Emerging Forest-based Products and Processes

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Forest Biomaterials
(formally Wood and Paper Science)

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Center on Global Change
Duke University
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- **PhD, Chemical Engineering, Polymer Physics, 1994 Princeton University**
- **Taught at NCSU in Forest Biomaterials Department for 17 years**
- **Research (papers)**
  - Separation (Solid-Solid) Processes, Recycling (45)
  - Novel materials from wood (plastics, gels, foams) (50)
  - Biofuel production (10)
  - Life Cycle analysis (0)
- **On sabbatical, Duke University, January-July, 2011, hosted by Robert Jackson and the Center for Global Change**
  - Goal: learn LCA, energy/environment, others
  - Goal: interact with all those interested, develop collaborations
Outline

• Challenges in biofuels
• Forest Biomaterials Biofuels Research
• Examples of biofuels research
  – Biomass procurement analysis
  – Harvesting products as byproducts from wood
  – LCA of biofuel production
• Summary
Sustainable Biofuel Industry?

• One should expect that, within a few thousand years of its entering the stage of industrial development, any intelligent species should be found occupying an artificial biosphere which completely surrounds its parent star. --Freeman Dyson, 1978.

• The notion that science will save us “is the sedative that allows civilization to march so steadfastly towards environmental catastrophe” --Kenneth Brower, Science, 2010.

• Biofuels?
Global Carbon Cycle and Forests?

- Atmospheric concentration of CO2 has increased by 31% since 1750 (to 390 from 280 ppm) and by 1.5 ppm/yr for 1980-2000 (IPCC 2001)

- Forests are significant in global GHG (Landsberg & Gower, 1997):
  - Cover 65% of the total land
  - Contain 90% of the total vegetation carbon
  - 80% of total soil carbon in terrestrial ecosystems
  - Assimilate 67% of the total CO2 removed from the atmosphere by all terrestrial ecosystems
Figure 1 Conceptual diagram of the forest C cycle. The forest C cycle is comprised of a biological cycle (i.e., forest ecosystem) and an industrial cycle (i.e., forest products).

Gower 2003
Global Carbon Cycle and Forests?

Fig. 1 Estimates of the global pools and fluxes between them.\textsuperscript{1,4,5,7,152}
The black numbers indicate how much carbon is stored in various reservoirs, in billions of tons ("GtC" stands for GigaTons of Carbon and figures are circa 2004). The dark blue numbers indicate how much carbon moves between reservoirs each year. The sediments, as defined in this diagram, do not include the ~70 million GtC of carbonate rock and kerogen.
State of Biofuels relative to US Energy Demands


**Figure 2: Summary of biomass resource consumption**

<table>
<thead>
<tr>
<th>Biomass Consumption</th>
<th>Million dry tons/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest products industry</td>
<td></td>
</tr>
<tr>
<td>Wood residues</td>
<td>44</td>
</tr>
<tr>
<td>Pulping liquors</td>
<td>52</td>
</tr>
<tr>
<td>Urban wood and food &amp; other process residues</td>
<td>35</td>
</tr>
<tr>
<td>Fuelwood (residential/commercial &amp; electric utilities)</td>
<td>35</td>
</tr>
<tr>
<td>Biofuels</td>
<td>18</td>
</tr>
<tr>
<td>Bioproducts</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>190</td>
</tr>
</tbody>
</table>

Forestlands and agricultural lands contribute 190 million dry tons of biomass - 3% of America's current energy consumption.
2007 Energy Independence and Security Act

- Replace 30% of petroleum consumption by 2022
- 36 Billion Gallons of Renewable Fuel
- 15 Billion Gallons from Corn Ethanol
- 16 Billion Gallons from Cellulosic Biofuels

Growing gap. Energy legislation from 2007 mandates an increasing share of cellulosic ethanol (dark green). But the industry is already falling behind.
Challenges: Quantities

- To replace 30% of petroleum consumption in the US, it is estimated that 1 billion OD tons of biomass/yr needed.
- 368 million OD tons/yr forest matl out of 8.4 billion tons standing, 1/20
- 998 million OD tons agricultural out of the 1.2 billion tons available per yr, 1/1
- Figures are optimistic: light economics, including assumed yield increases, no till, changing crops and land uses

Challenges: Quantities

- International Energy Agency estimates a 50% reduction of GHG by 2050 to require a factor of 4 increase in bioenergy production, up to 20% of the world primary energy.

