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Life Cycle Assessment of Cellulosic Biofuels and Bio-Energy In the Southern U.S.

Jesse Daystar[1,2], Carter Reeb[1,2], Ronalds Gonzalez[1],
Richard Venditti[1], Steve Kelley[1]

[1]Department of Forest Biomaterials
North Carolina State University
[2]Triangle Life Cycle Assessment

Triangle Life Cycle Assessment

IBSS Webinar Series
September 24th, 2013

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Outline

- Introduction to LCA
- Feedstock production LCA
- Thermochemical ethanol production LCA
- Final conclusions

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Policy forces driving adoption of biofuels

Energy Security

Climate Change

Rural Development

Convergence of forces will accelerate biofuels adoption

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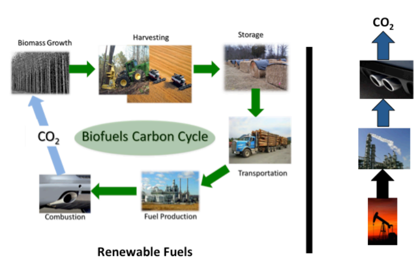
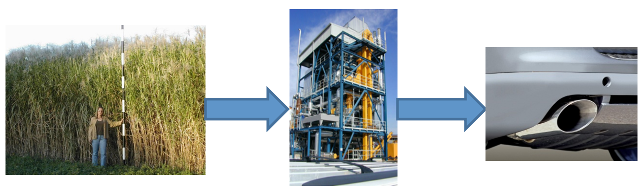
RFS 2 Feedstocks for Cellulosic Biofuels

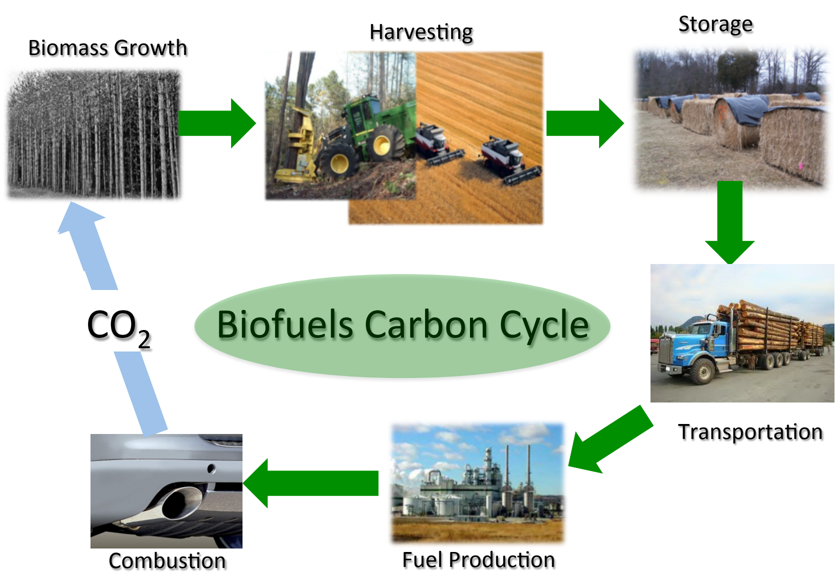
- Approved Cellulosic Feedstocks
  - Cellulosic crop residue
  - Slash
  - Pre-commercial thinnings and tree residues
  - Cellulosic components of yard waste
  - Cellulosic components of MSW
  - Annual cover crops
  - Switchgrass
  - Miscanthus
  - Energy cane
  - Arundo donax
  - Pennistetum purpureum



RFS2 Greenhouse Gas Reduction Thresholds

Required Green House Gas Reductions (EISA and RFS) (percent reduction from 2005 baseline fossil fuel equivalent)	
Renewable fuel	20%
Advanced biofuel	50%
Biomass-based diesel	50%
Cellulosic biofuel	60%





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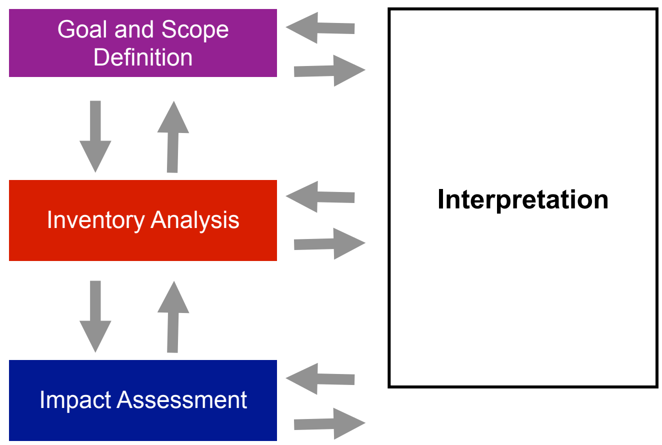
Life Cycle Assessment

LCA is the evaluation of environmental impacts from a product, service or good



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Environmental Life Cycle Assessment

- LCA Method
  - Develop a goal
  - Define a scope (boundaries, functional unit)
  - Life cycle inventory
    - Tabulation of all material flows that cross the system boundary
  - Life cycle impact assessment
    - Flows into and out of the environment
  - Interpretation, sensitivity/uncertainty analysis, and recommendations
  - The last activity typically redefine the analysis and iterate

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Biofuel Greenhouse Gas Studies

Feedstock	GHG Displacement %	S	Feedstock	GHG Displacement %	S
Switchgrass	-114	1	Corn	-86	9
Switchgrass combustion compared with coal combustion	-109	2	Corn-soy	-38	10
Miscanthus (gasification)	-98	3	Corn (starch)	-25	11
Switchgrass	-93	4	Corn (starch)	-24	12
Switchgrass	-73	5	Corn	-3	13
Switchgrass	-11	6	Corn (starch)	66	14
Switchgrass	43	7	Corn (starch)	93	15
Switchgrass	50	8			

