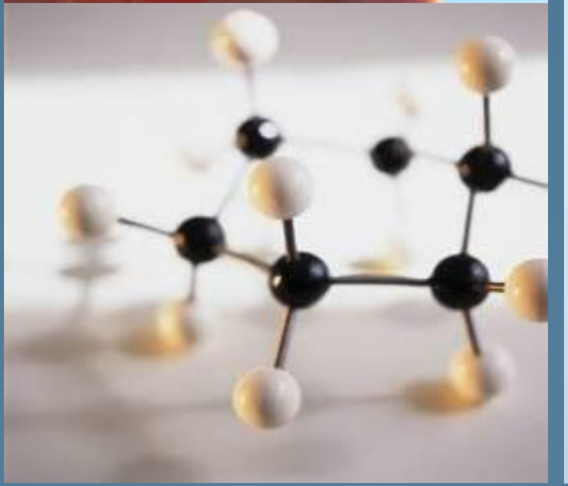


Feedstock Logistics for a Biofuels Industry

J. Richard Hess
Idaho National Laboratory

Biomass Research and Development Technical Advisory Committee Meeting

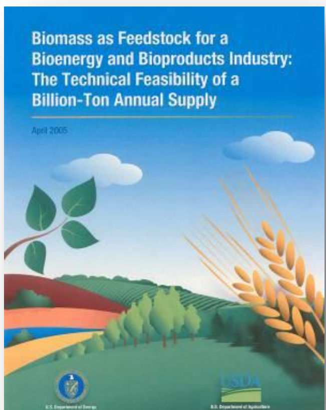
2 March, 2011 – Washington, DC

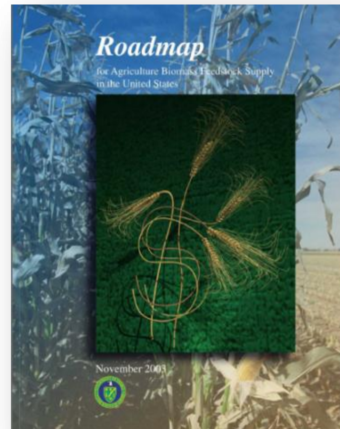
Scope of Feedstock Supply System R&D

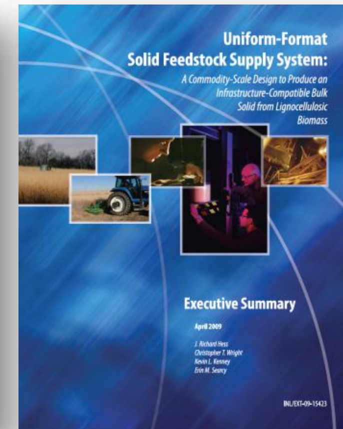
Equipment Performance Metrics:
- Equipment Efficiency / Capacity
- Dry Matter Losses
- Operational Window

Biomass Performance Metrics:
- Physical, Chemical, & Rheological Properties
- Product Bulk/Energy Density
- Material Stability

Documents Guiding Supply System Logistics Core R&D







Biomass Production:
- Ag. Resources
- Forest Resources

Feedstock Production Interface

Harvest & Collection → Storage → Preprocessing → Transportation → Handling & Queuing → Biomass Conversion

Harvest & Collection
- Equipment Capacity
- Compositional Impacts
- Pretreatment Impacts

Storage
- Shrinkage
- Compositional Impacts
- Pretreatment Impacts
- Soluble Sugar Capture

Preprocessing
- Equipment Capacity
- Equipment Efficiency
- Material Bulk Density
- Compositional Impacts
- Pretreatment Impacts

Transportation
- Truck Capacity
- Loading compaction
- Loading efficiencies

Handling & Queuing
- Handling efficiencies
- Handling compaction
- Material Bulk Properties

Biomass Conversion:
- Biopower
- Biofuels
  - Biochem
  - Thermochem

Feedstock Conversion Interface

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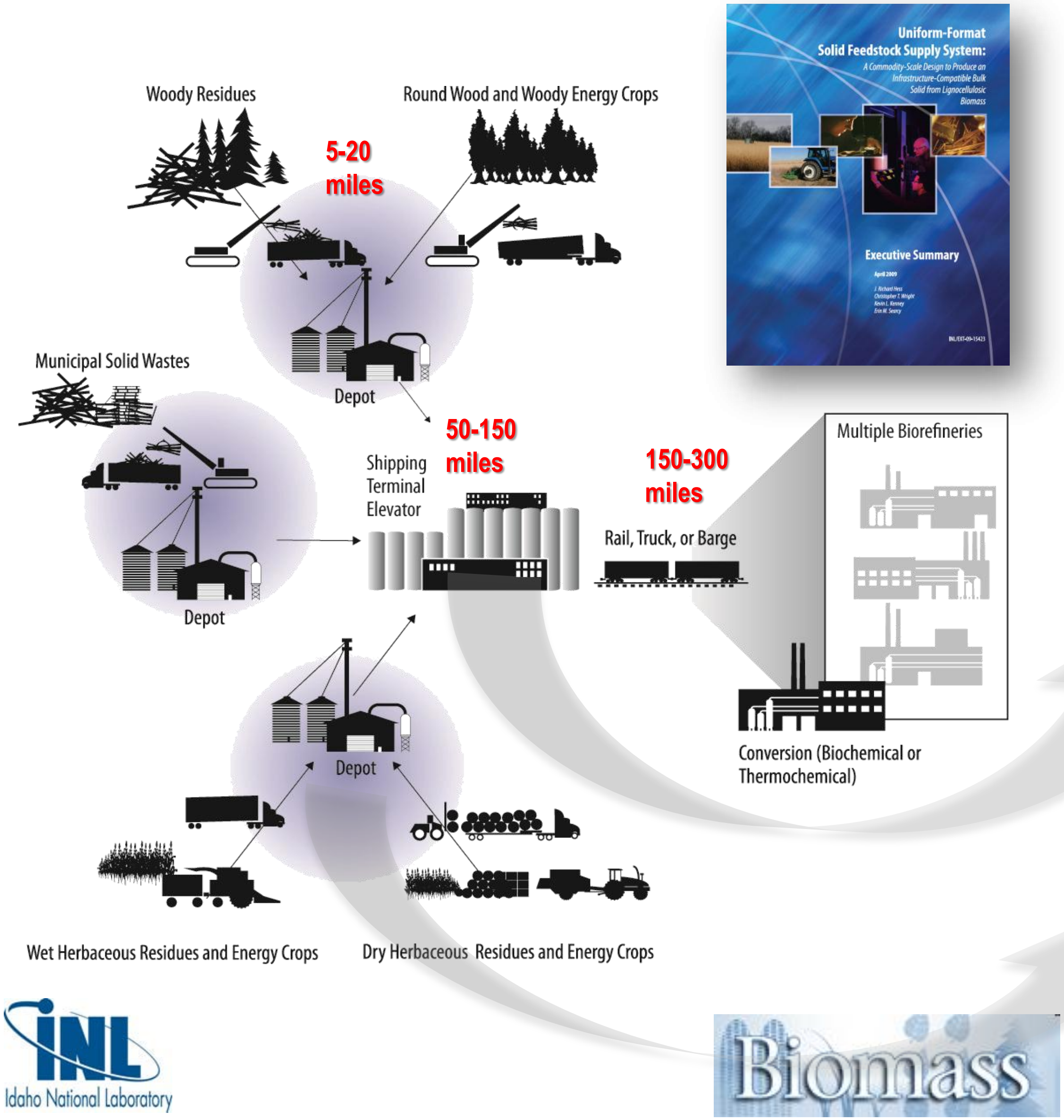
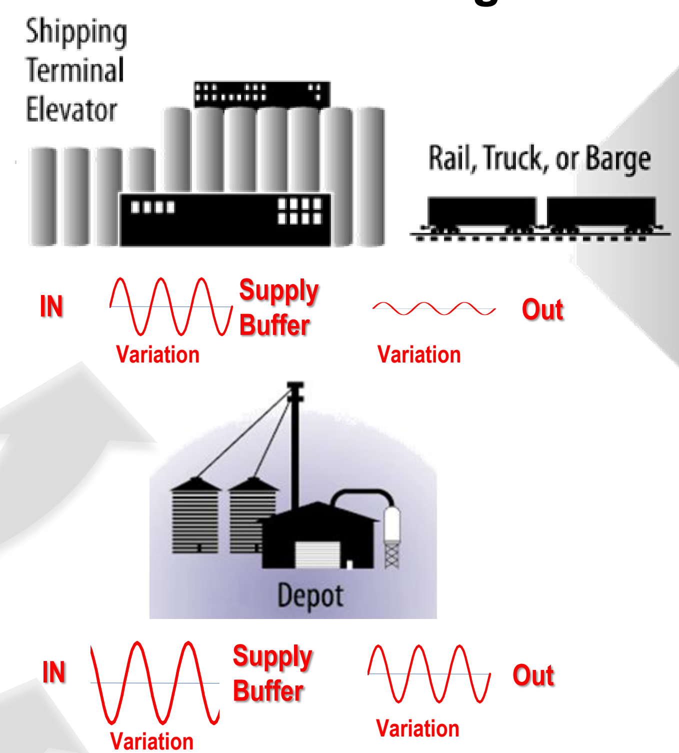
The Uniform Format Solution: A Commodity-Scale Design

