Remote sensing of the terrestrial ecosystem for climate change studies

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Outline

1 Introduction

2 Observation of the terrestrial ecosystem

3 Integration with climate models

4 Limitations

5 Prospects
1 INTRODUCTION
1 Introduction

Terrestrial ecosystem-Impacts

- Species
- Biomes
- Phenology
- Disturbances
- Global biogeochemistry
1 Introduction

Terrestrial ecosystem-Feedbacks

C feedbacks

Physical feedbacks

(Field et al., Annu. Rev. Environ. Resour. 2007)
1 Introduction

Why remote sensing?

1. Global coverage and high frequency
2. You have no other options
1 Introduction

Climate observation
-the foundation of our understanding of the climate system (Overpeck, 2011, Science)
1 Introduction

- Global coverage and frequency
  - Essential climate variables (ECVs)

<table>
<thead>
<tr>
<th>Domain</th>
<th>Essential Climate Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric (over land, sea and ice)</td>
<td>Surface wind speed and direction; precipitation; upper-air temperature; upper-air wind speed and direction; water vapour; cloud properties; Earth radiation budget (including solar irradiance); carbon dioxide; methane and other long-lived greenhouse gases; and ozone and aerosol properties, supported by their precursors.</td>
</tr>
<tr>
<td>Oceanic</td>
<td>Sea-surface temperature; sea-surface salinity; sea level; sea state; sea ice; ocean colour.</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>Lakes; snow cover; glaciers and ice caps; ice sheets; albedo; land cover (including vegetation type); fraction of Absorbed Photosynthetically Active Radiation (FAPAR); Leaf Area Index (LAI); above-ground biomass; fire disturbance; soil moisture.</td>
</tr>
</tbody>
</table>

(GCOS, 2010)
<table>
<thead>
<tr>
<th>ECVs / Global Products requiring Satellite Observations</th>
<th>Fundamental Climate Data Records required for Product Generation (from past, current and future missions)</th>
</tr>
</thead>
</table>
| **Lakes**  
For lakes in the Global Terrestrial Network for Lakes:  
Maps of lakes;  
Lake levels;  
Surface temperatures of lakes | VIS/NIR imagery, and radar imagery;  
Altimetry;  
High-resolution IR imagery |
| **Glaciers and Ice Caps**  
Maps of the areas covered by glaciers other than ice sheets;  
Ice-sheet elevation changes for mass-balance determination | High-resolution VIS/NIR/SWIR optical imagery;  
Altimetry |
| **Snow Cover**  
Snow areal extent | Moderate-resolution VIS/NIR/IR and passive microwave imagery |
| **Albedo**  
Directional-hemispherical (black sky) albedo | Multispectral and broadband imagery |
| **Land Cover**  
Moderate-resolution maps of land-cover type;  
High-resolution maps of land-cover type, for the detection of land-cover change | Moderate-resolution multispectral VIS/NIR imagery;  
High-resolution multispectral VIS/NIR imagery |
| **fAPAR**  
Maps of fAPAR | VIS/NIR imagery |
| **LAI**  
Maps of LAI | VIS/NIR imagery |
| **Biomass**  
Research towards global, above-ground forest biomass and forest-biomass change | L band / P band SAR;  
Laser altimetry |
| **Fire Disturbance**  
Burnt area, supplemented by active-fire maps and fire-radiated power | VIS/NIR/SWIR/TIR moderate-resolution multispectral imagery |
| **Soil Moisture**  
Research towards global near-surface soil-moisture map (up to 10 cm soil depth) | Active and passive microwave |
1 Introduction

- You have no other options!!!
2 Observation of the terrestrial ecosystem
2 Observation of the terrestrial ecosystem

- **Land use/land cover change**
  - Impacts of the climate change
    - Snow and ice cover melt
    - Land degradation
  - Feedbacks to climate
    - Surface albedo
    - Surface fluxes of mass and energy
      - \( \text{CO}_2 \)
      - Water vapor
      - Aerosols
      - Momentum
2 Observation of the terrestrial ecosystem

- Land use/land cover change
  - Remote sensing methodology

<table>
<thead>
<tr>
<th>Method</th>
<th>Data</th>
<th>Samples</th>
<th>Time</th>
<th>Resolution</th>
</tr>
</thead>
</table>
| Classification
Visual ISODATA MLC SVM| AVHRR    | GLCC2.0   | 1992         | 1km        |
|              | ENVISAT  | GlobCover | 2006,2009    | 300m       |
|              | MODIS    | MCD12Q1   | Yearly       | 500m       |
|              | Landsat  | FROM-GLC  | 2000,2010    | 30m,250m   |

The most **efficient** approaches to monitor land cover and its changes in time over a variety of spatial scales.