Sources: [1](Adler, Grosso et al. 2007), [2](Ney and Schnoor 2002), [3](Lettens, Muys et al. 2003), [4](Schmer, Vogel et al. 2008), [5](Wu, Wu et al. 2006), [6](Lemus and Lal 2005), [7](Delucchi 2006), [8](Searchinger, Heimlich et al. 2008), [9](Delucchi, 2006), [10](Adler, Grosso et al. 2007) [11](DiPardo 2004), [12](Wu, Wu et al. 2006), [13](Niven 2005), [14](Delucchi, 2006), [15](Searchinger, Heimlich et al. 2008) (Table modified from Davis et al 2009)

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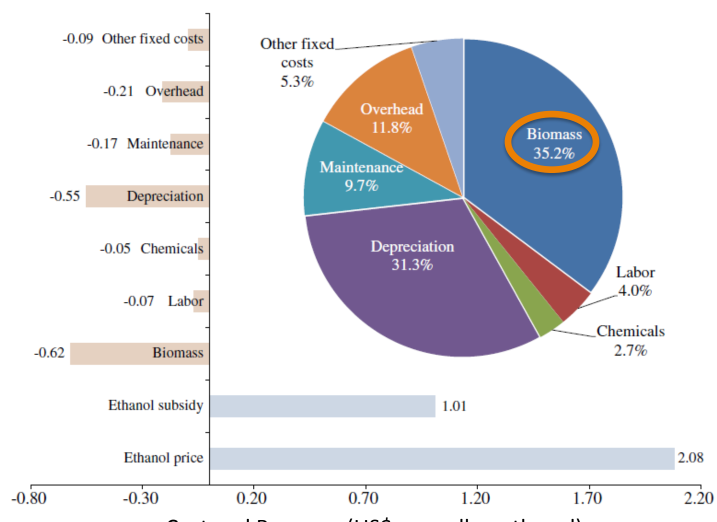
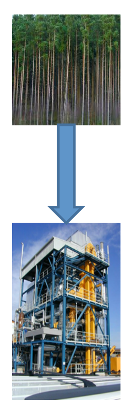
Ethanol Production Costs





2. Ethanol production costs (US$ per gallon ethanol) and cost share (%), using loblolly pine as feedstock. 1 gal = 3.7854 l.

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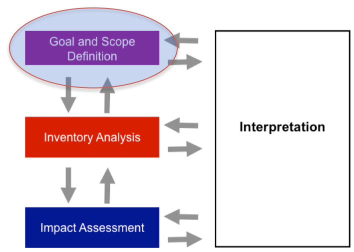
Objectives:

Environmental assessment and financial analysis of cellulosic feedstock production for biofuels

- Goal
  - Identify feedstock production scenarios with lowest environmental impacts and GHG emissions
  - Determine feedstocks with the lowest delivered costs
- Scope
  - Functional units:
    - Tonne dry biomass
    - Tonne carbohydrates
    - Million BTU
  - Cradle-to-Gate



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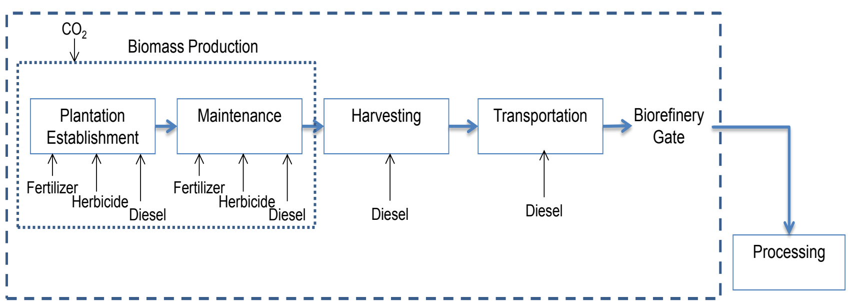
System Boundaries:

Loblolly Pine & Eucalyptus



Loblolly Pine

Eucalyptus

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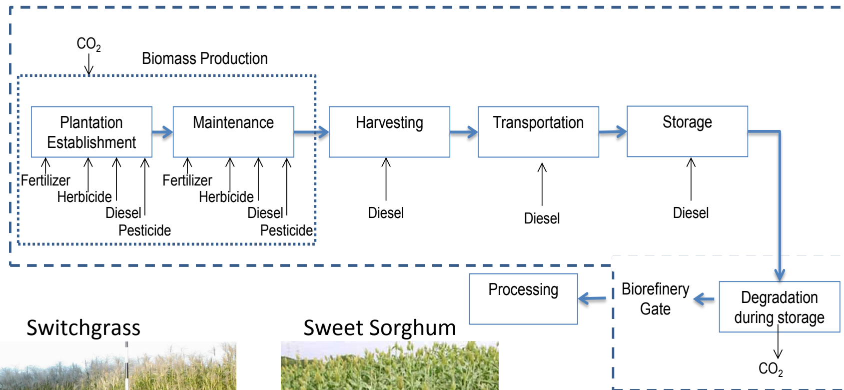
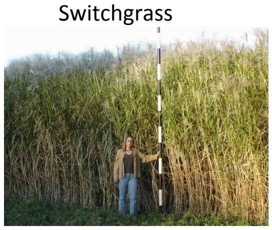
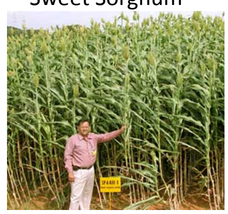
System Boundaries:
Switchgrass & Sweet Sorghum



Switchgrass



Sweet Sorghum



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Financial Analysis

Set variable
Tons per year

Establishment and Maintenance

Input
- Growth
- Establishment cost
- Maintenance cost
- Moisture content
- Energy content
- Chemical composition
- Discount rate
- Expected IRR
- Tax

