non-disturbance factors

Chen et al. (2003, *Tellus*); Ju et al. (2006, *Tellus*)
NPP-Age Relationships Derived from FIA biomass and mortality data

Afforestation of land in the Pacific Northwest, West

Afforestation of land in the Northeast

Afforestation of land in the Pacific Southwest

Afforestation of land in the Southeast
NEP vs. Forest Age in Oregon, USA
Law et al., (2003, GCB)

\[ y = -239.4 + 399.9 \exp(-0.5(\ln(x/95.63)/1.098)^2) \]
\[ \text{Adj } r^2 = 0.61 \]
North America Forest Stand Age Distribution in 2000
(Version 1)

- Canada:
  - Inventory (CFS)
  - Large Fire Polygons (CFS)
  - Fire Scars (U of T, CCRS)
- USA
  - FIA (USDA)

FIA data: Rich Birdsey, Yude Pan, Kevin McCullough
North America Forest Stand Age Distribution in 2000
(Version 2)

- **Canada:**
  - Inventory (CFS)
  - Large Fire Polygons (CFS)
  - Fire Scars (U of T, CCRS)

- **USA**
  - FIA (USDA)
  - Disturbance (LEDAPS, NASA)
With the regrowth curve shape determined by temperature, we can estimate NPP at any year from a measured NPP at a given age.
Age Factor for Inversion

\[ \Lambda = \frac{NPP(\text{age})}{NPP} - 1 \]

Adjustment of the neutral biosphere flux (annual NEP=0) using the age factor:

\[ \text{NEP} = NPP - (1 - \Lambda)R_h \approx \Lambda NPP \]
Forest Age Factor for Adjusting NEP *A Priori*
Top-down
Nested Global Inversion System
30 small regions in North America, 20 large regions for the rest of the globe (Transcom 3), and 88 CO$_2$ stations (GlobalView)

Deng et al. (2007, *Tellus*)
Key Datasets Used in Inversion

**Meteorology:** ECMWF (European Center for Medium-range Weather Forecast) and NCEP (National Center for Environmental Prediction) meteorology datasets are used in TM5 and BEPS modeling, respectively.

**CO₂ emission from fossil fuels:** The following relevant datasets were used to construct the temporal and spatial distributions of global CO₂ emissions from fossil-fuel burning and industrial processes.
1). The global, regional and national fossil-fuel CO₂ emission from 1871 to 2004 (CIDAC) (Marland, Boden, and Andres, 2007);
2). The EDGAR 3.2 database provides global annual CO₂ emission on a 1x1 degree grid for 1990 and 1995 ([http://www.mnp.nl/edgar/model/](http://www.mnp.nl/edgar/model/))

**CO₂ emission from vegetation fires:** The fire emission was based on the Global Emissions Fire Database version 2 (GFED v2). (van der Werf et al., 2003; Giglio et al., 2006).

**Ocean surface flux:** The flux of CO₂ across the air-water interface are constructed based on five ocean inversion flux (OIF) estimates, and optimized in Carbon Tracker (Peters et al. 2007)
Nested Grid System Used by the Transport Model TM5 (Krol et al., 2005; Peters et al., 2007)
Comparison of Inversion Results

Nested Inversion (U of T)  Carbon Tracker (NOAA)
Comparison of Inversion Results

Nested Inversion (U of T)  Carbon Tracker (NOAA)
## Comparison with Carbon Tracker

<table>
<thead>
<tr>
<th></th>
<th>NBP 2002</th>
<th>NBP 2003</th>
<th>NBP 2004</th>
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<tr>
<td>Carbon Tracker</td>
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<tr>
<td>NA-Boreal</td>
<td>0.07 ± 0.41</td>
<td>-0.22 ± 0.40</td>
<td>-0.07 ± 0.33</td>
</tr>
<tr>
<td>NA-Temperate</td>
<td>-0.19 ± 0.51</td>
<td>-0.74 ± 0.42</td>
<td>-0.75 ± 0.39</td>
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<tr>
<td>Nested Inversion (U of T)</td>
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<tr>
<td>NA-Boreal</td>
<td>-0.067 ± 0.18</td>
<td>-0.060 ± 0.18</td>
<td>-0.201 ± 0.18</td>
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<tr>
<td>NA-Temperate</td>
<td>-0.715 ± 0.23</td>
<td>-0.883 ± 0.23</td>
<td>-1.048 ± 0.23</td>
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</tbody>
</table>
Bottom-up and Top-down Results for NA Boreal Regions in 2003

