Sampling & Mapping Forest Resources Using Satellite LiDAR Data

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Code 614.4

With guest appearances by:

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Erik Næsset, Terje Gobakken,
Jonathan Boudreau, Hank Margolis,
André Beaudoin, Chhun-Huor Ung,
Luc Guindon, Philippe Villedaine,
Tim Gregoire, Göran Ståhl
But first, a little background....

Outline:
- Siberia
- Quebec
WILL LAND ECOSYSTEMS
EXACERBATE OR MITIGATE WARMING?

Largest remaining uncertainties about the Earth’s carbon budget are in its terrestrial components.

Global Carbon Budget (Canadell et al., 2007)

- To Atmosphere: 4.1 ± 0.04 Peta (10^15) grams of carbon/year
- Fossil Fuels: 7.6 ± 0.4 Peta (10^15) grams of carbon/year
- Land Use Change: 1.5 ± 0.5 Peta (10^15) grams of carbon/year
- Ocean Uptake: 2.2 ± 0.4 Peta (10^15) grams of carbon/year
- Terrestrial Sink: 2.8 ± 0.7 Peta (10^15) grams of carbon/year

TROPICAL BIOMASS LARGEST CONTRIBUTOR

NEED TO REDUCE THESE UNCERTAINTIES
The map shows areas with a canopy cover of at least 40% by woody plants taller than 5 meters.

From 1990 to 2000, the global area of temperate forest increased by almost 3 million hectares per year, while deforestation in the tropics occurred at an average rate exceeding 12 million hectares per year over the past two decades.

Uncertainty in biomass change is greatest in tropics. Biomass density more uncertain than changes in forested area.
So how can we use lasers to measure the amount of wood on the ground?

Airborne lasers (LiDARs) measure distance:

ground dist – tree dist. → tree height

tree height $\propto$ biomass $\propto$ carbon
GLAS Waveform Range Offsets & Elevations

1064 nm Laser Pulse

Travel Time

Return Amplitude
Study Area #1: South Central Siberia (Ranson/Sun/Kimes/Kharuk/Montesano)

- just NW of Lake Baikal (N of Irkutsk to Krasnoyarsk,
- 10° x 12° area,
- 811,414 km²,
- 55 GLAS orbits, L2a,
- 101,831 GLAS pulses,
- ~17.6 km between fls.
- MODIS for land cover,
- GLAS for biomass
Study Area in Central Siberia

- 80° to 110° Longitude and 50° to 75° Latitude
- The Russian forest contains 22% of the Earth’s forest area.
- Biomass/carbon estimates for these vast forest have only recently been characterized.
- Forest inventory data in this region is lacking and decades old.

MODIS MOD09 8-day composite, date: July 12 2003, Band combination: True Color
Goals:

• Produce the most accurate maps possible of timber volume and above ground forest phytomass/carbon stocks for the Siberian study area.

• Develop, test, and integrate new remote sensing methods for extracting forest canopy structure measures using MODIS and GLAS data.

• Compare these new remote sensing methods with existing ground estimates.

• Produce a realistic error bound on the remotely sensed carbon and timber volume estimates.
Predicted Timber Volume - NN - 6 GLAS Variables
(MedH, Ht2, Fslope, Mjp2loc, Ga3, Npk); $R^2=0.78$, RMSE=81 m³/ha
Methods

- Produce MODIS classification (500 m res.)
- Process waveform data for each GLAS shot
- Develop models to extract timber volume, biomass, and height using field data.
- Apply models to all GLAS shots in the study area.
- Produce timber volume and biomass maps and a statistical error bound on the estimates for each class and for the total study area.
Timber Volume Map

10° x 12° Study Area

GLAS and MODIS data:

- MODIS forest classes
- MODIS % tree cover
- GLAS timber volume

Total Timber Volume (m³/ha):
Mean Forested Area:
MODIS/GLAS (10° slope)
163.4 ± 11.8 m³/ha

MODIS/GLAS (90° slope)
171.9 ± 12.4 m³/ha

Shepashenko et al. (1998)
162.1 m³/ha
Above Ground Phytomass
10° x 12° Study Area
Using GLAS and MODIS data:
- MODIS forest class,
- MODIS % tree cover,
- GLAS timber volume

Total Phytomass:
forested area (10° slope):
86.7 ± 6.3 ton/ha
forested area (90° slope):
90.3 ± 6.7 ton/ha
Forest:

Above Ground Carbon Estimates (Pg)

Central Siberia (10X12 degree study area)

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Weight (petagrams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russian Forest Map (1990)</td>
<td>2.0</td>
</tr>
<tr>
<td>Land Resources of Russia</td>
<td>3.4</td>
</tr>
<tr>
<td>SPOT-based 1km Global Land Cover (2000)</td>
<td>2.5</td>
</tr>
<tr>
<td>MODIS MOD12-IGBP 1km Land Cover (2001)</td>
<td>1.8</td>
</tr>
<tr>
<td>MODIS-based 500m Land Cover (2003)</td>
<td>1.5</td>
</tr>
<tr>
<td>GLAS/MODIS 500m (2003)</td>
<td>1.2</td>
</tr>
</tbody>
</table>

95% CI: [1.95 ± 0.14 Pg]

Stolbovov et al. (2002)

Nelson et al. (2008)
Siberia – results:

1. **Siberia**: GLAS estimates of merchantable volume agree with ground estimates on a 811,414 km² study area in south-central Siberia.

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated Volume (m³/ha) ± Error (m³/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS/GLAS (10° slope)</td>
<td>163.4 ± 11.8 m³/ha</td>
</tr>
<tr>
<td>MODIS/GLAS (90° slope)</td>
<td>171.9 ± 12.4 m³/ha</td>
</tr>
<tr>
<td>Shepashenko et al. (1998), ground</td>
<td>162.1 m³/ha</td>
</tr>
</tbody>
</table>

- **10° forest estimates**: + 0.8% difference, CV: 7.2%
- **90° forest estimates**: + 6.0% difference, CV: 7.2%
Outline:
- Siberia
- Quebec
1995 Landcover of Canada
Couverture du sol du Canada, 1995

Produced by / produit par:
Canada Centre for Remote Sensing
Centre canadien de télédétection
Canadian Forestry Service, Laurention Forestry Centre
Service canadien des forêts, Centre de foresterie des Laurentides
QCLP – Quebec Carbon LiDAR Project

“A Realistic Analysis of the Variability of Carbon Estimates Using Airborne and Space LiDAR”

The QCLP Team:
- Ross Nelson – NASA/GSFC
- Dan Kimes – NASA/GSFC
- Hank Margolis – Laval Univ.
- Jonathan Boudreau – Laval Univ.
- André Beaudoin – CFS
- Chhun-Huor Ung – CFS
- Luc Guindon – CFS
- Philippe Villemaire - CFS
- Tim Gregoire – Yale Univ.
- Erik Næsset – Nor. Univ. Life Sci.
- Terje Gobakken – Nor. Univ. Life Sci.

+ Ryan Collins, Capitol Air
The Quebec sampling plan:

Satellite LiDAR:
GLAS (9-11/03)

Airborne LiDAR:
PALS (8/05)

Ground Reference:
MNRQ and CFS ground plots (400 m²).
(y2000 – 2004)
The Quebec sampling plan:

\[ \hat{b}_{\text{PALS}} = (-4.515) + 3.846(w_{\text{GLAS}}) - 6.587(f_{\text{GLAS}}) - 0.753(r_{\text{SRTM}}) \]

Satellite LiDAR: GLAS (9-11/03)

Airborne LIDAR: PALS (8/05)

Ground Reference:
MNRQ and CFS ground plots (400 m²).
(y2000 – 2004)
Accuracy Assessment: Quebec Southern Ecozones - Regional Estimates:

<table>
<thead>
<tr>
<th>Northern Temperate Ecozone: (109,769 km²)</th>
<th>MNRQ Ground Reference</th>
<th>GLAS estimates</th>
<th>percent difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conifer</td>
<td>76.60</td>
<td>64.69</td>
<td>- 15.5</td>
</tr>
<tr>
<td>Deciduous</td>
<td>77.85</td>
<td>89.91</td>
<td>+ 15.5</td>
</tr>
<tr>
<td>Mixedwood</td>
<td>65.91</td>
<td>82.22</td>
<td>+ 24.7</td>
</tr>
<tr>
<td><strong>Remote Sensing Estimate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>74.61</td>
<td>81.80</td>
<td>+ 6.1</td>
</tr>
<tr>
<td><strong>Standard Error</strong></td>
<td>3.14</td>
<td>1.53</td>
<td></td>
</tr>
<tr>
<td><strong>Sample Size</strong></td>
<td>583</td>
<td>1177</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mixedwood Ecozone: (98,101 km²)</th>
<th>MNRQ Ground Reference</th>
<th>GLAS estimates</th>
<th>percent difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conifer</td>
<td>85.90</td>
<td>74.61</td>
<td>- 13.1</td>
</tr>
<tr>
<td>Deciduous</td>
<td>75.00</td>
<td>82.98</td>
<td>+ 10.6</td>
</tr>
<tr>
<td>Mixedwood</td>
<td>87.15</td>
<td>81.80</td>
<td>- 6.1</td>
</tr>
<tr>
<td><strong>Remote Sensing Estimate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>81.80</td>
<td>81.80</td>
<td></td>
</tr>
<tr>
<td><strong>Standard Error</strong></td>
<td>1.53</td>
<td>1.53</td>
<td></td>
</tr>
<tr>
<td><strong>Sample Size</strong></td>
<td>1177</td>
<td>1177</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Southern Boreal Ecozone: (374,665 km²)</th>
<th>MNRQ Ground Reference</th>
<th>GLAS estimates</th>
<th>percent difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conifer</td>
<td>86.36</td>
<td>63.80</td>
<td>- 26.1</td>
</tr>
<tr>
<td>Deciduous</td>
<td>56.71</td>
<td>60.68</td>
<td>+ 7.0</td>
</tr>
<tr>
<td>Mixedwood</td>
<td>82.16</td>
<td>68.54</td>
<td>- 16.6</td>
</tr>
<tr>
<td><strong>Remote Sensing Estimate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>60.68</td>
<td>60.68</td>
<td></td>
</tr>
<tr>
<td><strong>Standard Error</strong></td>
<td>3.42</td>
<td>1.93</td>
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</tr>
<tr>
<td><strong>Sample Size</strong></td>
<td>617</td>
<td>3602</td>
<td></td>
</tr>
</tbody>
</table>

**Provincial Comm. For.** 81.90 0.50 16814 76.14 2.52 - 7.0

‡ SRS standard errors, stratified linear model, w/prediction error, w/covariance.
...that would be $5.04 \pm 0.42 \text{ Gt dry biomass},$

or $2.52 \pm 0.21 \text{ Gt C}$

in Quebec

Thank you.
Summary:

1. **Quebec**:
   - GLAS estimates of dry biomass within 1-26% of MNRQ ground estimates for commercial forest cover types - 582,536 km².
   - assessed 1.27 million km² using a space LiDAR.

<table>
<thead>
<tr>
<th>Method</th>
<th>Average Biomass (t/ha)</th>
<th>Standard Deviation (t/ha)</th>
<th>Number of Orbits/Plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETM+/PALS/GLAS:</td>
<td>76.1 ± 2.5</td>
<td></td>
<td>97 orbits</td>
</tr>
<tr>
<td>MNRQ (ground):</td>
<td>81.9 ± 0.5</td>
<td></td>
<td>16,814 plots</td>
</tr>
<tr>
<td>% difference:</td>
<td>-7.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV, GLAS:</td>
<td>3.3%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

So can you do large area forest inventories with ICESat/GLAS?

Yes.

Any problems associated with using GLAS for large area forest inventory and monitoring?

Yes, significant problems.
**Problems include:**

1. An apparent inability of GLAS to accurately measure short-stature, open forest.
PALS Mean Height

GLAS Mean Height

PALS & GLAS Heights x Latitude
solid line: GLAS biomass retrieval

dashed line: GLAS h75 height retrieval
Problems include:
2. Slope + large footprint waveform LiDAR = a convolved topography-forest canopy waveform

Slope effects can be mitigated with DTMs.
Problems include:


4. A possibility that ICESat II (launch ~2015) will have degraded forest measurement capability due to - $\Delta$ footprint size (50m to 70m), - $\Delta$ pulse width (6 ns to 10 ns).

5. Unable to assess/measure forest degradation, i.e., the intermittent, scattered removal of individual high-value trees from a forest.
Satellite **optical data**, e.g., ETM, SPOT, MODIS → forest location and type.