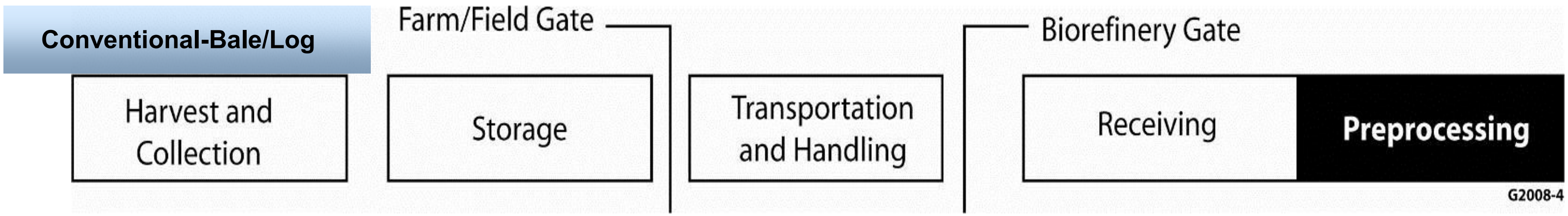


Commodity Attributes:

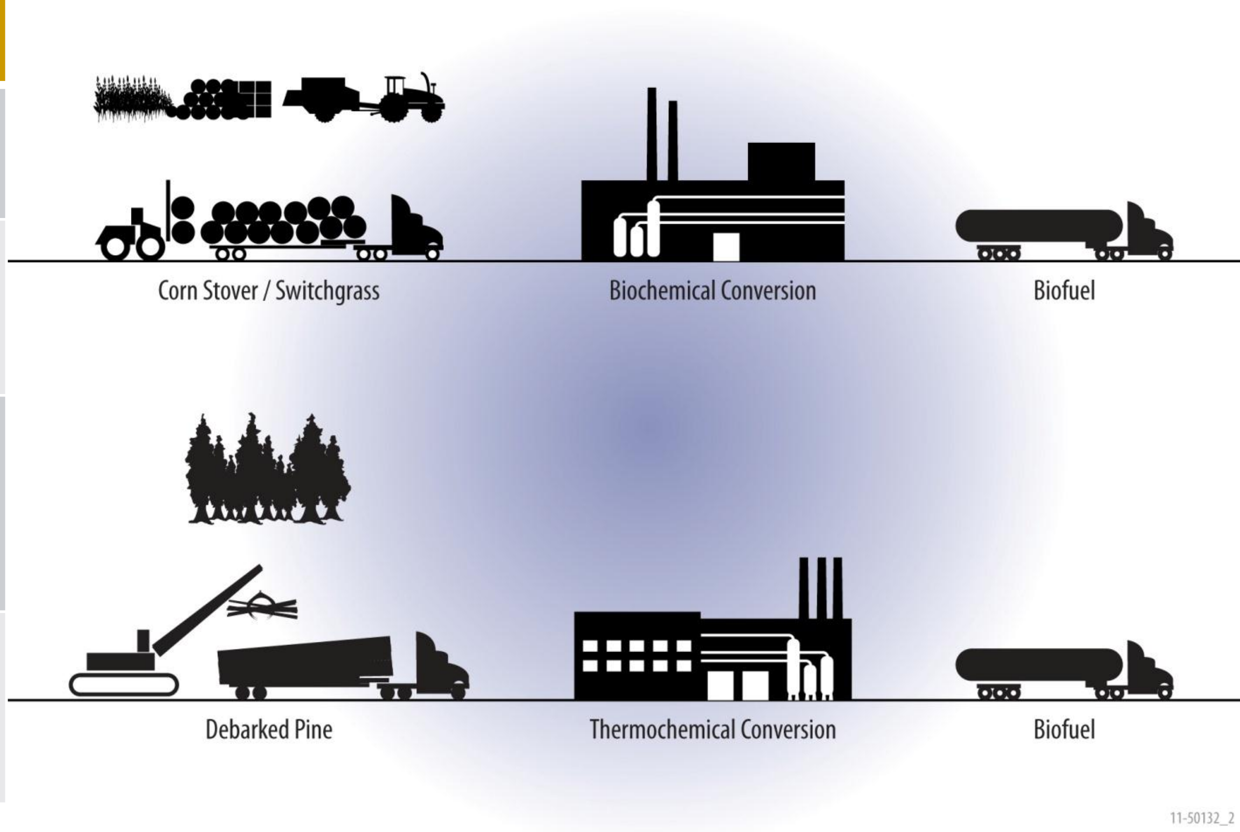
- Standardized Material/Quality
- National Market
- Biomass Exchange Market



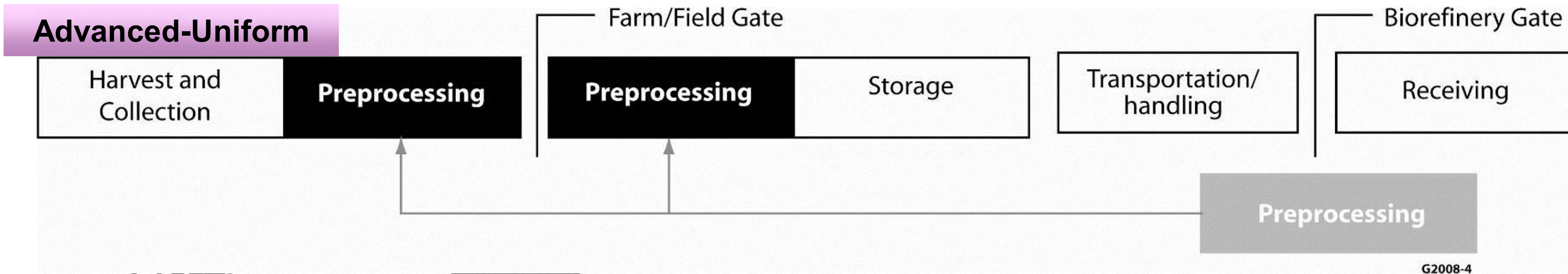
Conventional Feedstock Supply System

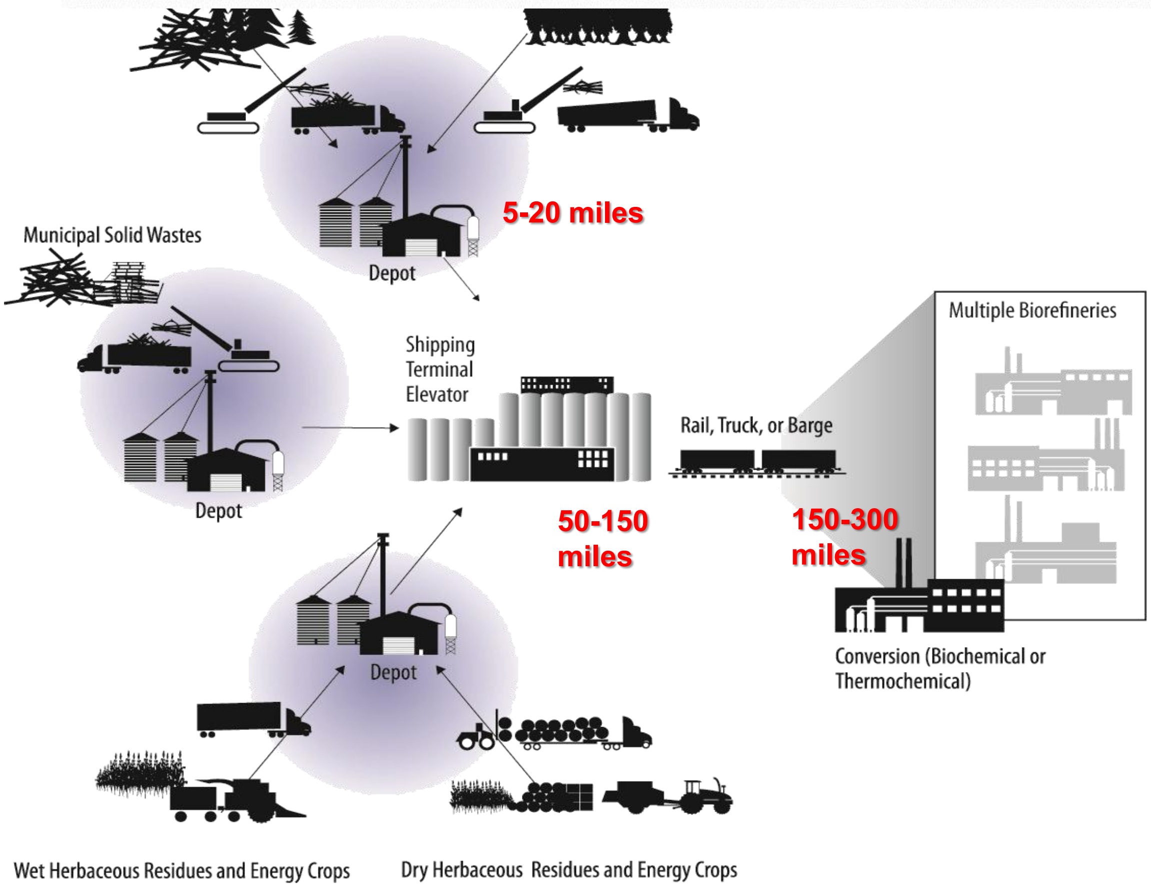


Existing Supply Systems	Depot Supply Systems
Nearer-term Platform Focus (through 2012)	Longer-term Platform Focus (2013+)
Access to a niche or limited feedstock resource	Access to a broader resource
Based on a dry supply system design (field-dried feedstocks)	Allows higher-moisture feedstocks into supply system
Designed for a specific feedstock type (dry corn stover)	Design addresses multiple feedstock types



