Mapping *Cladophora* Extent in Lake Michigan Using Multi-scale Satellite Imagery

Dr. Robert Shuchman¹, Michael Sayers¹, Colin Brooks¹, Liza Jenkins¹, Dr. Martin Auer², and Dr. Guy Meadows³

Robert Shuchman, Ph.D., MTRI
shuchman@mtu.edu
734-913-6860

Michigan Tech Research Institute¹, Michigan Technological University², The University of Michigan³

September 27, 2011
SOLM – Michigan City, Indiana
State of Lake Michigan Conference
Cladophora Study: Goal and Objectives

- Overall goal
  - Quantify the role of remote sensing in mapping, monitoring, and managing *Cladophora* growth in the Great lakes

- Specific objectives
  - Quantify ability of Landsat, MODIS, and MERIS and commercial satellites to first map *Cladophora* extent and then characterize biomass based on observed depth corrected reflectance values
    - maximum depth
    - seasonal performance
    - annual variability
    - best satellite bands
    - optimum depth correction (ratio vs. extinction coefficient)
    - optimum satellite viewing geometry
  - Used two locations (Sleeping Bear, MI, USA and Pickering Nuclear Power Plant, Ontario, Canada) to demonstrate initial feasibility of technique
The *Cladophora* Problem

- *Cladophora* is a native, filamentous, green alga that grows attached to solid substrate in all of the Laurentian Great Lakes (sparse in Lake Superior).
- Becomes detached after significant storm events and washes up on nearby beaches.
- Avian botulism outbreaks in northern Lake Michigan associated to large deposits of detached washed up *Cladophora*.
- Was a problem in the 1970s due to high levels of phosphorus.
- Great Lakes Water Quality Agreement management strategies helped to reduce phosphorus loadings to lessen nuisance *Cladophora* growth.
- Nuisance growth has become an increasing problem over the past decade due mostly to the arrival of invasive mussel species.
- More light is able to reach deeper allowing *Cladophora* to grow
- Mussel “colonies” create areas of hard substrate where *Cladophora* can grow.
Cladophora Mapping Algorithm

- Assuming uniform inherent optical properties, a depth corrected radiance algorithm arises, of the form:
  - log-transformed radiance, $X_j = \ln(L - L_s)$
  - $L = $ Upwelling radiance
  - $L_s = $ Upwelling radiance in water of ‘infinite’ depth
  - Eliminates radiance due to the water column, leaving upwelling radiance due to bottom component.
  - Values less than zero indicate optically deep water signature.
- Based on upwelling radiance detected by sensor
- The Depth Invariant Index uses multiple depth corrected radiance band inputs along with the specific diffuse attenuation coefficients ($K_d$) to solve a linear model for multiple bottom types.

Figure displays scatter plot of depth corrected satellite bands and distinct parallel lines indicating different bottom types. Image from http://www.unesco.org/csi/pub/source/rs10.htm
Cladophora Study: 2009-2010 Field Activity (Sleeping Bear)

- Acquired imagery to guide sampling sites
- Overlaid image with depth and bottom substrate
- Based on depth, rock versus sand and radiance values classified image as sand, dense Cladophora, moderate Cladophora, or deep water
- Test area truthing: Sampled 19 sites
  - At most sites sampled:
    - location (GPS)
    - depth
    - secchi disk
    - diver observations
    - diver photos
    - diver collected Cladophora or sand sample
    - YSI water properties (temp, pH, conductivity, turbidity, and DO) as a function of depth (profile of water column)
    - ROV video, temperature, and side scan sonar
    - ASD spectro-radiometer measurements of bottom samples as well as detached floating Cladophora
    - dry weights of Cladophora samples
Cladophora Study: 2010 Field Map

Actual July 2010 Sample Sites Along Sleeping Bear Dunes National Lakeshore
Cladophora Study: Initial Observations