Output
- Acres
- Cost per ton
- Cost per ton of carbohydrate
- Cost per million BTU

Harvesting

Input
- Published harvesting cost

Output
- Harvesting cost per green ton
- Harvesting cost per dry ton

Storage

Input
- Bulk density
- Moisture content
- % Biomass to storage
- CAPEX per square foot
- Discount rate
- Tax
- Expected IRR

Output
- Storage cost per ton

Transportation cost

Input
- Bulk density
- Moisture content
- % covered area
- Transportation fee
- Biomass productivity
- Transportation unit capacity

Output
- Freight cost per ton

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Biomass Production Input Parameters

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Description	Loblolly pine	Eucalyptus	Unmanaged hardwood	Switchgrass	Sweet sorghum	Forest residues
Productivity (dry ton acre^{-1} year^{-1})	7.6	7.8	1.0	8.0	0.4	.04
Rotation length (years)	12	4	50	n/a	n/a	n/a
Harvesting window	Year round	Year round	Year round	Three months	Three months	Year round
Moisture content	45%	45%	45%	16%	74%	45%
Delivery form	Logs	Logs	Logs	Square bales	Cane	Chips
Trees per ha	2,965	1,400	n/a	n/a	n/a	n/a
Establishment cost ($/acre)	257	223	0.0	73	168	n/a
Maintenance cost ($/acre)	25 [1]	25[1]	0.0	35[2]	n/a	n/a

1 = Second year of plantation; 2 = Maintenance cost per year, year 2 through 10

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Life Cycle Inventory

Feedstock Production Outputs

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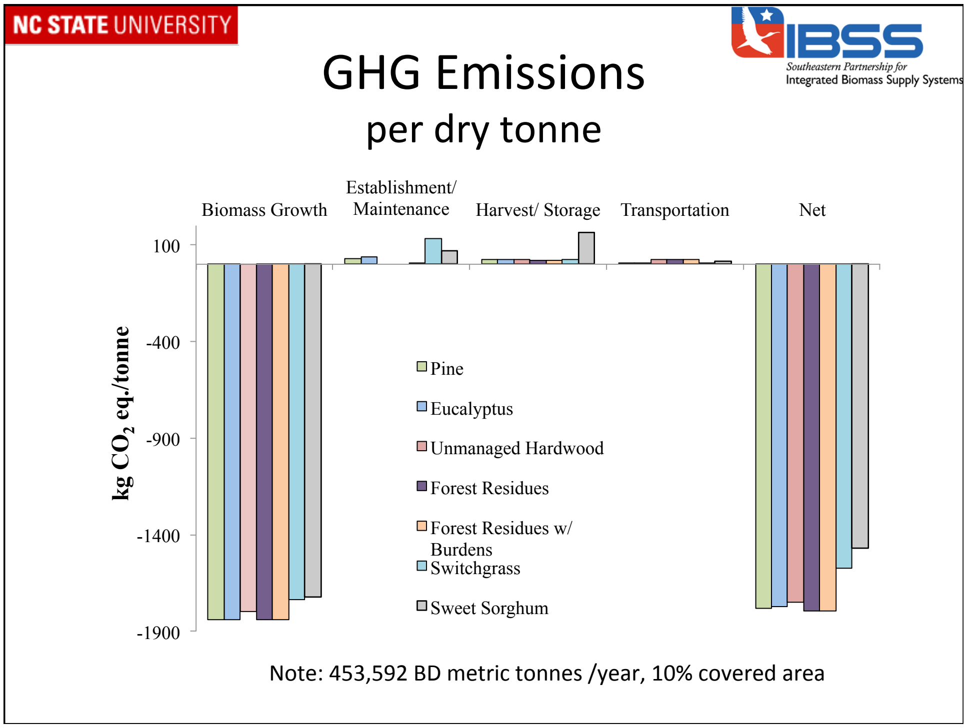
		Loblolly Pine			Eucalyptus			Unmanaged Hardwood			Forest Residues			Switchgrass			Sweet Sorghum		
	Productivity level →	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Fuel Use	**Fuel use**	Liter per dry tonne			Liter per dry tonne			Liter per dry tonne			Liter per dry tonne			Liter per dry tonne			Liter per dry tonne		
	Fuel consumption, collection	-	-	-	-	-	-	-	-	-	0.05	0.04	0.03	-	-	-	-	-	-
	Plantation establishment and maintenance, diesel	0.86	0.65	0.52	2.47	1.85	1.48	-	-	-	0.61	0.45	0.36	-	-	-	-	-	-
	Plantation establishment and maintenance, gasoline	0.04	0.03	0.03	0.12	0.09	0.07	-	-	-	8.0	6.0	4.8	3.93	2.95	2.36	-	-	-
	Harvesting, diesel	10.1	7.58	6.06	10.1	7.58	6.06	10.1	7.6	6.1	-	-	-	6.02	4.51	3.61	4.13	3.1	2.48
	Storage													0.6	0.6	0.6	0.84	0.84	0.84
Transport	**Transportation**	Dry tonne*km			Dry tonne*km			Dry tonne*km			Dry tonne*km			Dry tonne*km			Dry tonne*km		
	Forest to facility	79	69	62	78	67	60	219	190	170	327	283	253	-	-	-			
	Farm to storage	-	-	-	-	-	-	-	-	-	-	-	-	51	44	39	175	152	136
	Storage to facility	-	-	-	-	-	-	-	-	-	-	-	-	9.5	9.5	9.5	31	31	31
Chemical Use	**Fertilizer**	kg per dry ton			kg per dry ton			kg per dry ton			kg per dry ton			kg per dry ton			kg per dry ton		
	Urea	2.1	1.6	1.3	2.9	2.2	1.7	-	-	-	0.13	0.1	0.08	-	-	-			
	Phosphorus	-	-	-	-	-	-	-	-	-	-	-	-	1.6	1.2	0.96	3.43	2.57	2.06
	Potassium	-	-	-	-	-	-	-	-	-	-	-	-	15.83	11.88	9.5	1.7	1.27	1.02
	Lime	-	-	-	-	-	-	-	-	-	-	-	-	62.28	46.71	37.37	-	-	-
	Nitrogen	-	-	-	-	-	-	-	-	-	-	-	-	8.47	6.36	5.08	-	-	-
	Herbicide	kg per dry ton			kg per dry ton			kg per dry ton			kg per dry ton			kg per dry ton			kg per dry ton		
	General herbicide, glyphosate	0.03	0.01	0.01	0.08	0.04	0.03	-	-	-	0.002	0.001	0.001	-	-	-	-	-	-
	Pursuit	-	-	-	-	-	-	-	-	-	-	-	-	2.36	1.77	1.41	-	-	-
	MSO	-	-	-	-	-	-	-	-	-	-	-	-	3.31	2.48	1.99	-	-	-
	2,4-D	-	-	-	-	-	-	-	-	-	-	-	-	1.14	0.85	0.68	-	-	-
	Alzarine 90 DF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.19	0.14	0.11
	Dipel ES	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.2	0.15	0.12