Addressing Feedstock Logistics Barriers and Costs via a Depot Supply System





Existing Supply Systems	Depot Supply Systems
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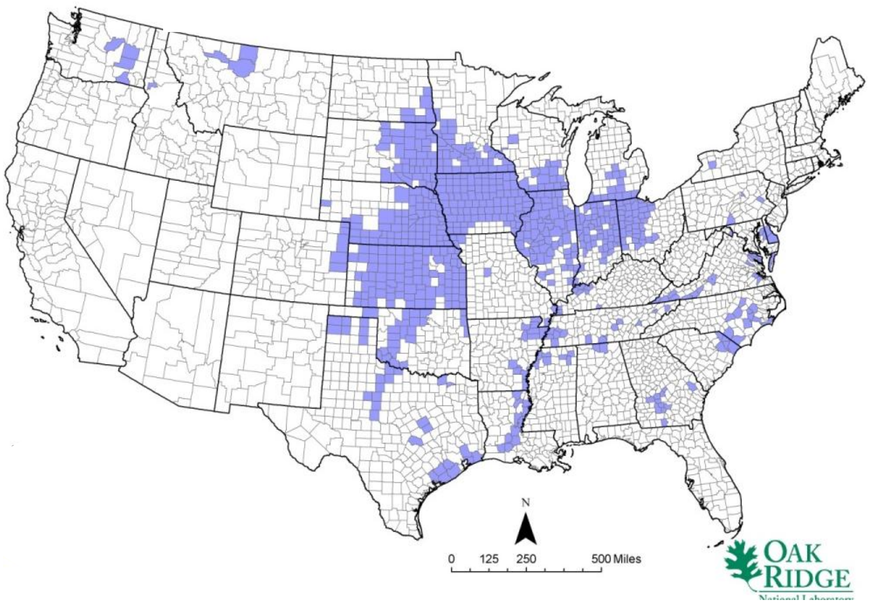
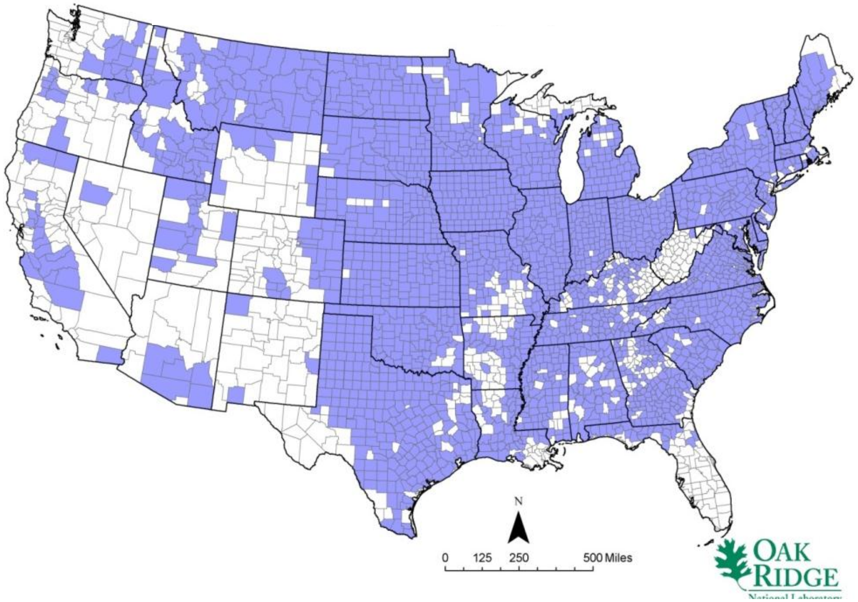
Unlocking the Resource – An illustrative example

Number of counties that could potentially produce high-density biomass feedstock resources under existing production and logistics systems



- Little to no improvement in feedstock yield
- Existing harvesting, collection, storage, and transportation techniques
- Sustainability considerations limited
- Conversion specifications for feedstock not addressed
- Supply risk due to price fluctuations, weather events, lack of year-round supply, etc.

Number of counties that could potentially produce high-density biomass feedstock resources under advanced production and logistics systems

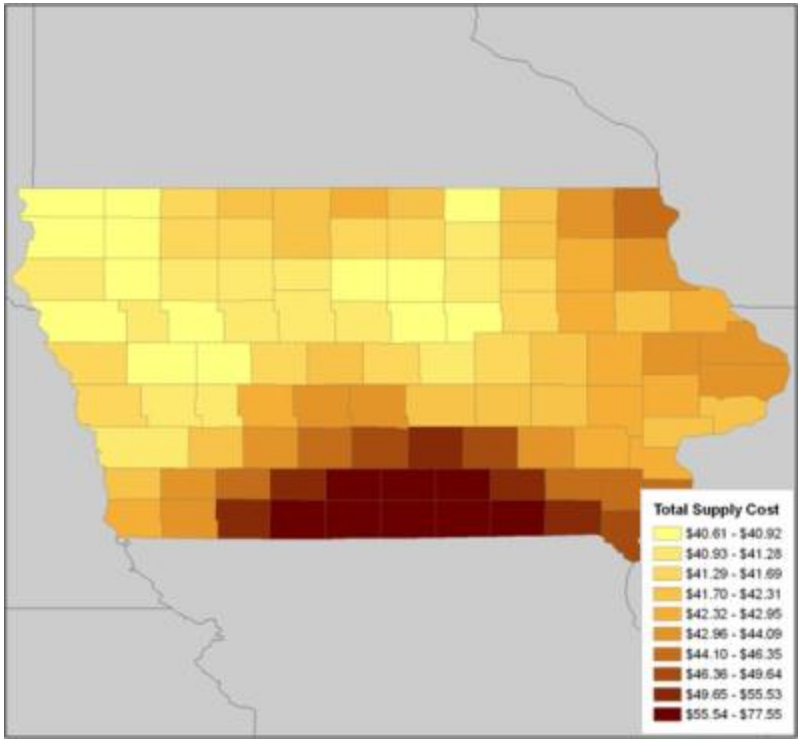


- Feedstock yield improved via genetics, genomics, breeding, improved production practices, etc.
- Shift to a uniform-format feedstock preprocessing depot logistics supply system
- Sustainability considerations expanded
- Conversion specifications for feedstock addressed
- Supply risk due to price fluctuations, weather events, lack of year-round supply, etc. decreased

Conventional and Advanced Supply Systems: Cost Dynamics

- Conventional system demonstrates high spatial variability in costs, even in highly productive regions. Iowa example:
  - Large range in costs
  - Local average supply costs impacted by resource density

- Advanced Uniform has higher average supply system costs, but reduced spatial and temporal variability
  - Smaller range in costs
  - Average cost more stable between locations

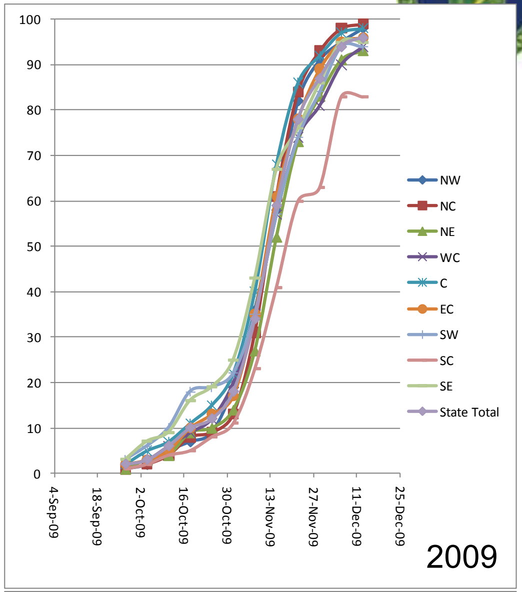


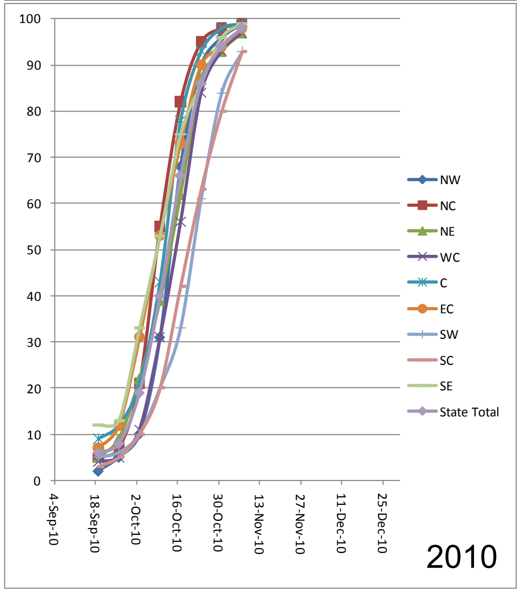
Conventional supply system design costs by county in Iowa for a projected resource draw of corn stover.