*(Bontemps et al., 2011, Biogeosciences Discuss)*
2 Observation of the terrestrial ecosystem

Land use/Land cover change

(Tucker et al., 1985, Science)

(GlobCover, 2009, ESA)

(FROM-GLC, 2010, Gong et al., 2012)
2 Observation of the terrestrial ecosystem

- **Land use/land cover change**
  - **Major discoveries**

![Radiative forcing components diagram](image)

(IPCC AR4, 2007)
¢ Land use/land cover change

- Existing problems
  - Data inventory and aggregation methods
  - Disagreements in heterogeneous landscapes or transition zones
  - Accuracy <70%
  - Hard to differentiating the stable and the dynamic components of the land cover

Verburg, 2011, Global Change Biology
2 Observation of the terrestrial ecosystem

- Land use/land cover change
  - Existing problems

Remote sensing the Netherlands (LGN4)  Remote sensing Europe (CLC2000)

Verburg, 2011, Global Change Biology
2 Observation of the terrestrial ecosystem

- **Land use/land cover change**
  - Future research
    - Data integration
    - Improve validation techniques
    - Harmonization of classification systems
    - Select data to fit the specific applications
    - Incorporate uncertainties in land cover into future assessments
    - Answer the question of global-scale teleconnections

*Pielke et al., 2011, WIRES Clim Change*
2 Observation of the terrestrial ecosystem

Phenological shifts

- A change in the timing of growth and breeding events
- Indicator of vegetation's response to climate variability
- Alter albedo, C cycle, and hydrological cycle

Graph showing atmospheric carbon dioxide levels measured at Mauna Loa, Hawaii from 1960 to 2000.
2 Observation of the terrestrial ecosystem

- Phenological shifts
  - Remote sensing methodology
    - AVHRR and MODIS data, also Landsat
    - Start of season (SOS) method
      - Find time breaks on Normalized difference vegetation index (NDVI) or Enhanced vegetation index (EVI) curves: first upturn and midpoint
      - Representing the vegetation indices (VI) curves: actual data and curve fitting
2 Observation of the terrestrial ecosystem

- **Phenological shifts**
  - Remote sensing methodology

Seasonal midpoint NDVI (SMN) *(White et al., 2001 Ecosystems)*
2 Observation of the terrestrial ecosystem

● Phenological shifts

Curve fitting method
(Fisher and Mustard, 2007, RSE)
Phenological shifts

- Major discoveries
  - Wall-to-wall coverage of global vegetation since 1982
  - Shift towards earlier spring greening in many region
2 Observation of the terrestrial ecosystem

- Phenological shifts
  - Existing problems
    - Different from ground observations
    - Do not agree with each other
2 Observation of the terrestrial ecosystem

- Phenological shifts
  - Existing problems
    - Possible reasons:
      - Lost of fine-grain distinction
      - Difference in retrieval methods
      - Implementation procedure
2. Observation of the terrestrial ecosystem

 Phenological shifts

 Future research

 • Intercomparison study
 • Validation with ground measurements
 • Complement the VIR/IR data using microwave data
2 Observation of the terrestrial ecosystem

❖ Productivity

- The productivities of the global ecosystem
  - GPP, NPP, NEP
- Impact: variations of productivities
- Feedbacks: global C cycle
2. Observation of the terrestrial ecosystem

**Productivity**

- **Remote sensing methodology**

\[ GPP = \varepsilon \times FPAR \times PAR \approx \varepsilon \times NDVI \times PAR \]

\[ NPP = \Sigma(PSN_{net}) - R_g - R_m \]

\[ PSN_{net} = GPP - R_{lr} \]

