Canada`s Forests and the Bio-economy – Potential Solutions to Climate Change!

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Research Scientist
Canadian Wood Fibre Centre
February 28, 2018

2017-18 CIF e-Lecture Series
“Innovative Solutions toRespond to the Challenge of a Changing Climate”
Canada’s Forests and the Bio-economy – Potential Solutions to Climate Change - CIF e-Lecture

Presenters + Collaborators

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Program Manager, CWFC, NoFC
Storage in Biomass Supply Chain:
Mitigating GHG Emissions and Improving Biomass Quality
Problem Definition

- **GHG RELEASE**
  - CO₂
  - Methane

- **HEAT BUILD UP**
  - Bacteria
  - Oxidation reactions
  - Water cycle
Trapped heat escaping from a disturbed biomass pile in the dead of winter

-30° C

- How can self heating fires be prevented?
- Can better storage methods improve feedstock quality?
- How much GHG’s do biomass piles release (CO₂, CH₄)?
What are we doing?

Measuring changes in temperature, moisture, bulk density, available sugars, CO₂ flux, O₂, CH₄

Pineland Forest Nursery

New pile

Old pile

Picture credit: FPInnovations
Findings and Impact

- Allows us to understand internal pile dynamics
- Quantify GHG emissions from various types of biomass
- Identify key control parameters for self heating
- Brings us closer to establishing best practices for minimizing biomass loss
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Partners and Collaborators

Canada
Natural Resources Canada

UNIVERSITY OF TORONTO

braingrid

FP Innovations

Pineland Forest Nursery
NEW GENERATION BIOMASS FEEDSTOCKS FOR BIOREFINERIES

- Green energy
- Biobased chemicals
- Biomaterials

Optimizing Feedstock characteristics
- Microbial

GHG RELEASE
- CO₂
- Methane
Biological Degradation

**Food Resources**
1. free sugars
2. cellulose
3. hemicelluloses
4. lignin

- Bacteria
- Brown Rot
- White Rot

**Factors**
- **Temperature**
  - mesophillic
  - thermophillic
  - increase growth rate

- **pH**
- **Gas environment**
  - aerobic
  - anaerobic

**Moisture**
$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$
\[ C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy} \]
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\[ C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy} \]

In 4 months -> dry-mass loss of 7.41% or 1.8/month

1. Hemicelluloses
2. Amorphous cellulose
3. Crystalline cellulose
4. Lignin

1. Lower energy for grinding
2. Increased enzyme access and faster reaction rates
3. Pre-processing for nano-cellulose?
4. Higher energy content
5. Higher lignin recovery

Increased porosity
Increased ratio of crystalline/amorphous cellulose
Higher ratio of lignin to carbohydrates
Sustainable Biomass Harvesting in the Great Lakes – St. Lawrence Forest Region
Finding ecological, economic and operational answers within mixed wood forest conditions

Jeff Fera
Forest Research Officer
Canadian Wood Fibre Centre
Canadian Forest Service
Natural Resources Canada

Dr. Trevor Jones
Hardwood Ecosystem Research Scientist
Ministry of Natural Resources and Forestry
Provincial Services Division
Science and Research Branch
OBJECTIVE: To evaluate the effects of biomass harvesting in partial harvest systems on stand-level productivity and biodiversity.

- 4 locations in Ontario including PRF
- Fully replicated scientific design and layout:
  - Ecological
  - Economical
  - Operational

GOAL: This research will provide sound and defensible scientific support for policy and guideline development towards best management practices for biomass harvesting in south and central Ontario.
Operational Biomass Trails in the Great Lakes-St. Lawrence Forest

Biomass harvesting, utilization and silviculture

Unproductive and unhealthy forest condition

High utilization biomass harvest

Traditional wood products

Biomass chips

Bio-heat

Healthy and productive forest condition

GL - SL FOREST

Finding ecological, economic and operational answers within mixed wood forest conditions
Research Site Locations

1. **Algoma Site** – 40 min north of SSM – It is a Uneven aged hardwood stand – Shelterwood cut (regen cut) EST. 2010