Conventional and Advanced Supply Systems: Accessibility Risk Dynamics

- Conventional system are limited by conditions on the ground, resulting in:
  - Lower and unpredictable accessible resource quantities
  - Higher and unpredictable losses due to inability to stabilize
  - Wide ranges of material specs delivered to the biorefinery: lower conversion yields

- Advanced Uniform design concept:
  - Responds to harvest conditions
  - Stabilizes material early in the supply chain reducing losses
  - Can guarantee material specifications





Harvest progress (corn grain) by week in Iowa: 2009, 2010 by Crop Reporting District

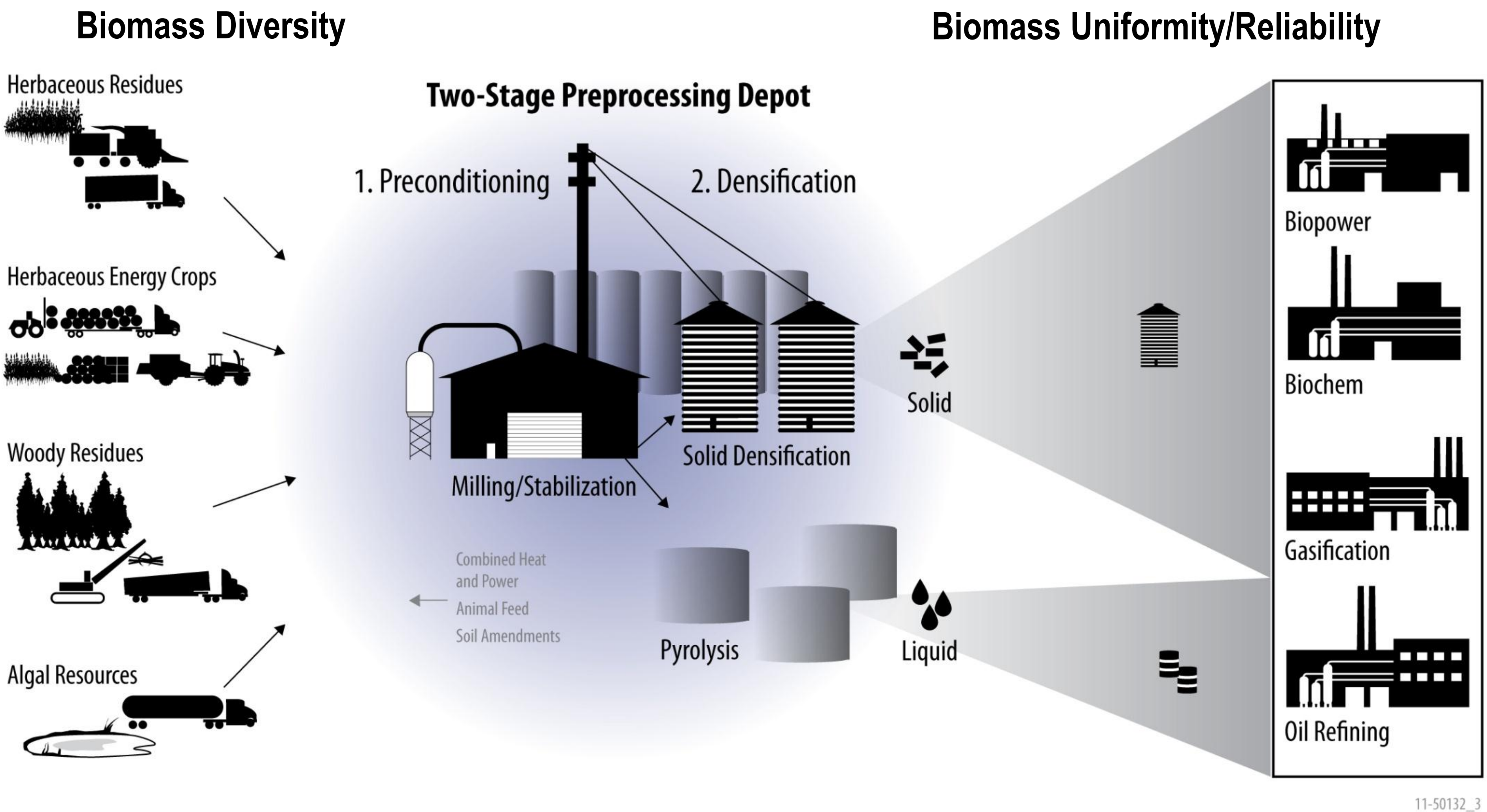
Factors Driving Commodity Scale Supply Systems

- Yield
  - Tons/acre
  - Tons/square mile (Landscape Scale Design, Increases Diversity)
- Stability
  - Shelf-Life
  - Chemical/Biological Reactivity
- Specifications Properties (e.g., quality)
  - Physical
  - Chemical
  - Rheological
- Density
  - Bulk Density
  - Energy Density

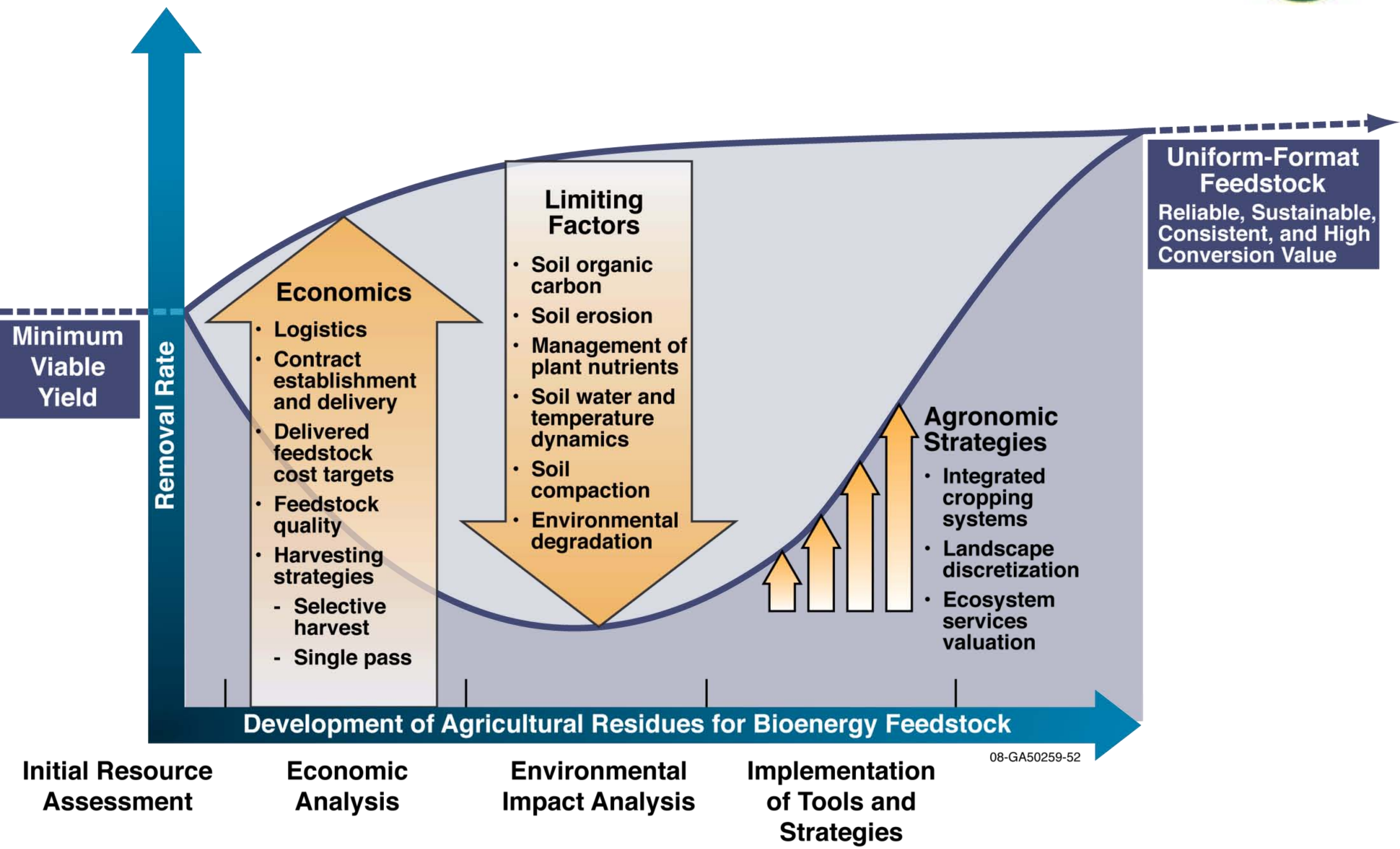
======================================

Factor Not on the List: Format

Depot Supply System Produces Uniform Commodity Spec Products – Densified Solid and Liquid Formats