<table>
<thead>
<tr>
<th><strong>FPAR</strong>, Fraction of photosynthetically active radiation</th>
<th><strong>PAR</strong>, radiation in photosynthetic wavelengths</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PSN_{netr}</strong>, daily net photosynthesis</td>
<td><strong>R_g</strong>, annual growth respiration</td>
</tr>
<tr>
<td><strong>R_{lr}</strong>, daily maintenance respiration of leaves and the fine roots</td>
<td><strong>R_m</strong>, maintenance respiration of live cells in woody tissues</td>
</tr>
<tr>
<td>( \varepsilon ), conversion efficiency or light use efficiency; normally annual plant, 2gC/MJ, woody, 0.2-1.5 gC/MJ</td>
<td></td>
</tr>
</tbody>
</table>

*(Running et al., 2004, Bioscience)*
2 Observation of the terrestrial ecosystem

- **Productivity**
  - Remote sensing methodology

<table>
<thead>
<tr>
<th>Model</th>
<th>Remote sensing based parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASA</td>
<td>Vegetation Distribution, $fPAR$</td>
</tr>
<tr>
<td>GLO-PEM</td>
<td>$fPAR$, Solar radiation, Temperature, Vapour Pressure Deficit, Soil water</td>
</tr>
<tr>
<td>TURC</td>
<td>Vegetation Distribution, $fPAR$</td>
</tr>
<tr>
<td>SDBM</td>
<td>$fPAR$</td>
</tr>
<tr>
<td>VPM</td>
<td>Vegetation Distribution, $fPAR$</td>
</tr>
</tbody>
</table>

Table 1. Remote sensing based parameters in PEMs

*(Liu et al., 2010, IGRASS)*
2. Observation of the terrestrial ecosystem

- Productivity
  - Major discoveries
Productivity

Major discoveries

- Overall increase of global NPP
- NPP/GPP ratio varied with climate and geography
- Total terrestrial NPP
  - $56.4 \pm 7.9$ Pg C yr$^{-1}$ averaged from 46 RS studies
  - $56.2 \pm 14.3$ Pg C yr$^{-1}$ averaged from 251 inventory and model studies
Productivity

Existing problems

- Overestimation at low-productivity sites and underestimation at high-productivity sites
- Low quality of meteorological inputs (PAR, Temperature, Vapor pressure deficit)
- Assumption of a constant light use efficiency is not true
- Inadequate environmental constrains (VPD, soil water, nutrient availability)
Productivity

Future research

- Use photochemical reflectance index (PRI) as a surrogate of light use efficiency
- More realistic representation of environmental constraints
- Better estimation of respiration components
2. Observation of the terrestrial ecosystem

- Species and biomes
  - Impacts
    - Ecology
    - Evolution
Species and biomes

Remote sensing methodology
- Biophysical characteristics of habitats
- Spatial variability in species richness
- Natural and anthropogenic changes
Species and biomes

Regime shift

- Aptly sudden shifts in ecosystems
- E.g.
  - The formation of Sahara desert
  - Shift in Caribbean coral reefs

(Scheffer and Carpenter, 2003, TREE)
2. Observation of the terrestrial ecosystem

- **Species and biomes**
  - Stable states and Regime shift

(Scheffer 2010, Nature)
2. Observation of the terrestrial ecosystem

- Species and biomes
  - Regime shift

*(Lin Songshan 2013)*
2 Observation of the terrestrial ecosystem

- **Species and biomes**
  - Regime shift
  
  **Early warming indicators**

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Method</th>
<th>Signal</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical slowing down</td>
<td>Autocorrelation; Return time</td>
<td>↑</td>
<td>Carpenter et al. 2011</td>
</tr>
<tr>
<td>Increased variability</td>
<td>Variance; $\sigma$</td>
<td>↑</td>
<td>Drake and Griffen 2010</td>
</tr>
<tr>
<td>Skewed responses</td>
<td>Skewness</td>
<td>↑</td>
<td>Biggs et al., 2009</td>
</tr>
<tr>
<td>More extremes</td>
<td>Kurtosis</td>
<td>↑</td>
<td>Biggs et al. 2009</td>
</tr>
<tr>
<td>Spatial pattern</td>
<td>Qualitative change</td>
<td>regular</td>
<td>Bailey 2011</td>
</tr>
</tbody>
</table>
2 Observation of the terrestrial ecosystem

- **Regime shifts**

  ![Diagram showing critical slowing down](image)

  Greenhouse–icehouse transition

  - CaCO₃ (%)
  - AR(1) coeff.