2. **Nipising Forest** – 40 min NE of North Bay, ON, - Uneven aged hardwood stand – Shelterwood (regen) cut EST. 2009

3. **Haliburton Forest** – Uneven aged hardwood stand – (Selection cut) EST. 2009

4. **Petawawa Research Forest** – Pine mixed wood site – Shelterwood cut (regen cut) EST. 2012
Results: Petawawa Research Forest Trial

SHelterwood System – REGEN CUT:
TREE LENGTH VS. FULL TREE / BIOMASS UTILIZATION

Figure 1. Volume (m³) of harvested material
Results: Economic (PRF)

**OPTIMIZED HARVESTING SCENARIO**:  
1 FELLER BUNCHER, 2 SKIDDERS, 1 SLASHER PLUS TOPPER AND CHIPPER

<table>
<thead>
<tr>
<th>Harvesting Operations</th>
<th>Tree Length</th>
<th>Full Tree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Felling</td>
<td>5.6 hr/day</td>
<td>7.4 hr/day</td>
</tr>
<tr>
<td>Skidding</td>
<td>8.0 hr/day</td>
<td>8.0 hr/day</td>
</tr>
<tr>
<td>Slashing</td>
<td>7.1 hr/day</td>
<td>7.7 hr/day</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product</th>
<th>Tree Length</th>
<th>Full Tree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sawlog</td>
<td>159.9 m³/day</td>
<td>144.5 m³/day</td>
</tr>
<tr>
<td>Pulp</td>
<td>68.5 m³/day</td>
<td>100.6 m³/day</td>
</tr>
<tr>
<td>Residue</td>
<td>X</td>
<td>106.7 m³/day</td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily subcontractor revenue</td>
<td>$5,156.30</td>
<td>$5,515.50</td>
</tr>
<tr>
<td>Daily subcontractor cost</td>
<td>$4,376.60</td>
<td>$4,552.70</td>
</tr>
<tr>
<td><strong>Total daily subcontractor profit</strong></td>
<td><strong>$779.80</strong></td>
<td><strong>$962.80</strong></td>
</tr>
</tbody>
</table>

Table 1. Potential profits and daily machine utilization under an optimized setup
Results: Economic (PRF)

OPTIMIZED HARVESTING SCENARIO: 1 FELLER BUNCHER, 2 SKIDERS, 1 SLASHER PLUS TOPPER AND CHIPPER

<table>
<thead>
<tr>
<th></th>
<th>Sawlog</th>
<th>Pulp</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market Value</td>
<td>$73.10/m³</td>
<td>$56.30/m³</td>
<td>$43.10/m³</td>
</tr>
<tr>
<td>Hauling costs</td>
<td>$16.20/m³</td>
<td>$16.20/m³</td>
<td>$16.20/m³</td>
</tr>
<tr>
<td>(standardized to 100 km)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed costs</td>
<td>$13.80/m³</td>
<td>$13.80/m³</td>
<td>$13.80/m³</td>
</tr>
<tr>
<td>Subcontracting costs</td>
<td>$24.00/m³</td>
<td>$19.20/m³</td>
<td>$14.00/m³</td>
</tr>
<tr>
<td>Product totals</td>
<td>$19.10/m³</td>
<td>$7.10/m³</td>
<td>$-0.90/m³</td>
</tr>
</tbody>
</table>

Landowner profit - Tree length  
$1069.60/ha  $170.40/ha  X
Landowner profit - Full tree  
$1069.60/ha  $276.90/ha  $-36.90/ha

<table>
<thead>
<tr>
<th></th>
<th>Tree length</th>
<th>Full tree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total landowner profitability</td>
<td>$1240.00/ha</td>
<td>$1309.60/ha</td>
</tr>
</tbody>
</table>

Table 2. Landowner costs (excluding stumpage) and revenue breakdown by product.
Amending Forest Soils with Wood Ash to Maintain Fibre Supply

1) How can we maintain fibre supply under more intensive forest harvesting?
2) How can we maintain fibre supply in light of forest health conditions (case study: beech bark disease) that compromise forest productivity?