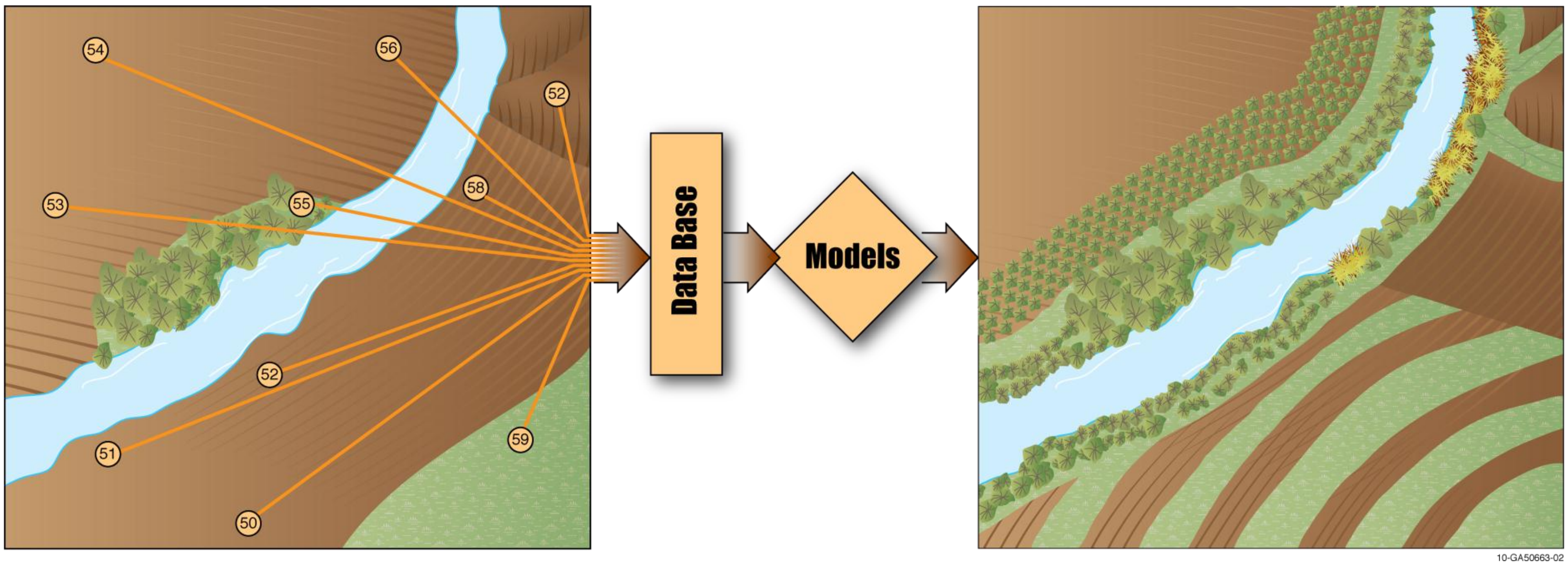
Sustainable Resource Access – The Yield Struggle



Limiting Factor Based Assessment: Guiding the Development of Sustainable Bioenergy Landscapes

Low Diversity
Large Volume per Square Mile

High Diversity
Multiple Low Volumes per Square Mile

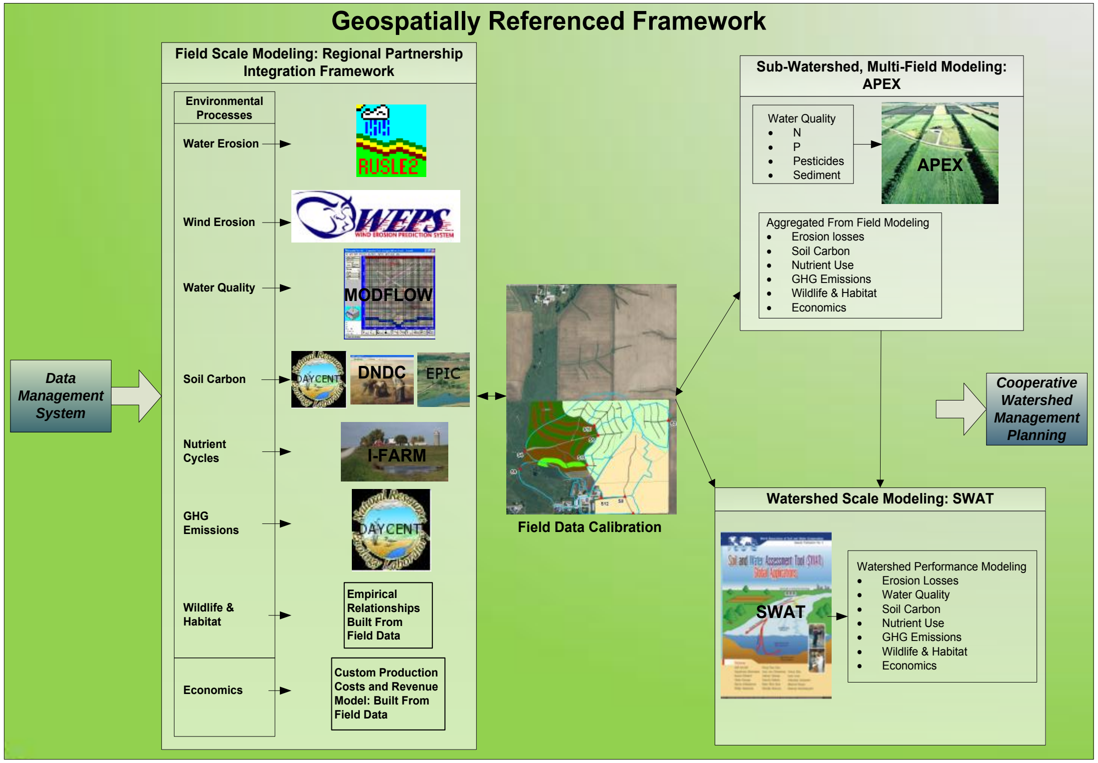


Using plot-based experimental methodologies and data, sustainable watershed-scale bioenergy cropping systems can be designed, verified, and implemented using integrated **Limiting Factor** models, thus avoiding the unintended consequences of independent field-level conversion of land to supply bioenergy markets

Linking Plot-Scale Data to Flexible Feedstock Selection and Production

Through carefully designed plot networks, data management, and integrated limiting factor modeling we can:

- **Implement bioenergy landscape design concepts at the plot scale**
- **Calibrate and test multi-factor environmental process modeling tools**
- **Quantitatively predict watershed scale performance**



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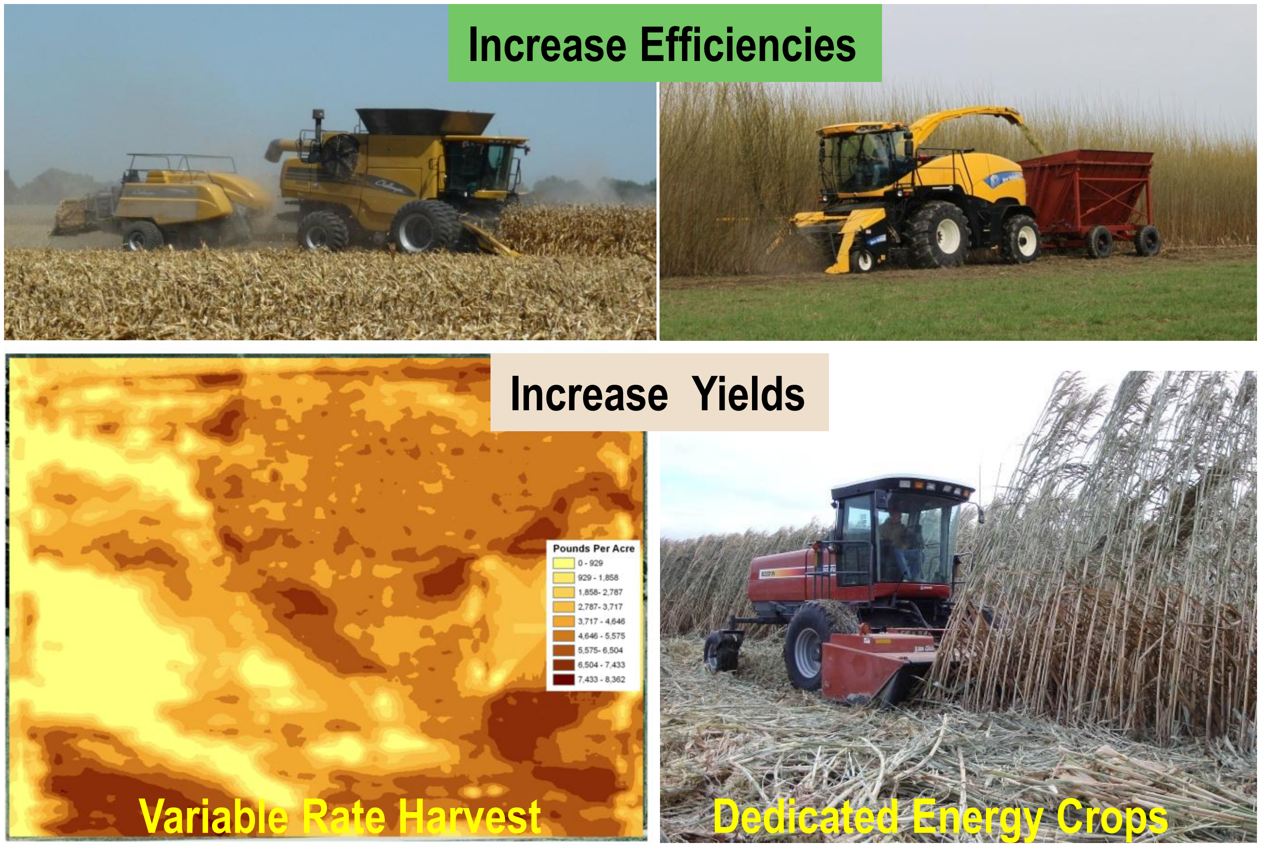
Solution: Landscape-scale Management Approach Using Integrated, Science-Based Assessment Techniques

Examine economic and social drivers associated with global need for renewable biofuels in tandem with other important issues:

- **Carbon sequestration**
- **Water and air quality**
- **Wildlife food and habitat**
- **Erosion, sedimentation, & hypoxia**
- **Community development**
- **Transportation infrastructure**

Unstable Biomass Harvest Intermediates

Crop Residues | **Dedicated Energy Crops**



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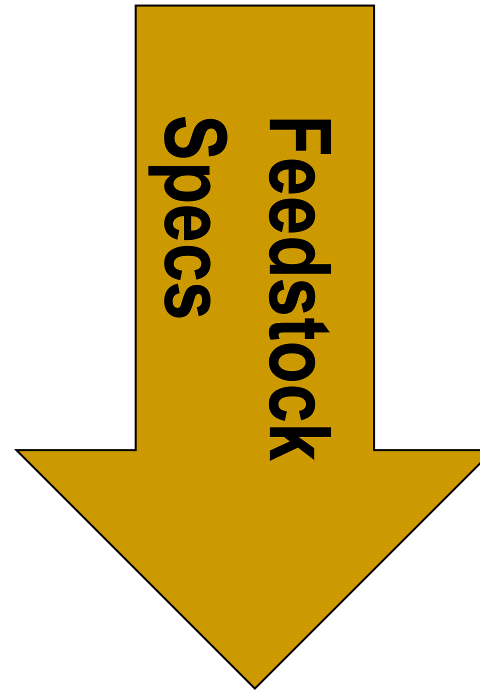

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Biomass specifications enable advanced technologies

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Corncob/Stover Project

After 10 months of storage

Open-air stack

Wrapped stack

Tarped stack

How do we determine best storage method?