![Graph showing CO2 Flux (Pg C/yr) for different regions. InTEC and Inversion (prior annual NEE=0) are compared.](image)

- Regions 6, 9, 10, 11, 12, 13, 14, 15, 16, 17 show notable CO2 flux.
- InTEC and Inversion results vary across regions, with some showing net release of CO2 and others net uptake.
Bottom-up and Top-down Results for NA Boreal Regions in 2003

- InTEC
- Inversion
- Inversion+age (prior annual NEE adjusted by forest age)

Regions

- Prior annual NEE=0
Bottom-up and Top-down Results for NA Boreal Regions in 2003

Prior annual NEE=0

Prior NEE adjusted by age

$y = 0.872x - 0.002$
$R^2 = 0.482$

$y = 1.101x - 0.003$
$R^2 = 0.350$
The influence of the age factor on the inversion of 30 regions in NA
Usefulness of $\delta^{13}\text{C}$ in CO$_2$ Inverse Modeling

- Differentiating between land ($\sim 17.5\%$) and ocean ($\sim 2\%$) sinks
- Differentiating between photosynthesis and respiration
\[ \Delta^{13}_{soil \ HR} = (\delta^{13}_{a*} - \Delta)NPP \]

9 Soil Carbon Pools

\[ \delta^{13}C_{soil} = \delta^{13}C_a(t\text{-age}) - \Delta \]

\[ \Delta = \text{Photosynthetic Discrimination} \]

\[ \Delta \text{ : annual mean } \Delta \]

\[ \text{Age} = \text{Time Lag} \]

Time Trends of Global \( \delta^{13}C \) in atmospheric CO\(_2\)

\[ \delta^{13}C_a(t\text{-age}) \]

\[ \delta^{13}C_a(t) \]

\[ \delta^{13}C(t\text{-age}) - \Delta \]
Soil Carbon Age

For Deciduous

Detritus

Microbes

Slow

Passive
Photosynthetic Isotope Dissemination
One-stage and Multi-stage

One-stage (Farquhar et al., 1989)

\[ \Delta = a + (b - a) \frac{C_i}{C_a} \]

Multi-stage (Farquhar et al., 1989; Fung et al., 1997; Suits et al., 2005)

\[ \Delta C_3 = \Delta_b \left( \frac{C_a - C_s}{C_a} \right) + \Delta_s \left( \frac{C_s - C_i}{C_a} \right) + \Delta_{\text{diss}} + \Delta_{\text{aq}} \left( \frac{C_i - C_c}{C_a} \right) + \Delta_f \left( \frac{C_c}{C_a} \right) \]

\[ \begin{align*}
C_s &= C_a - r_b A_n \\
C_i &= C_s - r_s A_n \\
C_c &= C_i - r_m A_n
\end{align*} \]
Comparison with Observations

Observations:
δ $^{13}$C of Ecosystem Respiration (ER) was estimated from the intercept of Keeling plot with δ $^{13}$C and CO$_2$ at 6 Canadian sites.

Model:  
$$
\delta^{13}_{ER_{model}} = \frac{(\delta_a - \Delta) \cdot AR + \delta_{soil} \cdot HR}{AR + HR}
$$

(Data source: Larry Flanagan)
Hourly $^{13}$C Flux Simulated by BEPS
(Example, July 1-3, 2003)
Simulated Monthly Ocean $^{13}$C Flux
Summary

- The spatial distribution of the CO2 flux in forests is closely related to the forest age distribution. The first order estimation based on a continent-wide forest age map indicates that the forest age structure in North America is in favor of carbon uptake.

- Atmospheric inversion with a neutral annual *a priori* surface flux produces a carbon source and sink distribution compatible with the forest age map in Canada. Using the continent-wide forest age information as an additional constraint in the inversion, the carbon sink increased significantly for most regions in NA.

- We are still exploring the possibility of using GlobalView $^{13}$C data in the inversion to improve the differentiation between land and ocean carbon fluxes and between photosynthesis and respiration.

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