- If one type of material was used to fulfill this, the corresponding volume required is shown.

- In contrast the global volumes handled currently:
  - Total of rice, wheat, soybeans, maize, others is 2.75 bcm
  - Coal 6.2 bcm/yr
  - Oil 5.7 bcm/yr

### Challenges: Low Energy Density

**Table 3.5. Density and volumetric energy content of various solid and liquid fuels**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Density (kg/m³)</th>
<th>Volumetric Energy Content (GJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>790</td>
<td>23.5</td>
</tr>
<tr>
<td>Methanol</td>
<td>790</td>
<td>17.6</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>900</td>
<td>35.6</td>
</tr>
<tr>
<td>Pyrolysis oil</td>
<td>1280</td>
<td>10.6</td>
</tr>
<tr>
<td>Gasoline</td>
<td>740</td>
<td>35.7</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>850</td>
<td>39.1</td>
</tr>
<tr>
<td>Agricultural residues</td>
<td>50–200</td>
<td>0.8–3.6</td>
</tr>
<tr>
<td>Hardwood</td>
<td>280–480</td>
<td>5.3–9.1</td>
</tr>
<tr>
<td>Softwood</td>
<td>200–340</td>
<td>4.0–6.8</td>
</tr>
<tr>
<td>Baled straw</td>
<td>160–300</td>
<td>2.6–4.9</td>
</tr>
<tr>
<td>Bagasse</td>
<td>160</td>
<td>2.8</td>
</tr>
<tr>
<td>Rice hulls</td>
<td>130</td>
<td>2.1</td>
</tr>
<tr>
<td>Nut shells</td>
<td>64</td>
<td>1.3</td>
</tr>
<tr>
<td>Coal</td>
<td>600–900</td>
<td>11–33</td>
</tr>
</tbody>
</table>


**Note:** GJ = Gigajoules.

- **R. C. Brown, Biorenewable Resources, Engineering New Products from Agriculture, Blackwell Pub, 2003.**
Challenges: Land Mass Required

Challenges: Solids Handling

- Transport, communication, measurement, and dosing problematic
- Storage conditions important
  - Moisture and temperature sensitive
  - Break down through the action of a naturally occurring microorganisms, such as bacteria, fungi, etc.
- Low bulk density

How the current forest products industry might fit in.

Chemical Components of Wood

- **LIGNIN**
  - SW 25%
  - HW 21%

- **CELLULOSE**
  - 45%

- **HEMICELLULOSE**
  - SW 25%
  - HW 30%

- **EXTRACTIVES**
  - 2-5%

**Wood**

- Carbohydrate
- Lignin
- Hemicellulose

**Cellulose:**
- DP=4000
- “Polymer” Value

**Lignin Crosslinked**
- “Heat” Value

**Hemicellulose:**
- DP=150
- “Sugar” Value
Current: wood to paper process

Logs → Debarking Drum → Chips → Chipper & Screens → Caustic Plant → Recovery Boiler → Turpentine

White Liquor (Na₂S, NaOH) → Lime Kiln → Lime Mud (CaCO₃) → Pulp & Black Liquor

Green Liquor (Na₂S, Na₂CO₃) → Evaporators

Lignin and Hemicellulose → Fatty Acids → To Paper Machine

CaCO₃ → Lime

Steam → Turbine Generator

Wash Water → Bleach Pulp Storage → Bleach Plant

Strong Black Liquor

Weak Black Liquor → Pulp & Cleaners

Boiler

Lime

Na₂S, NaOH

Na₂S, NaOH

CaCO₃
Current Wood Processing Industry

Wood used to manufacture paper

90xE6 MT CO2

O2

Purchased Fossil Fuel & Power: 0.9 Quads

Black Liquor & Residuals

Steam, Power & Chemicals

Source: Bioenergy Deployment
Proposed: Biorefinery Industry

- **Steam, Power & Chemicals**: $17 billion
- **Black Liquor & Residuals**: Extracted Hemicellulose and other chemicals
- **Gasifiers**: Combined Heat/Power Conversion to chemicals and biofuels
- **Wood used to manufacture paper**: Paper Products $5.5 billion
- **O2**: $66x10^6 MT CO2
- **Biofuels/Chemicals**: $17 billion