- Movement to renewable energy to reduce fossil fuel usage - in Canada the contribution of biomass to electricity generation doubled from 2005 to 2015
- Intensive harvesting has the potential to decrease soil nutrients and forest productivity
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Wood ash utilization

• Currently 2/3 of the wood ash produced in Canada is landfilled - varies by province - 2020 prohibited in Quebec
• Wood ash applications would return nutrients to soil (Ca, Mg, K, P) - beech bark disease, productivity stagnation - ash as a silvicultural tool - accepted management practice in Europe
• Social license essential to grow the bio-economy - negative perception of increased utilization
Approach

1) Building on existing Beech Bark Disease Project (OMNRF) in Ontario (Porridge Lake) and long-term research trials at Station de recherche forestière de Valcartier in Quebec (Valcartier) establish two new wood ash application experiments - Westwind Forest Stewardship, Murray Brothers Lumber, Resolute Forest Products
Approach

2) Building on a national network of wood ash trials – AshNet

www.nrcan.gc.ca/forests/research-centres/glfc/ashnet/20279

UNBC USask UManitoba
Lakehead Laurentian UToronto
Trent UQAT TELUQ
CFS OMNRF
Wood Pellet Assn Canada
Ontario Power Generation
Friends of Muskoka Watershed
FP Innovations
Project Overview

**Beech problematic:** increase beech abundance in tolerant hardwoods stands → threat to industry

**Goal:** Effect of mechanical treatment and amendments on the regeneration success of beech vs. sugar maple/yellow birch in thinned stands
Project Overview

**Location:** Station de recherche forestière de Valcartier, near Québec City.

**Treatments:**
Amendments: ash, lime, fertilizer
(why? acid deposition)
Mechanical: light scarification « La Taupe »
(why? mineral exposure)
Control

Year established ➔ 2017-18
Project Overview

• Measurements:
  • Seedlings
  • Soil properties
  • Microbiome
Partners

• Canadian Forest Service
  • David Paré
  • Sébastien Dagnault
  • Fanny Michaud
  • Olivier Jeffrey
  • Serge Rousseau
  • Christine Martineau
  • Armand Séguin

• Resolute Forest Products
  • Bernard Ferland
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Biomass Sources

Opportunity Residues: Harvest Roadside, Mill and Urban Wood Waste

Purpose Grown Woody Crops: Afforestation & Concentrated Biomass

Other Potential Sources: Juvenile Hardwood, Utility Line Maintenance, Mountain Pine Beetle Salvage and FireSmart Operations
Canadian Wood Fibre Centre
Creating sustainable forest solutions

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“Spatial Wood Biomass Residue Inventory”

Canadian Forest Service (CFS)

Biomass Inventory Mapping and Analysis Tool (BIMAT)

Biomass Search

1. Search By:
   - Distance
     - 100 km
   - Volume (ODT)
     - 100000

2. Residue Types
   - Hardwood Road
   - Softwood Road
   - Hardwood Mill
   - Softwood Mill
   - Urban Wood
   - Historic Mill

3. Click Map
   - Single Click

Point of Interest:
Latitude: 53.014783245859235
Longitude: -115.13671875

Click Here to Search for Woody Biomass Residues Within 100 km.

BIMAT
Biomass Inventory Mapping and Analysis Tool
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“Spatial Wood Biomass Residue Inventory”

Search Results (53.2°N, -115.3°E) → Drayton Valley, AB

Legend
- Biomass (ODT)
- 2.571 - 35.698
- 2.298 - 2.570
- 1.190 - 2.297
- 1.155 - 1.189
- 23 - 154

Radius: 100 kilometers
Volume: 430,455 ODT
Avg. Distance: 64 kilometers
Cell Count: 243 cells

Bar Chart | Pie Chart

1. Reported figures represent residues annually available prior to mill recovery activities.

www.agr.gc.ca/atlas/bimat
Sustainable Opportunity Woody Biomass Sources

Legend:
- Red: Roadside Harvest Residues
- Orange: Mill Residues
- Green: Urban Wood Residues

Forest:
- Green: Coniferous
- Brown: Mixed
- Yellow: Deciduous

Supplied by: D. Sidders and B. Iose, Canadian Wood Fibre Centre resulting from Canadian Biomass Innovation Network TDK-258.