Note: 453,592 BD metric tonnes /year, 10% covered area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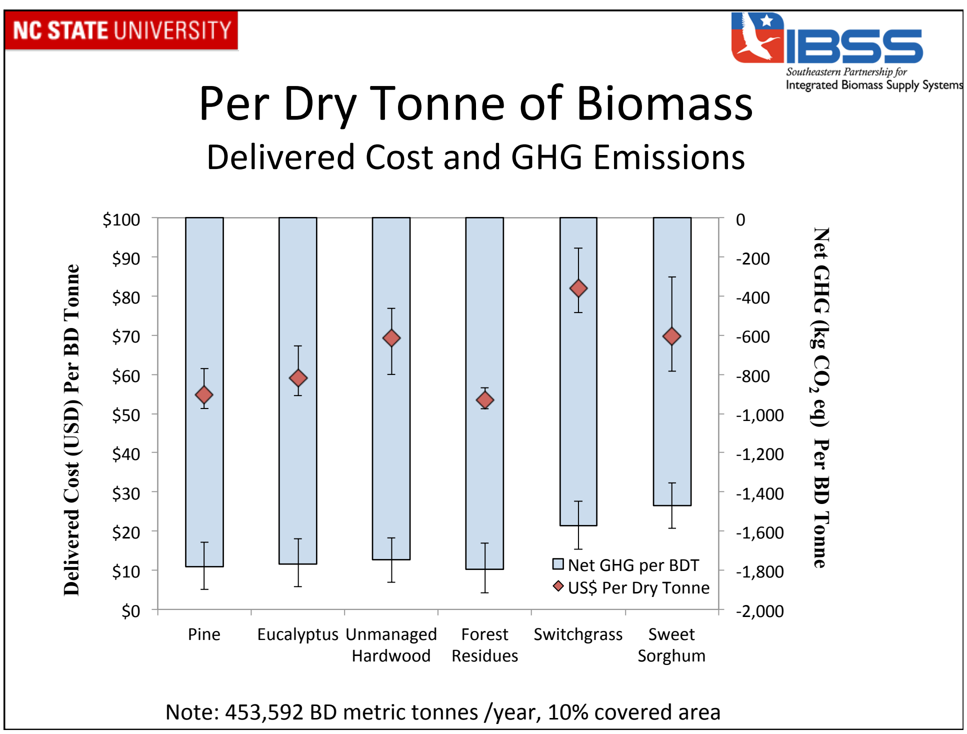
GHG Emissions
per dry tonne
Biomass Growth
Establishment/ Maintenance
Harvest/ Storage
Transportation
Net
kg CO2 eq./tonne
100
-400
-900
-1400
-1900
Pine
Eucalyptus
Unmanaged Hardwood
Forest Residues
Forest Residues w/ Burdens
Switchgrass
Sweet Sorghum
Note: 453,592 BD metric tonnes /year, 10% covered area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Per Dry Tonne of Biomass
Delivered Cost and GHG Emissions
Delivered Cost (USD) Per BD Tonne
$100
$90
$80
$70
$60
$50
$40
$30
$20
$10
$0
Net GHG (kg CO2 eq) Per BD Tonne
0
-200
-400
-600
-800
-1,000
-1,200
-1,400
-1,600
-1,800
-2,000
Pine
Eucalyptus
Unmanaged Hardwood
Forest Residues
Switchgrass
Sweet Sorghum
Net GHG per BDT
US$ Per Dry Tonne
Note: 453,592 BD metric tonnes /year, 10% covered area

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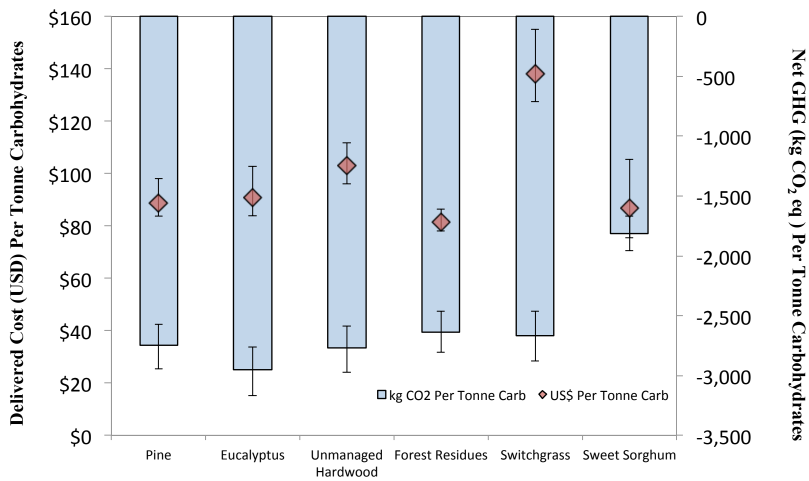
Per Tonne Carbohydrate