Source: Bioenergy Deployment
Faculty in Bioenergy Science and Technology

Dimitris Argyropoulos  
Professor  
Wood Chemistry

Med Byrd  
Associate Professor  
Process Development

Hou-min Chang  
Professor Emeritus  
Wood Chemistry

Vincent Chiang  
Professor  
Forestry Biotechnology

John Heitmann  
Professor  
Enzyme Biotechnology

Martin Hubbe  
Professor  
Surface Chemistry

Hasan Jameel  
Professor  
Process Engineering

Stephen Kelley  
Dept Head & Professor  
Polymer Chemistry

Adrianna Kirkman  
Professor  
Process Simulation

Lucian Lucia  
Associate Professor  
Wood Chemistry

Sunkyu Park  
Assistant Professor  
Bioenergy Process

Richard Phillips  
Executive in Residence  
Bioenergy Economics

Orlando Rojas  
Associate Professor  
Surface Chemistry

Daniel Saloni  
Assistant Professor  
Process Development

David Tilotta  
Associate Professor  
Wood Chemistry

Richard Venditti  
Professor  
Process Engineering
Bioenergy Projects

- Bioethanol Pilot Plant
- Wood-to-Ethanol Research Consortium
- Value Prior to Pulping (VPP)
- Ethanol from Transgenic Hardwoods
- Ethanol from Coastal Bermuda Grass
- Enhancing Wood Penetration for More Efficient Hydrolysis and Optimized Saccharification
- Opportunities with Dissolved Wood for the Forest Biorefinery
- Validation of Therminator Syngas Cleanup
- Advanced Technology for Low Cost Ethanol from Engineered Cellulosic Biomass
- Economics and Feasibility of North Carolina Biomass Conversion
- Producing Ethanol from Biomass by Extracting Value Prior to Extraction
- Low Cost Conversion of Industrial Sludges to Ethanol
- Integrated Torrefaction-Gasification for the Production of Biofuels
- Economic Analysis of Pine Biomass Varieties for Ethanol Production
- Life Cycle Analysis for the Production of Transportation Fuels
- Fast Pyrolysis of Forestry Biomass
Wood to Ethanol Research Consortium (1)

• Paper industry in US has idled about 25% of its production, about 50 million tons/yr of wood processing (potential of 4 billion gallons of ethanol)

• Concept: Repurposing a kraft pulp mill into a ethanol mill

• Develop cost effectiveness by reusing existing asset: a pulp mill is about $1 Billion in capital
80% of sugars in wood can be converted by enzymatic hydrolysis when wood is pretreated with green liquor.
Ethanol from Transgenic Hardwoods

- Challenge: bioconversion of wood to ethanol, wood is recalcitrant to enzyme hydrolysis, low sugar yields
- Must pretreat wood with alkali, acid...
- Evaluate potential for simplifying pretreatments for low/modified lignin hardwood (aspen)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Lignin</th>
<th>S/G</th>
<th>Glucan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wildtype</td>
<td>23</td>
<td>2.2</td>
<td>44</td>
</tr>
<tr>
<td>TG96</td>
<td>24</td>
<td>6.4</td>
<td>45</td>
</tr>
<tr>
<td>TG141</td>
<td>11</td>
<td>2.6</td>
<td>54</td>
</tr>
</tbody>
</table>

Figure 1. Effect of lignin content on glucose yield from wildtype and transgenic woods
Low Cost Conversion of Industrial Sludges to Ethanol

- Biofuels Center of North Carolina
- Demonstrate an effective technology to convert industrial papermaking sludge as a cost effective feedstock for the efficient biochemical biomass conversion to ethanol

Papermaking Sludges

![Graph showing composition of sludges]

Negative feedstock cost
Contains CaCO$_3$ and inorganics
A closer look at three Biofuels projects:

1. Integrated biomass supply and financial models
2. Extraction of hemicellulose for higher valued products
3. Thermoconversion of Biomass to Liquid Fuel
1: Integrated Biomass Feedstock Supply and Financial Models

Ronalds Gonzalez, Hasan Jameel, Richard Phillips
Biorefinery

- Dilute acid
- Thermochem
- GL
- ZeaChem

Freight

- $/BDT
- Bulk density

Storage

- $/BDT
- Sugar/Biomass loss

Integrated Supply and Financial Models

- Land available to grow biomass?
- What are the strategies for conversion of land use?
- Whole tree chemical composition?