1 Figures estimated for mills consuming greater than 100,000 m³/year.
2 Figures estimated based on centres with populations of greater than 1,000 persons according to the 2006 Census.
Adapting Afforestation Scenarios to Address a Changing Climate

Canadian Wood Fibre Centre is actively involved in the operational research of innovative practices to establish, manage and utilize various afforestation scenarios. Establishing a “National Network of Sites” demonstrates the benefits of innovative afforestation systems to grow wood fibre and woody biomass at rates 8-10 times the growth of “native forests” on previously non-forested lands to create significant carbon sinks and produce feedstock for an evolving green or renewable energy industry, contributing to a low-carbon economy.

**High Yield Afforestation**
- Grid style plantations
- Consisting of hybrid poplar or aspen
- 11-1600 stems ha\(^{-1}\)
- 1 x 16-20 yr rotation
- 13.6-20 m\(^3\) ha\(^{-1}\) yr\(^{-1}\)
- 25cm+ DBH at harvest
- 20m+ HT at harvest
- 19-29 t CO\(_2\) e ha\(^{-1}\) yr\(^{-1}\)

**Concentrated Biomass**
- Hedge style plantations
- Consisting of hybrid poplar or willow
- 13-16,000 stems ha\(^{-1}\)
- 7 x 3 yr rotations
- 6-12 ODT ha\(^{-1}\) yr\(^{-1}\)
- Small diameter (<10cm)
- High bark to white wood ratio
- 14-28 t CO\(_2\) e ha\(^{-1}\) yr\(^{-1}\)

**Mixedwood Afforestation**
- 11-1600 st ha\(^{-1}\)
  - Hybrid poplar or aspen
- 8-1200 st ha\(^{-1}\) White spruce
- Flexible design and management
- Long term carbon sequestration option
- Fast growing overstory harvested at year 20
- 644 – 820 t CO\(_2\) e ha potentially sequestered over 20 + 50 yr rotation
Afforestation Site Suitability Classification of Non-Forested Lands in Canada
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Woody Biomass Supply Chain Optimization

Innovative Sources

Harvesting Options

Chipper Mulching Head High Compaction Baling System 800-1000kg Bales

Processing and Transportation Options
Woody Biomass Supply Chain Optimization

Woody Biomass Compaction and Long Term Storage Capability!

### February 2015 Moisture Content

<table>
<thead>
<tr>
<th>Type</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
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</thead>
<tbody>
<tr>
<td>Shavings</td>
<td>14.40%</td>
<td>20.50%</td>
<td>16.90%</td>
</tr>
<tr>
<td>Seasoned Chips</td>
<td>35.30%</td>
<td>41.20%</td>
<td>38.25%</td>
</tr>
<tr>
<td>Unhugged Bark</td>
<td>60.90%</td>
<td>62.90%</td>
<td>62.00%</td>
</tr>
<tr>
<td>MPB Harvest Residue</td>
<td>45.00%</td>
<td>50.40%</td>
<td>46.44%</td>
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</table>

### 20+ Month Open Storage Moisture Content

<table>
<thead>
<tr>
<th>Type</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
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</thead>
<tbody>
<tr>
<td>Shavings</td>
<td>9.07%</td>
<td>34.80%</td>
<td>17.83%</td>
</tr>
<tr>
<td>Seasoned Chips</td>
<td>16.47%</td>
<td>38.67%</td>
<td>25.60%</td>
</tr>
<tr>
<td>Unhugged Bark</td>
<td>22.69%</td>
<td>67.29%</td>
<td>46.97%</td>
</tr>
<tr>
<td>MPB Harvest Residue</td>
<td>15.20%</td>
<td>28.83%</td>
<td>21.70%</td>
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</table>