Delivered Cost and GHG Emissions



Note: 453,592 BD metric tonnes /year, 10% covered area

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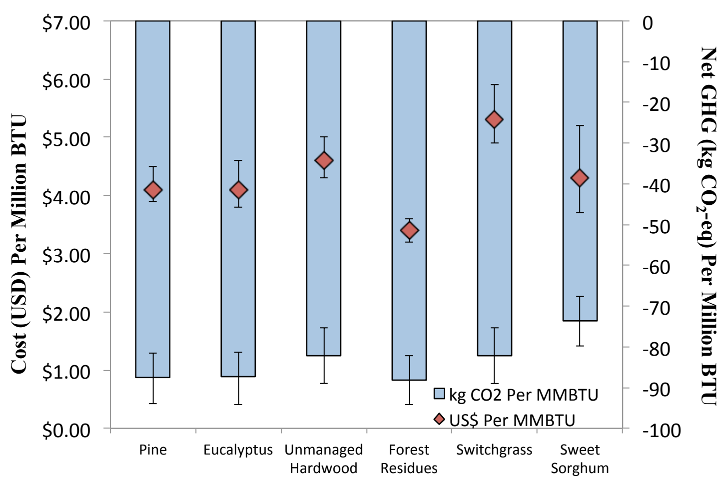
Per Million BTU

Delivered Cost and GHG Emissions



Note: 453,592 BD metric tonnes /year, 10% covered area

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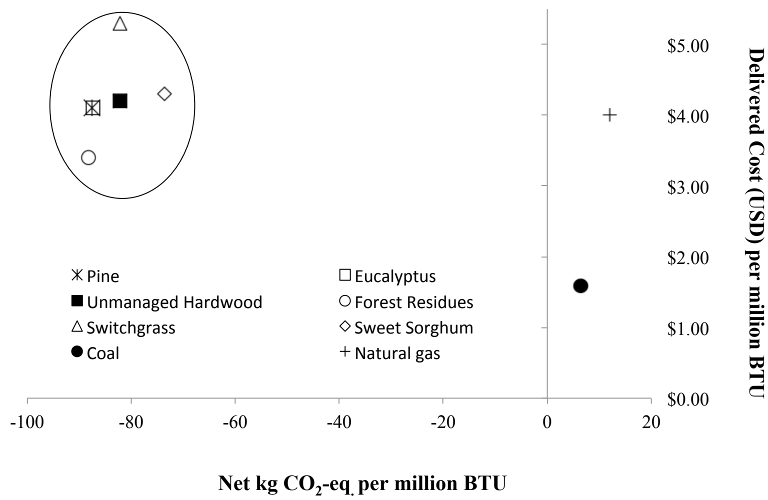
Cost and Net GHG Emissions Per MMBTU



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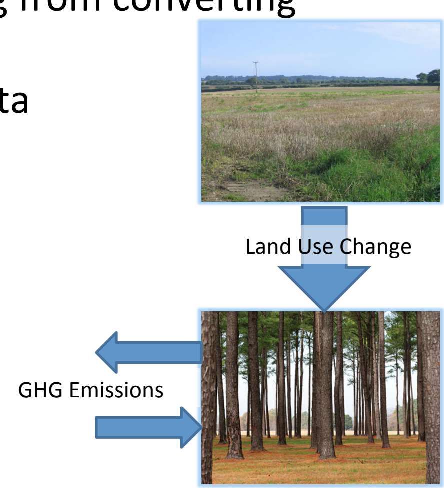
Direct Land Use Change

- Emissions resulting from converting uses of land
- IPCC and FICAT Data
- Factors:
  - Soil type
  - Land type
  - Moisture type
  - Region



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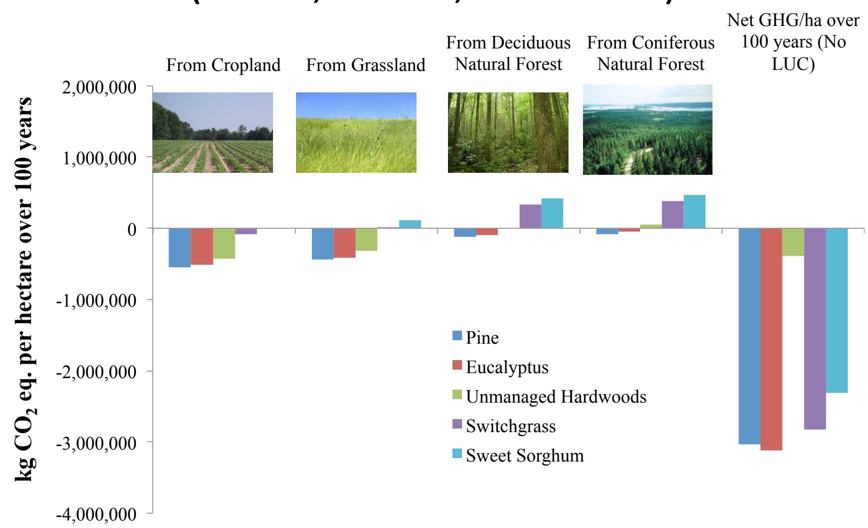
Land Use Change (LUC) Results (FICAT, NCASI, IPCC data)



