Dynamic Regional Carbon Budget Based on Multi-Scale Data-Model Fusion

Mingkui Cao, Jiyuan Liu, Guirui Yu

Institute Of Geographic Science and Natural Resource Research
Chinese Academy of Sciences
High uncertainties exist in the magnitude, regional distribution, and temporal variations of the terrestrial carbon sink.

Dynamic regional carbon budgets will:

- Provide *spatially and temporally explicit, quantitative* information on the terrestrial carbon sink.
- Link the spatio-temporal variations to *specific driving forces and mechanisms*.
The quantitative and mechanistic information is fundamentally important to

- Effective implementation of the Kyoto Protocol, which request each signatory country to report annual GHG inventory

- Planning and practicing regional ecosystem carbon management
Various approaches based on different techniques have been used in regional carbon budgets.
The estimates using different approaches vary widely, for example,

- **For the US**, from 0.1 to 0.8 Gt C yr\(^{-1}\), and atmosphere-based estimate is about twice of land-based estimate (e.g. Pacala et al. 2001; Houghton, 2003)

- **For Europe**, from 0.1 to 0.5 Gt C yr\(^{-1}\), and atmosphere-based estimate is about 3 times of land-based estimate (e.g. Jassens et al. 2003)
The estimates using differ approaches vary widely, for example,

- **For the tropics**, from a substantial source to a moderate sink (Malhi and Grace 2001). Land use-induced C release is 2.2 Gt C yr$^{-1}$ based on statistical data (Houghton et al. 2003), but just 0.9 Gt C yr$^{-1}$ based on remote sensing data (DeFries et al. 2002)

- **For China**, from 0.02-0.09 Gt C yr$^{-1}$ based on forest inventories (e.g. Fang et al. 2002, Li et al. 2003) and ecosystem modeling (Cao et al. 2003)
And the studies did not clearly identify the causal factors or mechanisms, for example,

- Some studies estimated the “natural” mechanism play a significant role (e.g. Friedlingstein et al. 1998), but others attributed primarily to land use mechanism (e.g. Caspersen et al. 2000)

- Remote sensing-based studies attributed the increasing carbon sink in the north to warming (e.g. Myneni et al. 2001), but ecosystem observations and modeling indicate to increases in precipitation (e.g. Nemani et al. 2002, Cao et al. 2002)
The high uncertainties arise mainly from incomplete carbon accounting or using inappropriate methodologies.

1. Incomplete carbon accounting

Existing regional carbon budgets are mostly based on measured changes in the carbon stocks or fluxes of single ecosystems (forest, grass, crop etc.) or single ecosystem components (standing biomass, soil carbon etc.)
2. Lack of quantification of the combined effect of different driving forces on both ecosystem pattern and process

- Land use change
- Climate/atmospheric change

Ecosystem pattern and structure

The terrestrial carbon sink

Ecosystem carbon processes
3. Most studies on mechanisms of ecosystem carbon cycle or on the response of environmental changes neglect their different effects at different scales.

- **Regional pattern**
- **Community composition**
- **Canopy structure**
- **micro-ecophysiology**
4. Regional carbon budgets are often based on measurements of changes in ecosystem carbon stocks or fluxes for a short time (few years)
In the past decade, there have been extensive and intensive observations at different scales using various technologies.

However, the rich data have not been exploited in regional carbon budgets because of lack of an approach to assimilate the data obtained at multiple scales.
Traditional cross-scaling approaches used in regional carbon budgets:

The “top-down” approach (based on atmospheric measurement and inverse modeling, satellite remote sensing) is difficult to identify the driving force and mechanisms of ecosystem changes.

The “Bottom-Up” approach directly extrapolates small-scale results (from controlled experiments and point observation) or uses mechanistic models based on small-scale studies, neglecting mechanisms that operate at large scales.
A new cross-scaling approach is emerging: data-model fusion based on multi-scale observation and cross-scale mechanistic modeling
A multi-scale data-model fusion system

**Multi-Scale Observations**
From site to landscape to regional scales using techniques, e.g. satellite remote sensing, eddy covariance, ecosystem inventory

**Cross-Scale Data-Model Fusion**
Integrate multi-scale data into new-generation ecosystem models to simulate cross-scale mechanistic interconnections

**Dynamic data assimilation**
Continuously assimilating multi-scale observational data into dynamic simulation to achieve realistic ecological forecasting
We have developed an approach to combine satellite observation and mechanistic modeling.