Harvesting

- Biometrics
- $/acre; $/BDT
- Ton Carbohydrate/acre
SUPPLY CHAIN ASSESSMENT

- Integrated feedstock supply
- Biomass availability – curve supply
- Delivery costs, economic analysis
- Supply chain and logistic analysis
Biomass to Cellulosic Ethanol in Southern U.S.: Supply Chain and Delivered Cost
Biomass productivity and hectares required for production to supply 453,597 dry ton yr\(^{-1}\).
Sourcing distance (km) and productivity (dry ton ha\(^{-1}\) yr\(^{-1}\)) for the different feedstocks
Biomass delivered cost for each of the feedstock, considering 5% covered area and annual supply of 453,597 dry ton year⁻¹
**PROCESS SIMULATION – CONVERSION ECONOMICS**

- Conversion simulation
- Lab demonstration, pretreatments
- Integrated analysis feedstock – final product
- CAPEX & OPEX
- Industrial contacts – real financial analysis

**Diagram Notes:***
- Logs → Debarking Drum → Chips
- Pulp & Black Liquor → Evaporators → Strong Black Liquor → Smelt → Weak Black Liquor → Washers → Pulp
- Green Liquor Na₂S, Na₂CO₃ → Clarifier → Digestor → Recovery Boiler → Steam
- Enzymatic hydrolysis → Lignin filter → Ethanol

**Diagram Labels:***
- Logs
- Debarking Drum
- Chips
- Pulp & Black Liquor
- Evaporators
- Strong Black Liquor
- Smelt
- Weak Black Liquor
- Washers
- Pulp
- Green Liquor Na₂S, Na₂CO₃
- Clarifier
- Digestor
- Recovery Boiler
- Steam
- Enzymatic hydrolysis
- Lignin filter
- Ethanol

**Costs and revenues (US$ per gallon ethanol):***
- Ethanol subsidy: 1.01
- Ethanol price: 36

**Cost Breakdown:**
- Other fixed costs: 5.3%
- Overhead: 11.8%
- Maintenance: 9.7%
- Depreciation: 31.3%
- Labor: 4.0%
- Chemicals: 2.7%
- Biomass: 35.2%

**Achieve:**
- Costs and revenues (US$ per gallon ethanol):
  - 0.80
  - 0.30
  - 0.20
  - 0.70
  - 1.70
  - 2.20

**Innovation in Action:**
- NCSU
- Stan 108
EXAMPLE CASE: COSTS AND REVENUES:

Production costs, cash cost and share cost for ethanol for natural mixed hardwood in the repurposing green liquor scenario.
2: Extraction of Hemicellulose from Wood for Ethanol and Biopolymer Gels

Abdus Salam, Richard Venditti, Joel Pawlak, Khaled El-tahlawy
Value Prior to Pulping or Combustion

- Extract hemicelluloses prior to pulping or combustion and convert to ethanol or chemicals
- Only hot water is required! (Autohydrolysis)
Hot water extraction of hardwood:

**Raw material:** 100g
- Arabinan: 0.78g
- Rhabinin: 0.47g
- Galactan: 0.97g
- Glucan: 39.22g
- Xylan: 16.17g
- Mannan: 1.63g
- Klason Lignin: 22.36g
- ASL: 3.74g
- Acetic acid: N/A
- Furfural: 0.68g
- Others: 13.98g

160 °C
1 hour

**Pretreated solids:** 78.13g
- Arabinan: 0g
- Rhabinin: 0g
- Galactan: 0g
- Glucan: 38.40g
- Xylan: 7.43g
- Mannan: 1.06g
- Klason Lignin: 19.95g
- ASL: 1.72g
- Acetic acid: N/A
- Furfural: 0.75
- Others: 8.71g

**Extract:** 15.59g
- Arabinan: 0.55g
- Rhabinin: 0.14g
- Galactan: 0.21g
- Glucan: 0.05g
- Xylan: 1.10g
- Mannan: 0.05g
- Klason Lignin: N/A
- ASL: 2.36g
- Acetic acid: 2.44g
- Furfural: 1.25g

**Sugar in filtrate:** 9.81g
- Arabinan: 0.54g
- Rhabinin: 0.28g
- Galactan: 0.61g
- Glucan: 0.25g
- Xylan: 7.56g
- Mannan: 0.57g

3% H$_2$SO$_4$
Cross Linking of Hemicellulose Citrate with Chitosan to Make High Value Foams

1. 