  Time (Myr before present)

  Critical slowing down

  *(Scheffer et al., 2009, Nature)*

  Self-organized spatial pattern

  Critical transition from a self-organized patchy state to a barren state
2. Observation of the terrestrial ecosystem

- **Regime shifts**
  - Remote sensing approach
    - Prove the existence of early warning signals
    - Prove the existence of the “tipping point”
    - Prove the existence of alternative states
2. Observation of the terrestrial ecosystem

**Regime shifts**

Transition between tropical forest and Savanna
1. Tropical forest and savanna represent alternative stable states
2. Threshold 5%, 60% tree cover
3. Driven by precipitation

*(Hirota et al., 2011, Science)*
Regime shifts

Thresholds for boreal biome transitions
1. Three states, treeless, savanna, and boreal forests
2. Thresholds: 20%, 40%, 75%
3. Driven by temperature and precipitation

(Scheffer et al., 2012, PNAS)
Regime shifts

- Remote sensing approach
  1. Get MODIS tree canopy cover data (MOD44B)
  2. Extract a random samples of pixels
  3. Analysis of multimodality of the tree cover frequency distribution using latent class analysis
  4. Build the correlation with precipitation and/or temperature
Regime shifts

Future research

- Find the mechanisms that drive the changes
- Identify the character and timing of the transition
- Answer the question: whether the vegetation-climate system has alternative stable states?
3 Integration with climate models
3 Integration with climate models

- **Input of climate models**
  - Provide boundary conditions
  - Reinitialize models
  - Update the state variables
  - Provide constrains
3 Integration with climate models

Homogeneous land cover

Dynamic vegetation model

Dynamic vegetation model with disturbances
3 Integration with climate models

**Improve climate models**

- Improve the accuracy of model predictions
  - Data assimilation: adjustment of the model state at observation times with measurements of a predictable uncertainties
  - Statistical linear estimation and ensemble assimilation
  - E.g., Land surface models + operational data assimilation schemes → lowered RMSE (27.4-32.2%) *(Ghent et al., 2010, JGR-Atmosphere)*
3 Integration with climate models

- **Validate/calibrate climate models**
  - Compared to the GCM’s outputs directly
  - Combine with in situ measurements
3. Integration with climate models

- Problems
  - Spatio-temporal mismatching
  - Lack of interfaces in climate models
  - Changing mix of observations over time
4 Limitations
4. Limitations

- Short data spans of satellite data
- Biases associated with instrument
- Uncertainties in retrieval algorithms
4 Limitations

- **Short data spans of satellite data**

  Time length of available observations

<table>
<thead>
<tr>
<th>Time length (year)</th>
<th>Terrestrial ECV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~9</td>
<td>Biomass, Glacier and ice caps</td>
</tr>
<tr>
<td>10~19</td>
<td>Land cover, Albedo, fAPAR, Fire disturbance</td>
</tr>
<tr>
<td>20~29</td>
<td>Lakes, LAI</td>
</tr>
<tr>
<td>30~39</td>
<td>Soil moisture</td>
</tr>
<tr>
<td>40~49</td>
<td>Snow cover</td>
</tr>
</tbody>
</table>

Yang et al. 2013, Nature Climate Change
4 Limitations

- **Biases associated with instrument**
  - Inadequate spatial resolution and temporal frequency
  - Poor calibrations
  - Merging data from different systems
4 Limitations

- Uncertainties in retrieval algorithms
  - Radiative transfer models
  - Uncertainties in common inputs
5 Prospects
5 Prospects

**Improvements in**

- **Future works**
  - Intercomparison of data sets
  - Innovative use of existing data
  - Rigorous reanalysis

- **Future systems**
  - Dedicated satellite missions
  - Combine passive and active remote sensing
  - High-quality validation networks