### Parameter Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Shavings</th>
<th>Unhugged Bark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Moisture Content</td>
<td>16.90%</td>
<td>62.00%</td>
</tr>
<tr>
<td>53&quot; Loaded Weight (Unbaled)</td>
<td>8,000 kg</td>
<td>33,010 kg</td>
</tr>
<tr>
<td>53&quot; Loaded Weight (Baled)</td>
<td>18,424 kg</td>
<td>46,544 kg</td>
</tr>
<tr>
<td>Payload Change</td>
<td>130.3% Increase</td>
<td>41% Increase</td>
</tr>
</tbody>
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Wood Biomass Supply Chain Optimization is a critical aspect in the context of Canada’s Forests and the Bio-economy, particularly in addressing Potential Solutions to Climate Change. The compaction and long-term storage capability of woody biomass are essential for efficient and sustainable forest management.
End-User Uptake, Commercialization and Monitoring of SRWC Plantations for Bioremediation

Researchers with the Canadian Wood Fibre Centre (CWF), Natural Resources Canada, have been studying the effects of applying municipal wastewater and biosolids on the fibre production of woody crops. This is an alternative to traditional waste treatment. They are looking at how these systems can utilize organic waste in the production of woody biomass from high-density willow and hybrid poplar plantations. Analysis of the full production process will enable municipalities to assess the system’s suitability for waste treatment and fibre production as well as options available to them in the full management cycle and end use of the crop.

CWF researchers are testing and demonstrating wastewater and biosolids application to both short rotation intensive culture (SRIC) and afforestation systems. These systems require a high level of management, and a predetermined and precise row spacing to optimize biomass yield and stem volume, respectively, and to facilitate weed control.

Short-rotation intensive culture woody crops are established at densities of 15,000–20,000 stems per hectare (shp) in a two-row bed pattern. Cropped are harvested on a three-year rotation with a full SRIC cycle encompassing seven to eight rotations or 21–24 years on the same root system. The SRIC crops research focuses on willow. Fast growth, ease of propagation, ability to be coppiced, high water use, and potential for genetic improvement make willow ideally suited for biomass production and treatment of wastewater and biosolids.

For the hybrid poplar afforestation system, planting densities range from 600 to 2000 shp. The trees are used for traditional forest product manufacture. Hybrid poplar planted on the research site at Claresholm, Alberta, at 900 shp are expected to be harvested approximately 5–7 years sooner with irrigation than the expected 10–15-year rotation with no irrigation. The harvested material will be used at the Almacor Engineering OSB plant in neighboring Grande Prairie, Alberta.

CWF’s researcher Richard Kogler started this project in the spring of 2006 with the establishment of western Canadian first municipal wastewater-irrigated SRIC willow and poplar plantations at Whitewood, Alberta. He wanted to determine if the proven European technology for wastewater and biosolids application to SRIC crops would work as well to increase woody biomass production in Alberta. Concurrently, the Canadian Council of Ministers of the Environment was developing new stricter standards for the discharge of municipal wastewater. Interest in this concept grew as municipalities looked at creative and cost-effective ways of not disposing of storm water flow in sewers.
**Revegetation of Phospho-Gypsum Stacks**

**Objectives**
- To improve the long term sustainability, ecosystem diversity, and aesthetic values,
- reducing long term maintenance costs of the site,
- provide biomass that could be used for energy production, sequestering carbon,
- utilize excess nutrients/water resulting in improved groundwater quality.

**Methods**
- Use SRWC as a revegetation/site rehabilitation option,
- establishing concentrated biomass beds of willow and hybrid poplar on reclaimed storage pond site,
- establishing high yield afforestation plantations of hybrid poplar on re-engineered phosphor-gypsum stacks,
- establish tolerant conifer (white spruce) in high yield afforestation plantations once sites close canopy.
Investigating the potential of willow biomass, used to treat wastewaters, for the production of biofuels and bioproducts

Frederic Pitre, Ph.D.
Researcher, IRBV
Adj. Prof. Université de Montréal
Lignocellulosic bioenergy and bioproduct platform from sustainable bioremediation

Cultivar Specific Responses
- Interactions between genotypic variation and bioremediation

Bioremediation
- Contaminated land cultivation
- Wastewater treatment ($2^\circ + 3^\circ$)

Phytochemical production
- Phenolic profiling and selection
  - High value green chemicals

Lignocellulosic bioenergy
- Biomass composition + accessibility
  - Pretreatment severity reduced