Note: 453,592 BD metric tonnes /year, 10% covered area

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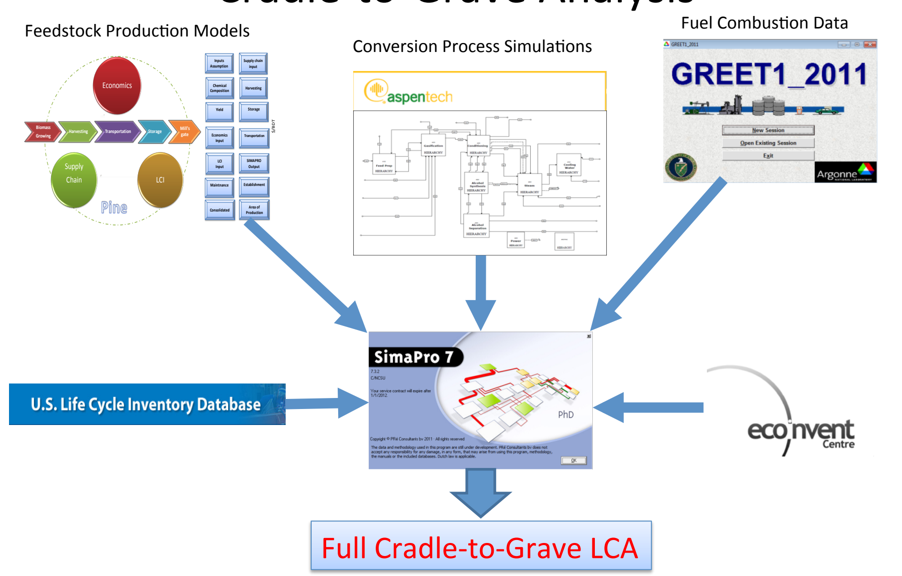
LCA Modeling Next Steps Cradle-to-Grave Analysis



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Feedstock and Conversion Technology Compatibility

- Feedstock
  - Loblolly pine 1,2
  - Natural mixed hardwood 1,2
  - Eucalyptus 1,2
  - Switchgrass 1,2
  - Sweet sorghum 1

Technology

1=Biochemical (Dilute acid)

2=Thermochemical (gasification)

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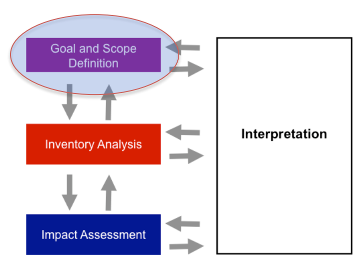
Objectives:

Thermochemical Ethanol Production

- Goal
  - Determine bioethanol **GHG reductions** compared to gasoline
  - Determine other environmental impacts
- Scope
  - Functional units:
    - 1 MJ of fuel combusted
    - Compare 0.028 L of gasoline to 0.042 L of ethanol
  - Cradle-to-grave



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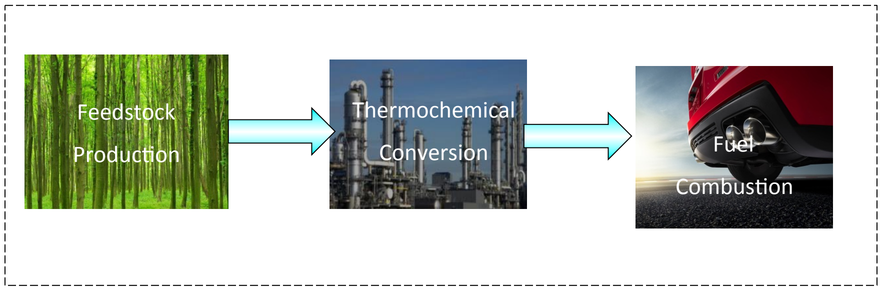
LCA Boundary: Cradle to Grave (Well to Wheel)



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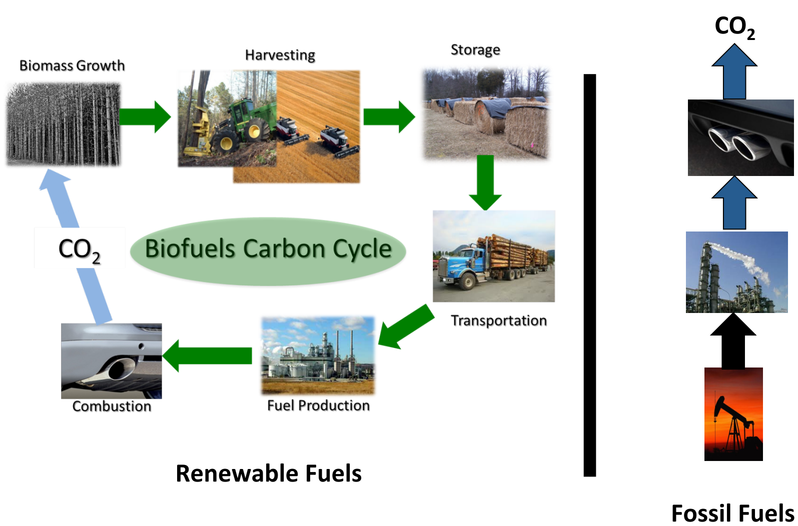
Carbon Flows



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NREL Thermochemical Biomass Gasification to Mixed Alcohol Process Simulation

- Facility size
  - Matches Aden et. A. biochemical process
    - 2,205 dry ton/day
    - 772,000 dry ton/year

- Feedstocks:
  1. Loblolly pine
  2. Eucalyptus
  3. Unmanaged hardwoods
  4. Forest residues
  5. Switchgrass

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Process Simulations

- Software packages from commercial vendors
  - ASPEN (basic chemical engineering, originated from petroleum industry)
  - WinGEMS (traditionally pulp and paper, more amenable to biomass)

- Utilize underlying thermodynamic relations/properties, reaction kinetics, physical property databases, empirical correlations, etc.