Remote Sensing observations

Vegetation pattern

Remote sensing-based Modeling

Process-based modeling

Climate and soil conditions

Land-based observations

Vegetation activity

Top-down

Bottom-up
Satellite remote sensing is currently the only means available to

- observe actual changes in ecosystem pattern and activity at regional scales and high resolutions
- reflect the combined effect of various driving forces

But cannot directly measure carbon fluxes or stocks, is weak in detecting mechanisms of ecosystem changes
Mechanistic modeling is the best approach to

- Integrate observational data at different scales, using different technologies,
- Build mechanistic, quantitative connections of ecosystem processes at different scales
- Conduct diagnostic analysis to understand ecosystem mechanisms
- Rebuild and predict ecosystem changes

But it is difficult to validate mechanistic models at large scale, particularly for modeling regional ecosystem pattern
A remote sensing-based ecosystem model: GLO-PEM

Biological variables
- NDVI
- Land cover
- LAI

Environmental variables
- Temperature
- VPD
- Rainfall

Other observations

PAR

FAPAR

LUE

GPP

NPP

Ra

Prince & Goward, 1995, Cao et al. 2004
GLO-PEM estimates LUE on a mechanistic basis

(Cao et al. 2004)
GLO-PEM’s calculation of NPP can be represented as:

\[ \text{NPP} = \sum_t (\text{PAR FPAR}) \left( \varepsilon_{\text{max}} \sigma \right) - (R_g + R_m) \]

where (PAR FPAR) represents plant light harvesting, \( \varepsilon_{\text{max}} \) is the maximum light use efficiency in terms of gross primary production (GPP), \( \sigma \) is the reduction of \( \varepsilon_{\text{max}} \) by environmental conditions, and \( R_m \) and \( R_g \) are the maintenance and growth respiration.

Prince & Goward, 1995, Cao et al. 2004
GLO-PEM Calculation of Light Using Efficiency

\[ \varepsilon_g^* = 4.42 \frac{P_i - \Gamma^*}{P_i + 2\Gamma^*} \quad \text{for C3} \]
\[ 2.76 \text{ g / MJ} \quad \text{for C4} \]

\[ \sigma = \delta f(g_s) \]

\[ \delta = 1 - \frac{1}{1 + \exp(8NDVI - \frac{4(PAR - \rho)}{\rho})} \]

\[ f(g_s) = f(T)f(\delta q)f(\delta \theta)f(Pa) \]

Potential light use efficiency

Radiation saturation

Effects of temperature, humidity, soil moisture, and Atmospheric CO2

Prince & Goward, 1995, Cao et al. 2004)
Climate, Atmospheric CO₂, Soil, land cover ...

A process-based ecosystem model
CEVSA

(Cao & Woodward 1998a, Cao et al. 2002)
CEVSA integrates the whole-plant and ecosystem processes.

It uses satellite-based land cover map as an input to account vegetation pattern.

(Cao & Woodward 1998a, Cao et al. 2002)
Couple the Remote Sensing- and Process-Based Model

- **GLO-PEM**
  - NDVI
  - LAI
  - Vegetation type
  - Radiation
  - Temperature
  - VPD
  - Rainfall

- **LUE**
  - APAR

- **GPP**
  - Leaves
  - Stems
  - Roots
  - Plant C & N

- **Net primary production**
  - Autotrophic respiration
  - Heterotrophic respiration

- **CEVSA**
  - Net ecosystem production

- **Carbon decomposition**
- **Nitrogen mineralization**
- **Evapotranspiration**
- **Soil water, C and N**
Satellite-based estimate of changes in annual NPP from the 1980s to the 1990s

(Cao et al. 2004)
Satellite-detected global NPP variability and the dynamic response to the El Niño/La Niña cycle

(Cao et al. 2004)
The regional pattern of NPP changes in a transition from an El Niño and to an La Niña year (Cao et al. 2004)
The different regional pattern of NPP changes in different El Niño year

NPP anomaly (g C m⁻² per 10 days)

-8 - -4
-4 - -2
-2 - -1
-1 - -0.2
-0.2 - 0.2
0.2 - 1
1 - 2
2 - 4
4 - 8

1982/1983
1993/1994
1997/1998

(Cao et al. 2004)
Seasonal and interannual changes in NPP in China

(Net Primary Productivity, CO₂ fixation by plants)

Increase by 2.5% during last 20 years

10 days NPP (g c/m²)
Interannual Variation in NPP (1981-2000)
NPP changes from the 1980s to the 1990s

Total NPP (Gt C/yr)

1980s  3.23
1990s  3.31
Seasonal and interannual change in HR
(Soil heterotrophic respiration, carbon release)

Increase by 4.1% during last 20 years
Interannual Variation in HR (1981-2000)
Soil HR changes from the 1980s to the 1990s

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<tr>
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<th>Total HR (Gt C/yr)</th>
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<tbody>
<tr>
<td>1980s</td>
<td>3.14</td>
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<tr>
<td>1990s</td>
<td>3.27</td>
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Soil HR

Temperature
Seasonal and interannual changes in NEP
(Net Ecosystem Productivity, net carbon uptake or release)

decreased from 0.09 Gt C/yr in the 1980s to 0.04 Gt C/yr in the 1990s
Interannual Variation in NEP (1981-2000)
Changes from the 1980s to the 1990s
Research direction

To conduct joint observations with remote sensing and eddy flux measurement at ChinaFlux sites.
Research direction

Assimilate data from intensive site measurement into remote sensing-based and mechanistic ecosystem models

Satellite remote sensing

Data-model fusion and simulation

ChinaFlux (8 sites)

CERN (36 stations)
Research direction

A comprehensive, dynamic national carbon budget

Quantification of naturally and human induced changes

Human driving force

Dynamic carbon budget

Natural driving force
Thank You !!