- Landsat is a useful sensor to map *Cladophora* in Lake Michigan
- *Cladophora* observed up to 100ft (33 meters) water depth; denser areas <15m
- Average *Cladophora* attached to substrate reflectance in .4 to .7 µm band was approximately 2-5% while sand was 7-20%. Detached *Cladophora* had reflectance values 2-8%
- *Cladophora* requires hard bottom to grow, zebra mussels can provide that required substrate
- *Cladophora* did colonize on dead zebra mussel-roots attached to shells
- Landsat observed *Cladophora* colonies up to approximately 45-60ft (15-20 meters) depth
- A storm with maximum significant wave height of 2.65 meters (8.45 ft) and maximum winds of 11.2 m/s (22.4 kts) was of sufficient strength to slough or rip *Cladophora* in 8-10 meters (25-30 ft) of water depth off the rocks two days after our 2009 field observations
- Water column at the site was well stratified range of values
  - DO 9-10 (mg/L)
  - pH 8.6
  - temp 18.5-19.5 (°C)
  - turbidity 0 (NTU)
  - conductivity .282 (mS/cm)
Cladophora Study: Reflectance Results

All Sites Averaged
Wet Cladophora, Indoors
Bare Fiber, Contact Probe

4/11/2009 Landsat 5 image and 10, 15, and 20 m bathymetric contours

11:14 am overpass
42.8 °F (6 °C)
Wind speed 8.1 mph

4/11/2009 Landsat 5 green band radiance

GLERL 5-m bathy: 10 to 20 m
Depth (m)

10
15
20
Classification achieved over 90% accuracy when compared to August 2009 sample sites.

Both dark and light *Cladophora* is classified.

Some confusion between dark *Cladophora* and optically deep water.

With accurate bathymetry, decision rules can be applied to correct confusion.
Cladophora Biomass Observations

**2009 Band 2 (Green) Sand Standardized Depth Corrected Radiance**

- **Depth Corrected Green Radiance - Standardized by Sand Reflectance**
- **4/11/2009**
- **5/11/2009**
- **6/11/2009**
- **7/11/2009**
- **8/11/2009**

- **Dense Cladophora**
- **Less Dense Cladophora**
- **Sparse Cladophora**
- **Sand**
- **Deep Water**
- **All Cladophora Avg**
Have anecdotal evidence of *Cladophora* deposition on North Manitou Island in early June 2010.

Implies that attached *Cladophora* biomass should be less than previous month.

Classified pre and post sloughing Landsat Images to examine *Cladophora* extent differences.

Found areas of extensive *Cladophora* sloughing.

Observed areas where *Cladophora* was still present but had higher reflectance than pre sloughing.

Indications that darker *Cladophora* has higher biomass than lighter *Cladophora*.

North Manitou, June 14, 2010
**Cladophora Biomass Estimates**

- **Cladophora** dry weights were calculated (grams/sq. meter) from samples collected during 2009-2010 field mission.

- Dry weights were categorized as dense and less dense **Cladophora**.

- Area was calculated by summing the number of pixels in each class and multiplying those totals by a single pixel area. (Landsat: 30m x 30m = 900 sq. meters)

- Dry weight biomass was calculated by multiplying the area of each **Cladophora** density class by the corresponding dry weight.

- Wet weight was calculated by multiplying by the standard factor of ten.

<table>
<thead>
<tr>
<th>Bottom Type</th>
<th>Dry Weight Density (g/m²)</th>
<th>Area (m²)</th>
<th>Dry Weight Biomass (grams)</th>
<th>Approximate Dry Weight Biomass (tonnes)</th>
<th>Approximate Wet Weight Biomass (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cladophora (Lighter green)</td>
<td>31</td>
<td>98,659,800</td>
<td>3,058,453,800</td>
<td>3058</td>
<td>30585</td>
</tr>
<tr>
<td>Dense Cladophora (Darker green)</td>
<td>53</td>
<td>9,802,800</td>
<td>519,548,400</td>
<td>520</td>
<td>5195</td>
</tr>
<tr>
<td>Sand</td>
<td>0</td>
<td>223,908,300</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Total**

- Approximate Dry Weight Biomass = 3578 tonnes
- Approximate Wet Weight Biomass = 35780 tonnes
2011 Progress
Lake Michigan; Lake Huron Next


Bottom Type
- Cladophora
- Dense Cladophora
- Sand
Lake Michigan Example

- In Lake Michigan 32% of the visible bottom consists of *Cladophora* (1530 km$^2$ out of the 4740 km$^2$).