- Tracks materials and energy flows in a system with large numbers of
  - Chemical components
  - Streams
  - Operations
- More robust than Excel based simulations

- Provides basis for technical, economic and life cycle analysis when production facilities do not exist

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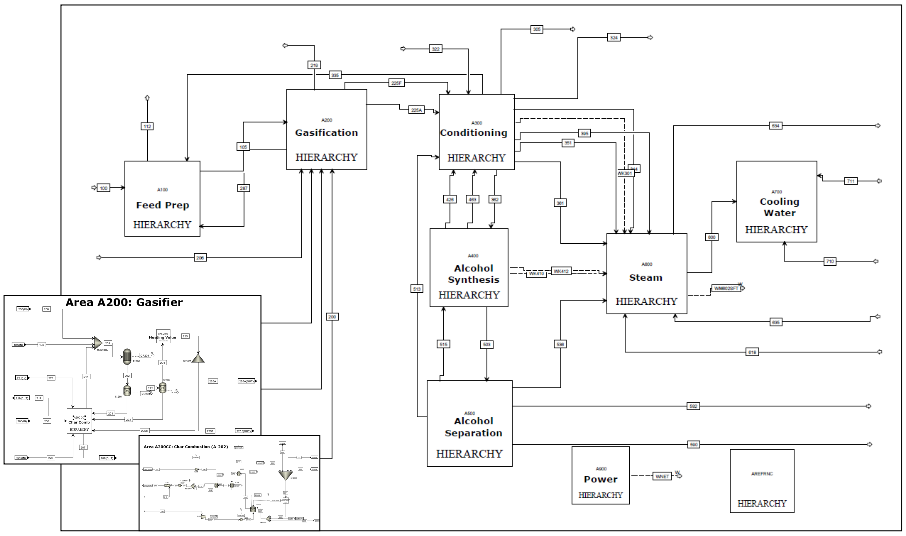
Aspen Model Overview:



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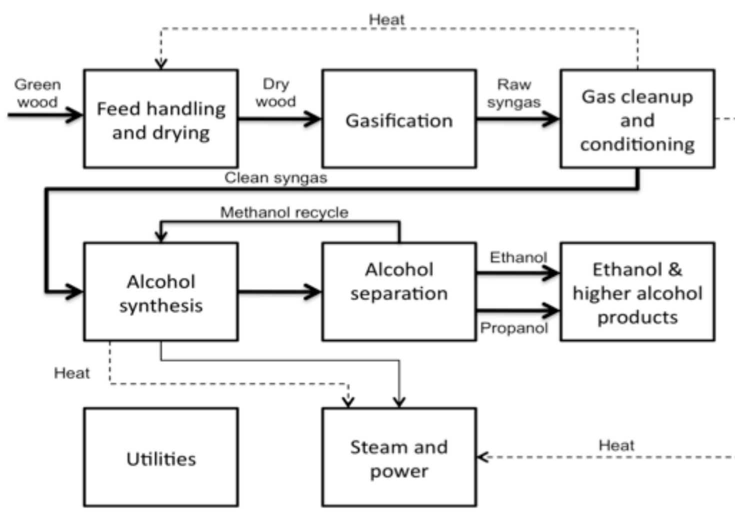
NREL Biomass Gasification to Mixed Alcohol Process Flow Diagram



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Biomass Composition

Feedstock type	%C	%H	%N	%O	%S	%Ash	% Fixed Carbon	% Volatile Matter	%Ash (prox)
Eucalyptus	49.74	5.95	0.20	42.59	0.02	0.98	18.2	81.1	1.0
Mixed hardwoods	50.43	6.54	0	42.48	0	0.6	18.94	80.39	0.67
Loblolly	51.85	6.45	0	41.3	0	0.4	14.21	85.34	0.45
Corn stover	46.62	5.66	0.68	39.36	0.08	11.95	21.1	72.5	11.9
Switch grass	47.3	5.6	0.6	40.6	0.1	5.8	20.6	74.2	5.8
Miscanthus	48	6	0.1	45.9	0	1.4	15.7	74.9	1.4

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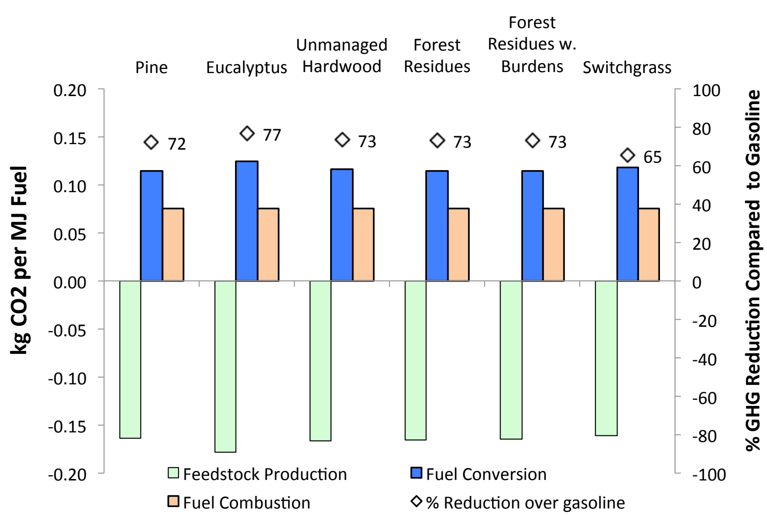
Cradle to Grave GHG Emissions