- Dry matter loss
- Moisture content
- Quality

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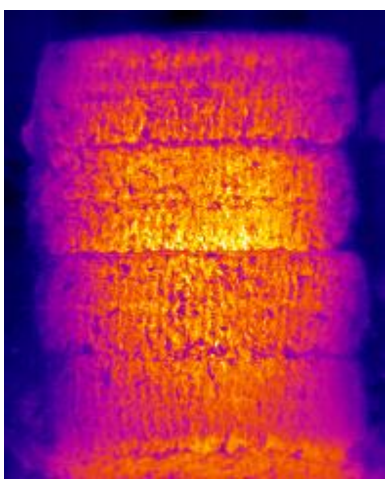
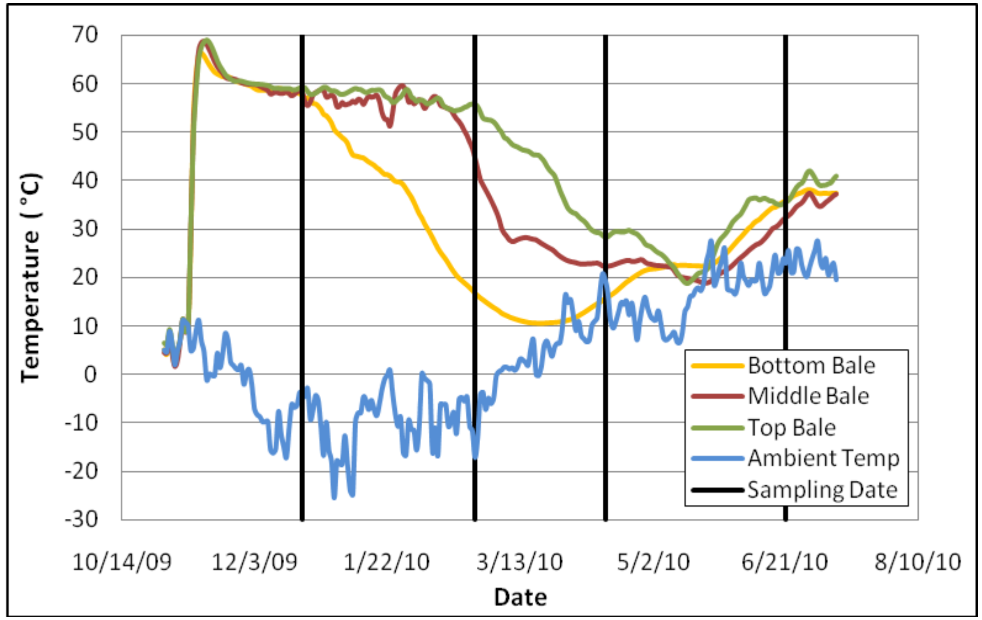
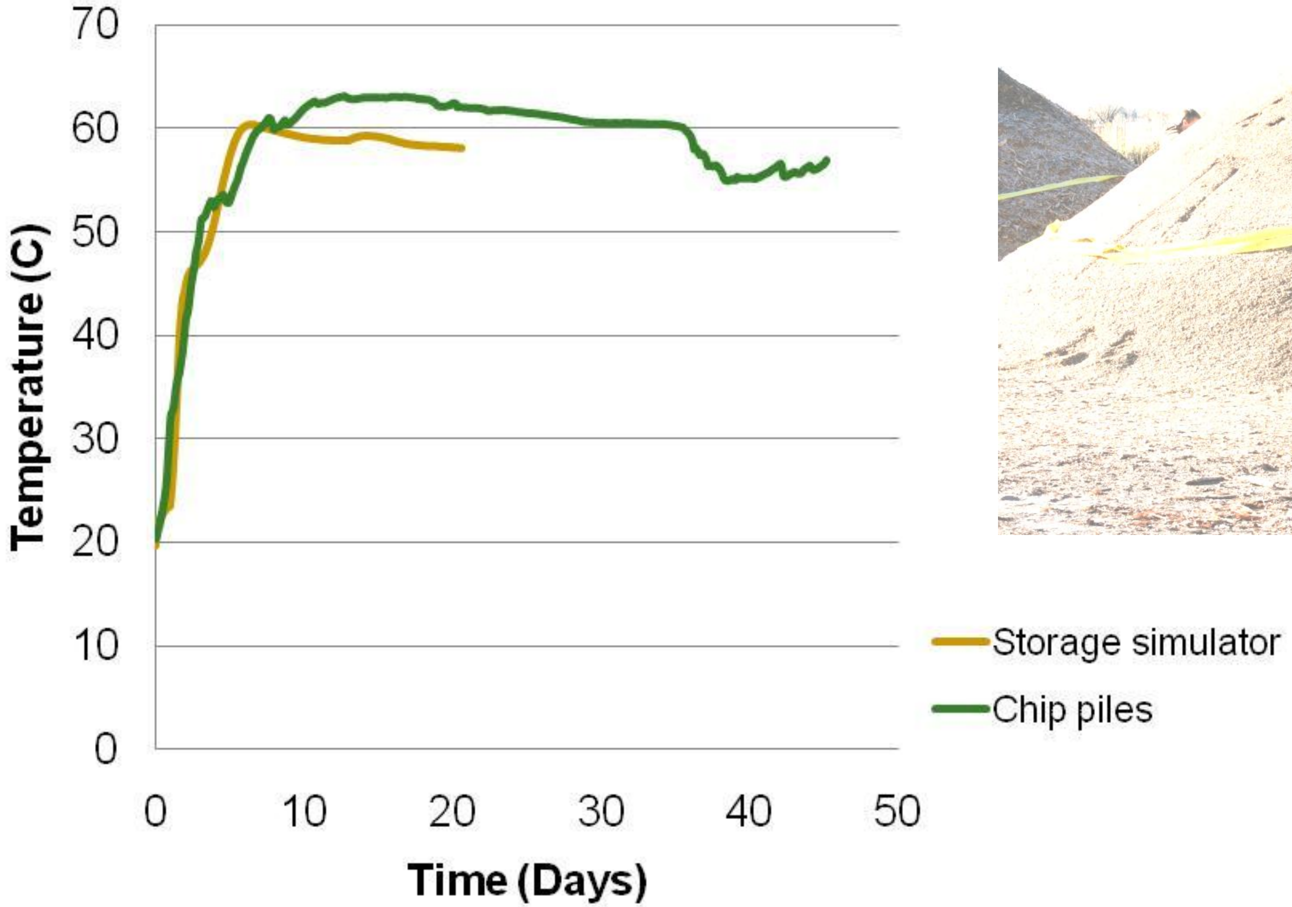
Corncob/Stover Project
2009 Baled-cob Storage Self-Heating Profile

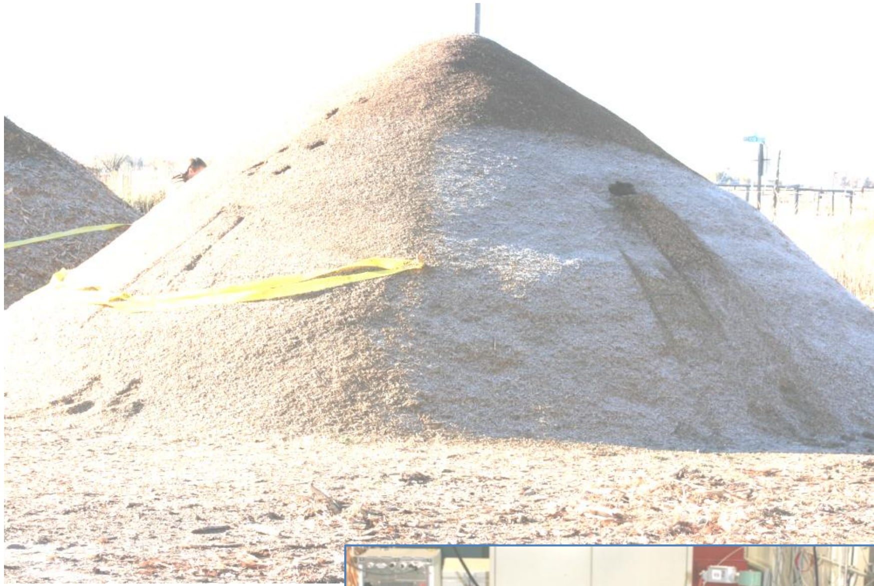




- Signature self-heating profile
  - Consistent over full range (25-40%) of moisture content
  - Consistent across all stack configurations except the Wrapped stacks
- "Drop-out" varies depending on moisture content and stack configuration