- The optical depth varied from 7m to 18m depth.
Multi-scale *Cladophora* Mapping Capability

<table>
<thead>
<tr>
<th>QuickBird</th>
<th>Worldview2</th>
<th>MODIS</th>
<th>MERIS</th>
<th>Landsat 5 TM</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="quickbird.png" alt="Image" /></td>
<td><img src="worldview2.png" alt="Image" /></td>
<td><img src="modis.png" alt="Image" /></td>
<td><img src="meris.png" alt="Image" /></td>
<td><img src="landsat5tm.png" alt="Image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth Corrected Bottom Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cladophora</td>
</tr>
</tbody>
</table>

**Path:** J:\project\Cladophora Feasibility\MXD\Imagery_comparision2.mxd
High resolution imagery (ie. < 5m pixels) allow for much more detailed classifications.

Decision rules were applied to help with classification confusion.
Historical Lake Michigan Water Clarity

- Derived from historical Landsat TM imagery.
- Used depth corrected radiance algorithm for visible channels.
- Water clarity measured historically over Sleeping Bear Dunes National Lakeshore (SBDNL) study site.
- Total area within 0-10 m depth contours is approximately 165 km²
Example of Landsat Image Inventory for *Cladophora* Extent & Biomass

Usable images need to be cloud free over near-shore areas of interest, good radiometric contrast

<table>
<thead>
<tr>
<th>Path/Row</th>
<th>p16r29</th>
<th>p16r30</th>
<th>p17r29</th>
<th>p17r30</th>
<th>p17r31</th>
<th>p18r29</th>
<th>p18r30</th>
<th>p18r31</th>
<th>p19r28</th>
<th>p19r29</th>
<th>p19r30</th>
<th>p19r31</th>
<th>p20r28</th>
<th>p20r29</th>
</tr>
</thead>
<tbody>
<tr>
<td>20080414</td>
<td>20080405</td>
<td>20080405</td>
<td>20080412</td>
<td>20080403</td>
<td>20080403</td>
<td>20080410</td>
<td>20080526</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20080430</td>
<td>20080421</td>
<td>20080421</td>
<td>20080428</td>
<td>20080419</td>
<td>20080419</td>
<td>20080426</td>
<td>20080529</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20080516</td>
<td>20080507</td>
<td>20080507</td>
<td>20080514</td>
<td>20080505</td>
<td>20080505</td>
<td>20080512</td>
<td>20080531</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20080601</td>
<td>20080523</td>
<td>20080523</td>
<td>20080530</td>
<td>20080521</td>
<td>20080521</td>
<td>20080528</td>
<td>20080531</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20080617</td>
<td>20080608</td>
<td>20080608</td>
<td>20080615</td>
<td>20080606</td>
<td>20080606</td>
<td>20080613</td>
<td>20080619</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20080401</td>
<td>20080424</td>
<td>20080424</td>
<td>20080401</td>
<td>20080401</td>
<td>20080401</td>
<td>20080401</td>
<td>20080401</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20080417</td>
<td>20080401</td>
<td>20080401</td>
<td>20080401</td>
<td>20080401</td>
<td>20080401</td>
<td>20080401</td>
<td>20080401</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20080503</td>
<td>20080408</td>
<td>20080408</td>
<td>20080408</td>
<td>20080408</td>
<td>20080408</td>
<td>20080408</td>
<td>20080408</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20080519</td>
<td>20080523</td>
<td>20080523</td>
<td>20080523</td>
<td>20080523</td>
<td>20080523</td>
<td>20080523</td>
<td>20080523</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20080604</td>
<td>20080510</td>
<td>20080510</td>
<td>20080510</td>
<td>20080510</td>
<td>20080510</td>
<td>20080510</td>
<td>20080510</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20080620</td>
<td>20080526</td>
<td>20080526</td>
<td>20080526</td>
<td>20080526</td>
<td>20080526</td>
<td>20080526</td>
<td>20080526</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20100404</td>
<td>20090620</td>
<td>20090620</td>
<td>20090620</td>
<td>20090620</td>
<td>20090620</td>
<td>20090620</td>
<td>20090620</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20100402</td>
<td>20090610</td>
<td>20090610</td>
<td>20090610</td>
<td>20090610</td>
<td>20090610</td>
<td>20090610</td>
<td>20090610</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20100308</td>
<td>20090606</td>
<td>20090606</td>
<td>20090606</td>
<td>20090606</td>
<td>20090606</td>
<td>20090606</td>
<td>20090606</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20100202</td>
<td>20090611</td>
<td>20090611</td>
<td>20090611</td>
<td>20090611</td>
<td>20090611</td>
<td>20090611</td>
<td>20090611</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20100126</td>
<td>20090627</td>
<td>20090627</td>
<td>20090627</td>
<td>20090627</td>
<td>20090627</td>
<td>20090627</td>
<td>20090627</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20100020</td>
<td>20090631</td>
<td>20090631</td>
<td>20090631</td>
<td>20090631</td>
<td>20090631</td>
<td>20090631</td>
<td>20090631</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20100012</td>
<td>20090620</td>
<td>20090620</td>
<td>20090620</td>
<td>20090620</td>
<td>20090620</td>
<td>20090620</td>
<td>20090620</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20100004</td>
<td>20090611</td>
<td>20090611</td>
<td>20090611</td>
<td>20090611</td>
<td>20090611</td>
<td>20090611</td>
<td>20090611</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20100002</td>
<td>20090627</td>
<td>20090627</td>
<td>20090627</td>
<td>20090627</td>
<td>20090627</td>
<td>20090627</td>
<td>20090627</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20100001</td>
<td>20090630</td>
<td>20090630</td>
<td>20090630</td>
<td>20090630</td>
<td>20090630</td>
<td>20090630</td>
<td>20090630</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20100000</td>
<td>20090613</td>
<td>20090613</td>
<td>20090613</td>
<td>20090613</td>
<td>20090613</td>
<td>20090613</td>
<td>20090613</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Images</td>
<td>17</td>
<td>17</td>
<td>18</td>
<td>18</td>
<td>16</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Usable Images</td>
<td>3</td>
<td>8</td>
<td>5</td>
<td>8</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>6</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Study Site: Nuclear Power Plant at Pickering, Ontario.