Satellite **LiDAR** data to measure structure, estimate biomass and carbon.
Current Outlook on U.S. Satellite LiDARs:

**ICESat I / GLAS:**  
- 65m footprint, 172 m post spacing, waveform, 6 ns pulse width,  
- single beam system, 15 km between orbits at equator (91 day repeat),  
- launched Jan. 2003,  
- died October 19, 2008 (will it rise again?)

**ICESat II/GLAS:**  
- launch due sometime in 2015,  
- 50-70m footprint, 140 m post spacing, waveform, 6-10 ns pulse width,  
- single beam system, 15 km between orbits, possible off-nadir pointing to pick up across-track slope,  
- 3-5 year mission.

**DESDynI:** with L-band radar (?)  
- launch ~2015-2017 (??),  
- 25 m footprint, contiguous, 3-5 beams across-track, 3-5 year mission.

**LIST:** a swath mapper, launch 2017++???
- 5 m footprint, contiguous footprints, waveform  
- complete global coverage over 5 years.
GLAS-related Publications:


Statistical Framework:

\[
\hat{b}_{ijk} = \frac{\sum_{p=1}^{n_{ijk}} \hat{b}_{ijkp}}{n_{ijk}}
\]

The orbit becomes my unit of observation.

\(i\) - vegetation zone, 
\(j\) - cover type, 
\(k\) - orbit, 
\(p\) – pulse.
Cover Type Biomass Estimate within Vegetation Zone:

\[ \hat{b}_{ij} = \sum_{k=1}^{n_{ij}} w_{ijk} \hat{b}_{ijk} \]

where

\[ w_{ijk} = \frac{n_{ijk}}{\sum_{k=1}^{n_{ij}} n_{ijk}} \]

\[ \sum_{k=1}^{n_{ij}} w_{ijk} = 1.0 \]

SRS:

\[ \text{vâr}(\hat{b}_{ij}) = \frac{\sum_{k=1}^{n_{ij}} w_{ijk} (\hat{b}_{ijk} - \hat{b}_{ij})^2}{n_{ij} - 1} \]

\[ i - \text{vegetation zone}, \]
\[ j - \text{cover type}, \]
\[ k - \text{orbit}, \]
\[ p - \text{pulse}. \]
Vegetation Zone Estimates of Biomass:

\[ \hat{b}_i = \sum_{j=1}^{n_i} w_{ij} \hat{b}_{ij} \]

\[ w_{ij} = \frac{a_{ij}}{a_i} \quad \text{and} \quad \sum_{j=1}^{n_i} w_{ij} = 1.0 \]

\[ \text{vâr}(\hat{b}_i) = \sum_{j=1}^{n_i} w_{ij}^2 \text{vâr}(\hat{b}_{ij}) + 2 \sum_{j=1}^{n_i-1} \sum_{m=j+1}^{n_i} w_{ij} w_{im} \text{côv}(\hat{b}_{ij}, \hat{b}_{im}) \]

\[ \text{côv}(\hat{b}_{ij}, \hat{b}_{im}) = \frac{\sum_{k=1}^{n_i(j,m)} \sum_{l=1}^{n_i(j,m)} (\hat{b}_{ijk} - \hat{b}_{ij}) (\hat{b}_{iml} - \hat{b}_{im})}{n_i(j,m) - 1} \]
## Provincial Estimates – four models:

*(n=104,044, 97 orbits, SRS)*

<table>
<thead>
<tr>
<th>model</th>
<th>dry biomass estimates</th>
<th>Prov. biom. totals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean(t/ha)</td>
<td>SE (t/ha)</td>
</tr>
<tr>
<td><strong>believe GLAS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sqrt, nostr, noreg</td>
<td>41.72</td>
<td>2.82</td>
</tr>
<tr>
<td>Lin, nostr, reg</td>
<td>40.65</td>
<td>5.13</td>
</tr>
<tr>
<td><strong>believe ETM</strong>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lin, str, reg</td>
<td>39.78</td>
<td>3.17</td>
</tr>
<tr>
<td>Sqrt, str, noreg</td>
<td>38.94</td>
<td>2.17</td>
</tr>
</tbody>
</table>

\[ \Delta C = 0.18 \text{ Gt} \]

\(~7\% \text{ diff.}\)

- cannot add regression error to sqrt model (positive bias)
- stratified models lower due to nonforest biomass = 0 regardless of GLAS