Outcomes
- Added-value cultivation
- Reduced energy input lignocellulosic yields
  - High value chemical induction

Integration
- Bioremediation with integrated value-added biomass production
- Energy and environmental impact optimised process for end-users
- Improved economic feasibility of each process through complementarity
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**Bioremediation**
- Contaminated land cultivation
- Wastewater treatment $(2^\circ + 3^\circ)$

**Phytochemical production**
- Phenolic profiling and selection
- High value antioxidants

**Lignocellulosic bioenergy**
- Biomass composition + accessibility
- Pretreatment severity reduced

Willow wastewater treatment can replace current engineering solutions at a 3rd of the cost and with positive environmental impact.

Phytoremediation can both clean contaminated land and drive urban greening for clear positive societal impact in Canada.

*Alberta Rural Organic Waste to Resources Network*

(Krygier and Blank)
Large Potential

Medical
Nutraceutical
Cosmetic
Assainissement

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**Induction**
Willow tolerate stress due to advanced chemistry (>8000 chemicals) – does bioremediation increase green chemical yields?

**Reduced inhibitors**
Extraction of supplementary valuable chemicals also improves pyrolysis efficiency – does extraction help enzymatic biofuel production?

**Bioremediation**
- Contaminated land cultivation
- Wastewater treatment (2° + 3°)

**Phytochemical production**
- Phenolic profiling and selection
- High value green chemicals

**Lignocellulosic bioenergy**
- Biomass composition + accessibility
- Pretreatment severity reduced

**Low/no cost feedstock**
Biomass produced from wastewater treatment or land decontamination can entirely negate cultivation costs – can it improve wood quality for biofuels?
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**Bioremediation**
- Contaminated land cultivation
- Wastewater treatment ($2^\circ + 3^\circ$)

**Phytochemical production**
- Phenolic profiling and selection
- High value green chemicals

**Lignocellulosic bioenergy**
- Biomass composition + accessibility
- Pretreatment severity reduced

High yields even *without* induction from phytoremediation stress

---

**Condensed tannins kg ha$^{-1}$ yr$^{-1}$**
- La Pocatiere
- Saint Siméon (Gaspésie)
- Beloeil
- Saint Roch de l’Achigan

**Flavonoids kg ha$^{-1}$ yr$^{-1}$**
- La Pocatiere
- Saint Siméon (Gaspésie)
- Beloeil
- Saint Roch de l’Achigan
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Phytoremediation
• Contaminated land cultivation
• Wastewater treatment (2o + 3o)

Phytochemical production
• Phenolic profiling and selection
• High value green chemicals

Lignocellulosic bioenergy
• Biomass composition + accessibility
• Pretreatment severity reduced

High genotype variability in biofuel potential (cell wall sugar accessibility)

Environmental stress can modify wood and increase biofuel potential

Graphs showing glucose release and final glucose yield g⁻¹ DM under low and high stress field conditions.
References


The CWFC has developed a comprehensive package of collaborative operational research to assist end users with research and technology development to position themselves into a thriving bio-economy!

✓ Combining biomass inventory information with operational harvesting and processing research and supply chain optimization enables end users to evaluate a wide range of potential bio-economy options!

✓ Developing establishment and management protocols for Short Rotation Woody Crops for afforestation and bio-remediation and carbon sequestration opportunities provides end users with multiple revenue streams!
Take Home Messages

The CWFC has developed a comprehensive package of collaborative operational research to assist end users with research and technology development to position themselves into a thriving bio-economy!

- Utilizing wood ash could improve soil fertility and forest health, divert materials from landfills and close a loop in the cycling of nutrients making forestry operations and the development of Canada’s bio-economy more sustainable.

- Incorporating storage options and real-time pile monitoring methods gives precision data on pile dynamics, leading to development of much better management techniques to minimize loss in biomass quality and quantity.

- Enhanced physical and chemical biomass characterization can be used to assist in the development and production of commercially viable bio-products.
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– Potential Solutions to Climate Change!

Questions!!!

2017-18 CIF e-Lecture Series
“Innovative Solutions to Respond to the Challenge of a Changing Climate”