Landsat 5 TM Imagery from 9/17/2007

Applied Depth Invariant Index algorithm and applied depth decision rule to derive Cladophora extent.

Optical light penetration depth in Lake Ontario is much shallower (~5 m) than observed in Lake Michigan (~20 m).

<table>
<thead>
<tr>
<th></th>
<th>OPG Quickbird</th>
<th>OPG Landsat</th>
<th>MTRI Landsat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary AOI Biomass (wet weight tonnes)</td>
<td>310</td>
<td>390</td>
<td>316</td>
</tr>
<tr>
<td>Regional AOI Biomass (wet weight tonnes)</td>
<td>1331</td>
<td>1833</td>
<td>1539</td>
</tr>
</tbody>
</table>

OPG reported Cladophora biomass vs. MTRI derived biomass
Comparison of *Cladophora* extent derived from 9/17/2007 Landsat imagery with ground truth observations yields positive results.

The majority of observations agree with corresponding classification pixels.

Confusion seems to be linked with overall *Cladophora* density and transitional pixels between bottom types.

Transition error can be associated with the integration of changing bottom type over a 30 meter pixel.

Further work will be done to relate density and substrate with optical reflectance to minimize density confusion.
Cladophora Study: Next Steps

- Analyze vegetation growing season
  - March through October
  - Extent
  - Biomass

- Additional “lake truth” for better quantification of biomass estimates

- Annual variability
  - May through June imagery
  - 1970s to present
  - Factor in water clarity changes over time

- GLRI – Great Lakes Restoration Initiative
  - Now doing a basin-wide assessment of extent and biomass under GLRI funding (lower 4 Great Lakes)
  - Will be sharing data through MTRI (www.mtri.org), GLOS (www.glos.us), and MichiganView web pages (www.michiganview.org)
Landsat data is a useful tool in mapping *Cladophora* extent and biomass.

Modified Depth Invariant Index algorithm (based on Lyzenga’s work) provides robust estimates.

Technique performance is a function of water clarity (secchi disk):
- Michigan 15-20 meters
- Ontario 5 meters

High resolution (~2-3 meter) commercial satellite data provides greater detail, but at increased cost.

Funded through NASA ROSES & EPA GLRI
Questions?

Robert Shuchman, PhD. shuchman@mtu.edu 734-913-6860, MTRI

Mike Sayers, mjsayers@mtu.edu, 734-913-6852, MTRI

Colin Brooks, colin.brooks@mtu.edu, 734-913-6858, MTRI