Hemicellulose: DP=150
“Sugar” Value

2. 

Citric Anhydride

3. 

Hemicellulose Citrate  Chitosan  Cross linked Hemicellulose Citrate–Chitosan
Hemicellulose Citrate Chitosan based elastic foam
Absorption properties of hemicellulose citrate-chitosan foam (vacuum filtration)

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Water absorption percent with DI water at 1hr</th>
<th>Water absorption percent with 0.9% NaCl at 1hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chitosan</td>
<td>640</td>
<td>550</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>120</td>
<td>160</td>
</tr>
<tr>
<td>Hemicellulose citrate</td>
<td>350</td>
<td>380</td>
</tr>
<tr>
<td>Hemicellulose/Chitosan foam</td>
<td>360</td>
<td>390</td>
</tr>
<tr>
<td>Hemicellulose citrate Chitosan foam</td>
<td>1520</td>
<td>1780</td>
</tr>
<tr>
<td>Commercial Cellulose foam</td>
<td>210</td>
<td>260</td>
</tr>
<tr>
<td>Acrylic Acid based Super Absorbent Polymer</td>
<td>14880</td>
<td>1800</td>
</tr>
</tbody>
</table>
Desalination

Proposed technology to reduce brackish water from 3000 to 500 ppm salt content with two applications of HCC gel at 1:40 ratio.
Water Remediation Material: Arsenic Removal

<table>
<thead>
<tr>
<th>Sample</th>
<th>Metal Loading (mg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemicellulose citrate-chitosan</td>
<td>1.28</td>
</tr>
<tr>
<td>Starch citrate-chitosan</td>
<td>1.84</td>
</tr>
<tr>
<td>Starch citrate</td>
<td>1.16</td>
</tr>
<tr>
<td>Starch</td>
<td>0.43</td>
</tr>
<tr>
<td>Chitosan</td>
<td>0.88</td>
</tr>
<tr>
<td>Sorba Tech 450</td>
<td>0.10</td>
</tr>
<tr>
<td>LaneRT</td>
<td>0.40</td>
</tr>
<tr>
<td>Alumina</td>
<td>0.48</td>
</tr>
<tr>
<td>Purolite FerrIX A33E</td>
<td>0.54</td>
</tr>
<tr>
<td>Absorbia GTO</td>
<td>0.04</td>
</tr>
</tbody>
</table>

- Arsenic uptake for various materials in a 5 PPM solution. (Absorbent 0.025g, 50ml, 6 minutes).
- TOF SIMS with a Bismuth(+3) primary ion beam.
3: Process Model Based LCA of Biofuels Production

Jesse Daystar, Richard Venditti, Hasan Jameel
Thermal conversion of biomass to ethanol
LCA Approach

Establish System Boundaries → ASPEN Plus Simulation → SimaPro → Inventory → Impact Assessment → Informed Biomass/Energy Decision Making

System Boundaries

- Raw materials
- Landfill
- Upstream fuel/emissions
- Energy
- Transport
- Intermediates
- Transport
- Production
- Product
Gate-to-Gate
Operating Parameters

• Facility size
  – Matches production of the NREL biochemical process model
    • 2,205 dry ton/day
    • 772,000 dry ton/year
    • 1,544,000 wet ton/year delivered
  – Evaluate Various promising feedstocks

• No full scale plant exists currently
System Boundary: Gate to Gate, circled operations considered
# Alcohol Yields

## Process Model Results

### Forest

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Hybrid poplar</th>
<th>Mixed hwd</th>
<th>Loblolly</th>
<th>Eucalyptus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units: (gal/OD ton)</td>
<td>Δ %</td>
<td>Δ %</td>
<td>Δ %</td>
<td>Δ %</td>
</tr>
<tr>
<td>Total gallons per OD ton</td>
<td>106</td>
<td>1.8%</td>
<td>5.6%</td>
<td>-3.5%</td>
</tr>
</tbody>
</table>