Wood Chip Pile Self-Heating Profile



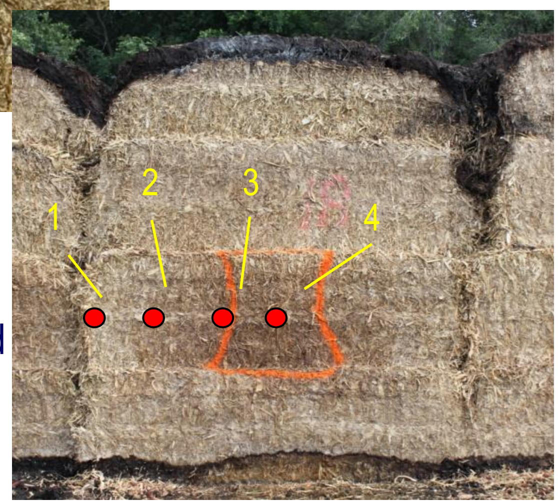


Harvest, Collection & Storage – Process Intermediate

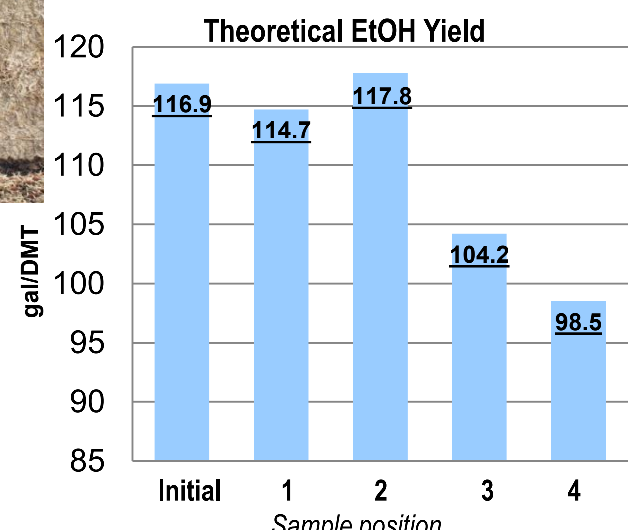
Field Demonstration

Focused on developing biomass specific harvest, collection & storage options

Dry matter loss converts structural carbohydrate to “water soluble carbohydrates”



- Direct bale system
- High moisture materials (≤45%)
- Multiple areas of perturbation
- Driver for development of lab based methods
  for studying mechanisms of dry matter loss, self-heating, & degradation
- Provides capability to fabricate & evaluate larger numbers of process intermediates



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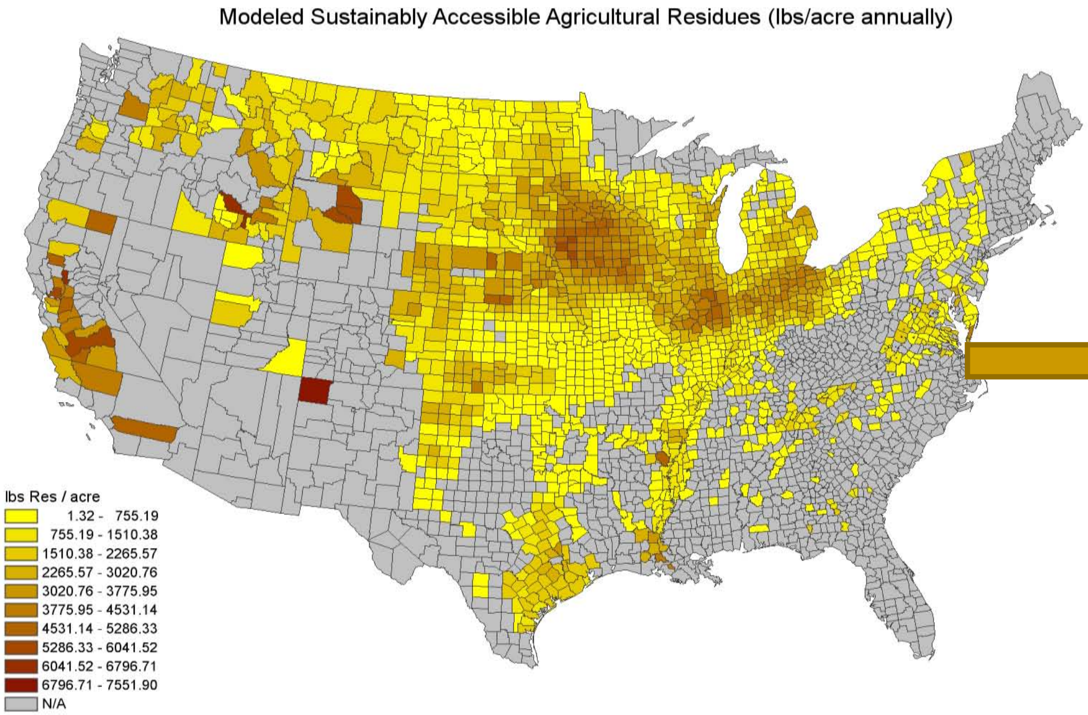
Specification-Based Commodity Scale Supply System



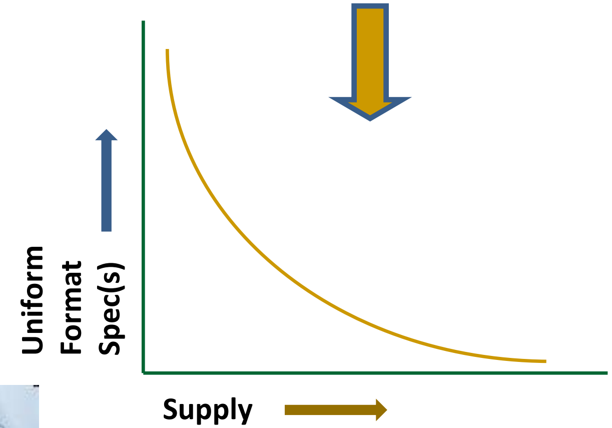
Feedstock Specs

Bio-Power Feedstock Specifications	Advanced Material (Thermally Treated)		Mechanically Densified (Pelletized or Similar)		For Comparison	Plant Operations Impacts
	Minimum Specification	Target Specification	Minimum Specification	Target Specification	Green Wood	
HHV (Btu/Lb) as received	8,600	9,200	7,650	8,200	3,200-5,700	Storage, Handling, Fuel Feed, Conversion Efficiency
Bulk energy density (Btu/Ft^3)	387,000	478,000	230,000	287,000	80,750 - 89,000	Transport, Handling, Storage, Conversion Efficiency
Bulk density (lbs/ft2)	46 (Pelletized)	52 (Pelletized)	30	35	19 - 21	Transport, Handling, Storage
Moisture Content/Stability	5 Hydrophobic	1 Hydrophobic	10 Hydrophilic	5 Hydrophobic	40 - 60 Hydrophilic	Heat Rate, Storage Handling
Grindability (HGI)	30	45	25	28	20 - 25	Heat Rate, Storage, Handling
Pulverized geometric mean particle size (mesh number)	No. 200 (74)	No. 200 (74)	No. 200 (74)	No. 200 (74)	1/8" in. max <15% cofire	Pulverizer Compatibility, Fuel firing, Fuel Feed
Ash content (Lb. Ash/MMB tu)	4	1	3	.5	1-6	Slagging, Fouling, and Byproducts/Waste
Chlorine (% d.b.)	0.13	0.01	<0.02	0.01	0.01 - 0.03	Corrosion
Alkalis (Lb. Alkalis/MMBtu)	0.4	0.1	0.4	0.1	0.2 - 0.5	Slagging and Fouling
Sulfur Content (lb/MMBtu)	.02	0.01	0.01	0.01	0.02 - 0.2	Fuel Contaminant, SoX Emissions
Slagging/fouling/corrosion limits (% cofiring / temp. F)	20% / 50% 1,800 / 1,600	20% / 50% 1,800 / 1,600	20% / 50% 1,800 / 1,600	20% / 50% 1,800 / 1,600	10% 2,150	Boiler Life and Operating Efficiency
Bun-out (98%) time for mean particle size (sec)	0.7	0.3	0.7	0.3	2 @ 1/8" in. max < 15% cofire	Carbon conversion, Safety and Fouling
Nitrogen(%db)	0.5	0.1	0.6	0.2	0.1 - 0.5	Fuelt Bound NOx Formation
Storage autoignition (F at RH > 50%)	>600	>600	*	*	*	Storage Parameters, Environmental Requirements
Explosion Index	150	100	150	100	>100	Explosive potential; Dust Control Requirements
Solid fuel off-gas 8 Hour Exposure Thresholds	CO: 35 and CO2: 5,000 ppm.	No emissions	CO: 35 and CO2: 5,000 ppm.	No emission	CO > 13,000 & CO2 > 25,000 Ppm at 30 degrees C	Health Risks. Transport and Storage
Spontaneous Combustion	None	None	*	*	*	Storage, Safety
Phytosanitation HACCP controls	None	None	None	None	56 C / 30 Min	Potential to transport and storage
Biodegradability	Minimal	None	Minimal	Minimal	Requires active management	Autoignition, self heating, off gas, dry matter loss
Densified Product Mechanical Strength	=Pellets	>Pellets	=Pellets	>Pellets	NA	Material Handling
Fines (%)	2	<1	2	<1	NA	Material Handling
Flow Rate (lb/min)	*	*	2432	*	N/A	Transport, Handling, Storage
Hausner Index	*	*	1.15	*	N/A	Transport, Handling, Storage
Bin Density (lb/ft^3)	*	*	30.0	*	N/A	Transport, Handling, Storage
Permeability (ft/sec)	*	*	0.24	*	N/A	Transport, Handling, Storage
Angle of Repose	*	*	39.2	*	N/A	Transport, Handling, Storage
Cohesion (kPa)	*	*	6.61	*	N/A	Transport, Handling, Storage