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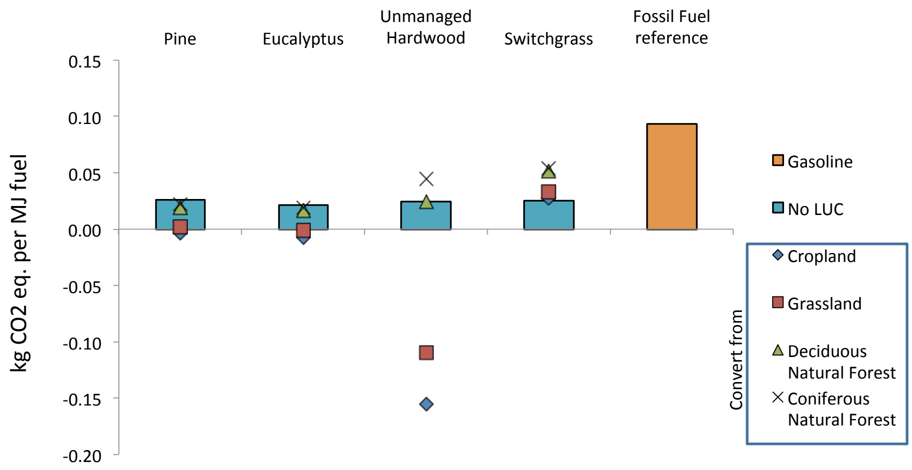
LUC Impacts on GHG Emissions



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TRACI Impact Assessment Method

- Global warming
- Acidification
- Carcinogenics
- Non Carcinogenics
- Respiratory effects
- Eutrophication
- Ozone depletion
- Ecotoxicity
- Smog

- Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI)

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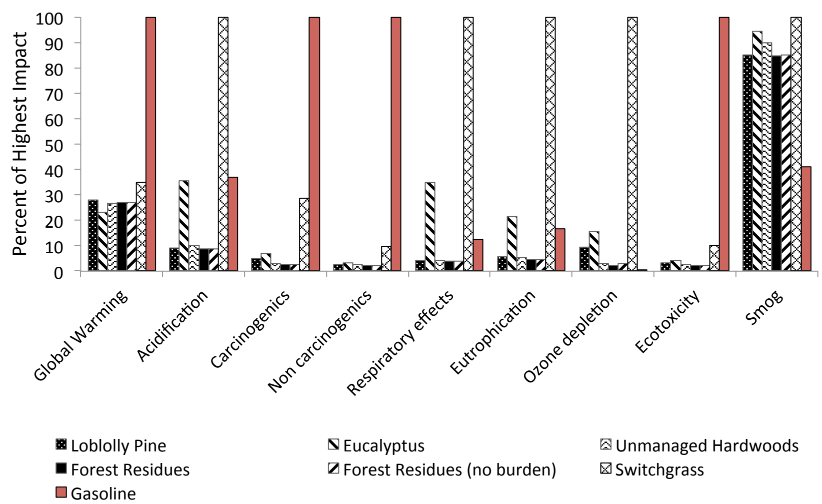
Other Environmental Impacts



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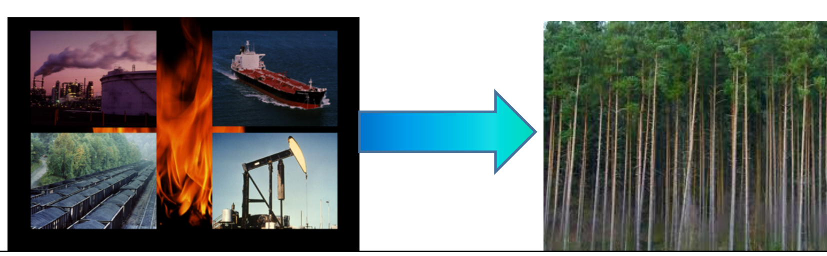
Fossil Fuel Usage

(MJ fossil fuel per MJ ethanol)	Feedstock Production	Conversion	Fuel Transport	Total Fossil Fuel	% Reduction Compared to Gasoline
Pine	3.50E-02	7.80E-04	3.24E-03	3.91E-02	97%
Eucalyptus	4.37E-02	1.22E-03	3.24E-03	4.82E-02	96%
Unmanaged hardwoods	5.17E-02	9.01E-04	3.24E-03	5.59E-02	95%
forest residues	4.59E-02	7.80E-04	3.24E-03	4.99E-02	96%
switchgrass	0.202	8.93E-03	3.24E-03	0.215	81%
Gasoline	1.05	7.22E-02	2.00E-03	1.12	0%



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Conclusions Feedstock Production

- Agricultural feedstocks (switchgrass & sorghum) harvest/storage impacts are significant
- Agricultural feedstocks have higher environmental impacts than forest based feedstocks
- Direct land use change significantly influences GHG emissions by as much as 20%
- Cellulosic feedstocks delivered costs per tonne was **Higher** for agricultural energy crops than forest based feedstocks
- Transportation represents minimal GHG impact

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Conclusions Biofuels from biomass gasification:

- Reduces GHG emissions as compared to gasoline
- Decreases some impacts while increasing others as compared to gasoline
- Feedstock type and compositions matter
- Land use change can influence GHG reductions significantly
  - Reduced switchgrass GHG emissions below the RFS thresholds (60% GHG reduction compared to gasoline)

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Conclusions

Biofuels from biomass gasification:

– Impact assessment compared to gasoline

Decreased Impact

1. Global warming potential
2. Acidification (except switchgrass)
3. Carcinogens
4. Non carcinogens
5. Ecotoxicity

Increased Impact

1. Respiratory effects
2. Eutrophication
3. Ozone depletion
4. Smog

Societal values play an important role in determining which fuel is better for the environment

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Conclusions

Life cycle assessment

- LCA is a useful tool to inform policy makers and society
- LCA will not likely drive decisions: financial performance is the primary influencer
- LCA cannot give you an exact answer
  – directional and value ranges are possible
- LCA combined with financial analyses creates a more robust and synergistic analysis

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- Biofuels Center of North Carolina

CORRIM Consortium for Research on Renewable Industrial Materials

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For More Information Contact

Jesse Daystar

919-800-7470

jsdaystar@trianglelca.com

www.triangleLCA.com

Triangle Life Cycle Assessment