### Energy Crops

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Hybrid poplar</th>
<th>Corn stover</th>
<th>Switch grass</th>
<th>Miscanthus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units: (gal/OD ton)</td>
<td>Δ %</td>
<td>Δ %</td>
<td>Δ %</td>
<td>Δ %</td>
</tr>
<tr>
<td>Total gallons per OD ton</td>
<td>106</td>
<td>-13.0%</td>
<td>-5.3%</td>
<td>-5.4%</td>
</tr>
</tbody>
</table>
# GHG Emissions

## Process Model Results

### Forest Resources

<table>
<thead>
<tr>
<th>GHG Emissions</th>
<th>Hybrid poplar</th>
<th>Mixed hardwood</th>
<th>Loblolly pine</th>
<th>Eucalyptus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>-</td>
<td>Δ %</td>
<td>Δ %</td>
<td>Δ %</td>
</tr>
<tr>
<td>lbs CO₂ eq. /gal eth</td>
<td>23</td>
<td>-4.1%</td>
<td>-5.4%</td>
<td>2.8%</td>
</tr>
</tbody>
</table>

### Energy Crops

<table>
<thead>
<tr>
<th>GHG Emissions</th>
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<th>Miscanthis</th>
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<tr>
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<td>-</td>
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<td>Δ %</td>
</tr>
<tr>
<td>lbs CO₂ eq. /gal eth</td>
<td>23</td>
<td>-0.3%</td>
<td>-2.8%</td>
<td>-2.5%</td>
</tr>
</tbody>
</table>
Sensitivity to Moisture Content

![Graph showing the relationship between Yield, Δ% gallon/ton, Δ% GHG per gallon, and % Moisture Content. The graph includes two lines: one for Yield gallon/OD ton (blue line) and another for lb CO2 per gallon (red line). The x-axis represents % Moisture Content ranging from 30 to 60, while the y-axis represents Yield Δ% gallon/ton and Δ% GHG per gallon ranging from -15% to 15%. The graph illustrates that as % Moisture Content increases, the Yield gallon/OD ton decreases, and the Δ% GHG per gallon increases.]
Cradle-to-Grave
Operating Parameters

• Facility size
  – Matches the NREL biochemical process
    • 2,205 dry ton/day
    • 772,000 dry ton/year
  – Moisture content @50%
    • 1,544,000 wet ton/year delivered
  – Feedstock:
    • Softwood chips: SimaPro data for preliminary analysis
Cradle to Gate System Boundary

- Raw materials
- Intermediate Materials
- Production
- Landfill
- Waste
- Energy
- Fuels
- Upstream fuel/energy emissions

System Boundary
## GHG Emissions

<table>
<thead>
<tr>
<th>GHG Emissions by process</th>
<th>tons CO₂ eq / yr</th>
<th>lb CO₂/OD ton wood</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hauling</td>
<td>4064</td>
<td>8</td>
<td>1.2%</td>
</tr>
<tr>
<td>Feller-buncher</td>
<td>51067</td>
<td>102</td>
<td>15.1%</td>
</tr>
<tr>
<td>Pick up truck</td>
<td>91</td>
<td>0</td>
<td>0.03%</td>
</tr>
<tr>
<td>Timber jack, Skidder</td>
<td>67664</td>
<td>135</td>
<td>20.1%</td>
</tr>
<tr>
<td>Prentice</td>
<td>37024</td>
<td>74</td>
<td>11.0%</td>
</tr>
<tr>
<td>450 hp 3-Knife Chipper</td>
<td>168704</td>
<td>337</td>
<td>50.0%</td>
</tr>
<tr>
<td>Reforesting emissions (no seedlings)</td>
<td>6227</td>
<td>12</td>
<td>1.8%</td>
</tr>
<tr>
<td>Seedlings emissions</td>
<td>1</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Fertilizer emissions</td>
<td>2465</td>
<td>5</td>
<td>0.7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>337307</strong></td>
<td><strong>675</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>
Gas vs. Ethanol
Single Score

Total Environmental Impacts

Pt is the unit of environmental impact in eco-points
Summary

• Enormous challenges exist for the Biofuels industry

• Impacts of a Biofuels industry are not known currently

• Selected biomass sources, technologies and products hold potential and may contribute to the world’s needs

• NCSU is active in developing new processes, products and analysis tools for biofuels
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Questions?