- **Resource Draw and Mix (Tons)**
- **Supply System Design (Uniform Product Specs)**
- **Cost at Reactor Throat (Cost)**

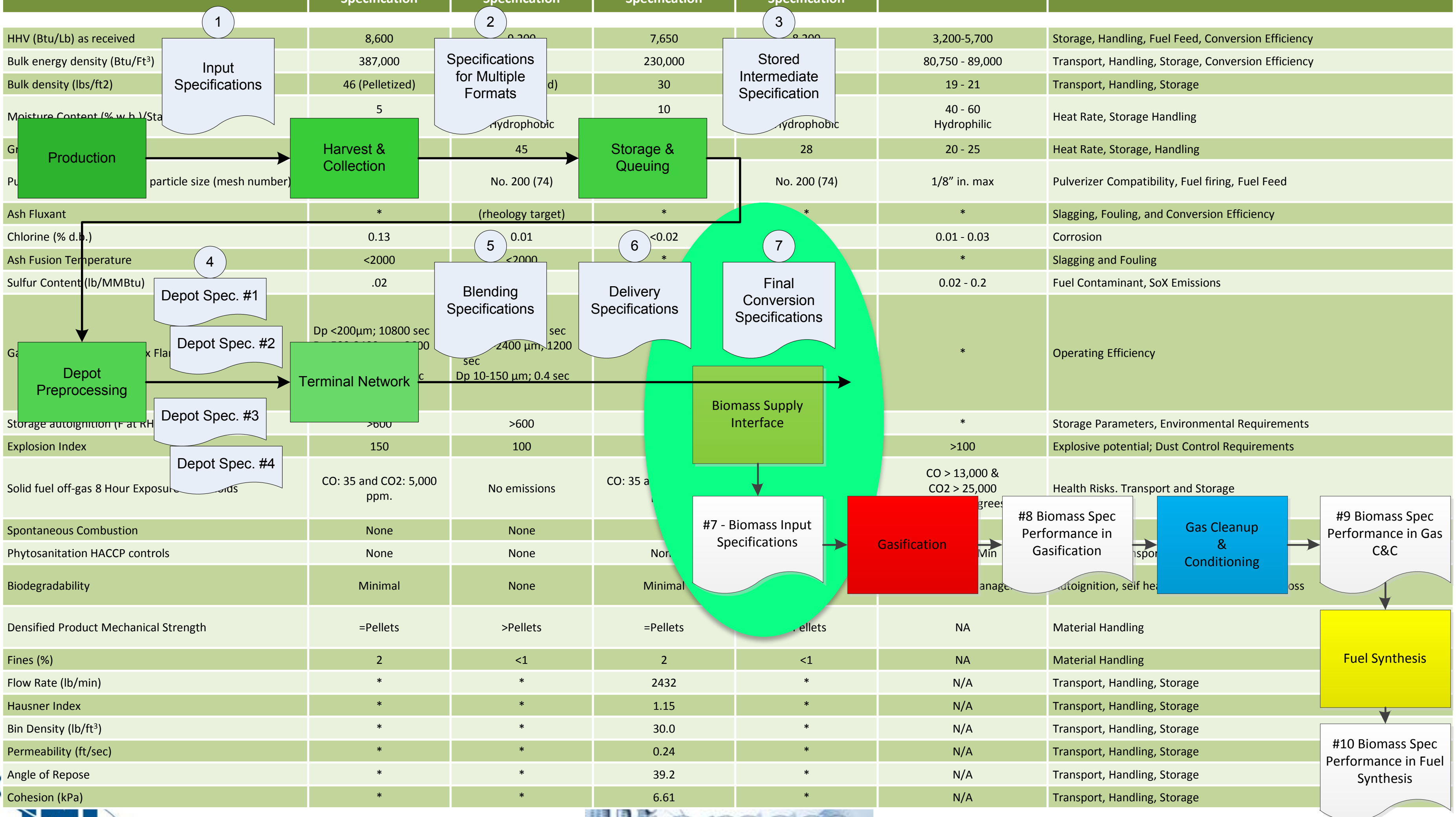
<u>Challenge</u> - Increasing Specifications Limits Supply; e.g., ---

- **Moisture**
- **Ash**
- **Density**



Development and Characterization of Process Intermediates

Gasification Feedstock Specifications	Advanced Material (Thermally Treated)		Mechanically Densified (Pelletized or Similar)		For Comparison	Plant Operations Impacts
	Minimum Specification	Target Specification	Minimum Specification	Target Specification	Green Wood	
HHV (Btu/Lb) as received	8,600	9,200	7,650	8,200	3,200-5,700	Storage, Handling, Fuel Feed, Conversion Efficiency
Bulk energy density (Btu/Ft³)	387,000		230,000		80,750 - 89,000	Transport, Handling, Storage, Conversion Efficiency
Bulk density (lbs/ft2)	46 (Pelletized)	d)	30		19 - 21	Transport, Handling, Storage
Moisture Content (% w.b.)/Sta	5	Hydrophobic	10	Hydrophobic	40 - 60 Hydrophilic	Heat Rate, Storage Handling
Gr		45		28	20 - 25	Heat Rate, Storage, Handling
Pu particle size (mesh number)		No. 200 (74)		No. 200 (74)	1/8" in. max	Pulverizer Compatibility, Fuel firing, Fuel Feed
Ash Fluxant	*	(rheology target)	*	*	*	Slagging, Fouling, and Conversion Efficiency
Chlorine (% d.b.)	0.13	0.01	<0.02		0.01 - 0.03	Corrosion
Ash Fusion Temperature	<2000	<2000	*		*	Slagging and Fouling
Sulfur Content (lb/MMBtu)	.02				0.02 - 0.2	Fuel Contaminant, SoX Emissions
Ga x Fla	Dp <200µm; 10800 sec ... 00 ... c	sec 2400 µm; 1200 sec Dp 10-150 µm; 0.4 sec			*	Operating Efficiency
Storage autoignition (F at RH	>600	>600			*	Storage Parameters, Environmental Requirements
Explosion Index	150	100			>100	Explosive potential; Dust Control Requirements
Solid fuel off-gas 8 Hour Exposure ...ids	CO: 35 and CO2: 5,000 ppm.	No emissions	CO: 35 a		CO > 13,000 & CO2 > 25,000 ...grees	Health Risks. Transport and Storage
Spontaneous Combustion	None	None				
Phytosanitation HACCP controls	None	None	Nor		Min	...nspor
Biodegradability	Minimal	None	Minimal		...anage	...utoignition, self hea... oss
Densified Product Mechanical Strength	=Pellets	>Pellets	=Pellets	...ellets	NA	Material Handling
Fines (%)	2	<1	2	<1	NA	Material Handling
Flow Rate (lb/min)	*	*	2432	*	N/A	Transport, Handling, Storage
Hausner Index	*	*	1.15	*	N/A	Transport, Handling, Storage
Bin Density (lb/ft³)	*	*	30.0	*	N/A	Transport, Handling, Storage
Permeability (ft/sec)	*	*	0.24	*	N/A	Transport, Handling, Storage
Angle of Repose	*	*	39.2	*	N/A	Transport, Handling, Storage
Cohesion (kPa)	*	*	6.61	*	N/A	Transport, Handling, Storage



Note: * = Values to be established based on research and interactive collaborations with other platforms

Harvest and Collection Systems – Process Intermediates

Field Demonstration

Focused on evaluating biomass specific harvest & collection operations

Significant variability in ash & fines content

Variability observed within windrowing treatment

- Sequential collection operation
- Chopped corn stover windrowed via 4 systems
- Low moisture materials (<30%)

- Secondary driver was the development of unit operation to produce representative process intermediates
- Provided insight into *non-pristine* stover quality attributes

Windrowing Treatment	***%Moisture (w.b.)***	***%Ash***
Wheel Rake	12-18	17.0
SP Windrower	11-31	22.8
Bar Rake	11-20	7.3
Flail Shredder	9-13	18.6

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Resolving Biochem Interface Paradox – Prevention & Mitigation Feedstock Issues

Interface Paradox

Feedstock Logistics	Biochemical Conversion
Fundamental Requirements	**Impact**

- **Stable**
- **Low Moisture**
- **Dense**

Uniform Format Targets

- **Sugars content** ↓
- **Recalcitrance** ↑

Biomass

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Solving Thermochem Interface Barriers – Improving Feedstock Feed Issues

Uniform Format Targets

¼ minus Feedstocks

Predicted Performance

10 ft Bin Diameter 2 ft Opening	Advanced Material	Corn Stover	
Flow Rate (lb/min)	2432	345	↑
Feed Density (lb/ft^3)	26.9	7.4	↑
Bin Density (lb/ft^3)	30.0	9.1	↑
Compressibility (%)	12.8	28.1	↓
Permeability (ft/sec)	0.24	0.18	↑
Springback (%)	3.76	4.72	↓
Hausner Index	1.13	1.28	↓
Cohesion (kPa)	3.83	6.61	↓
Angle of Repose	39.2°	35.3°	↓
Flowability Factor	5.8 easy flowing	1.2 very cohesive	↑

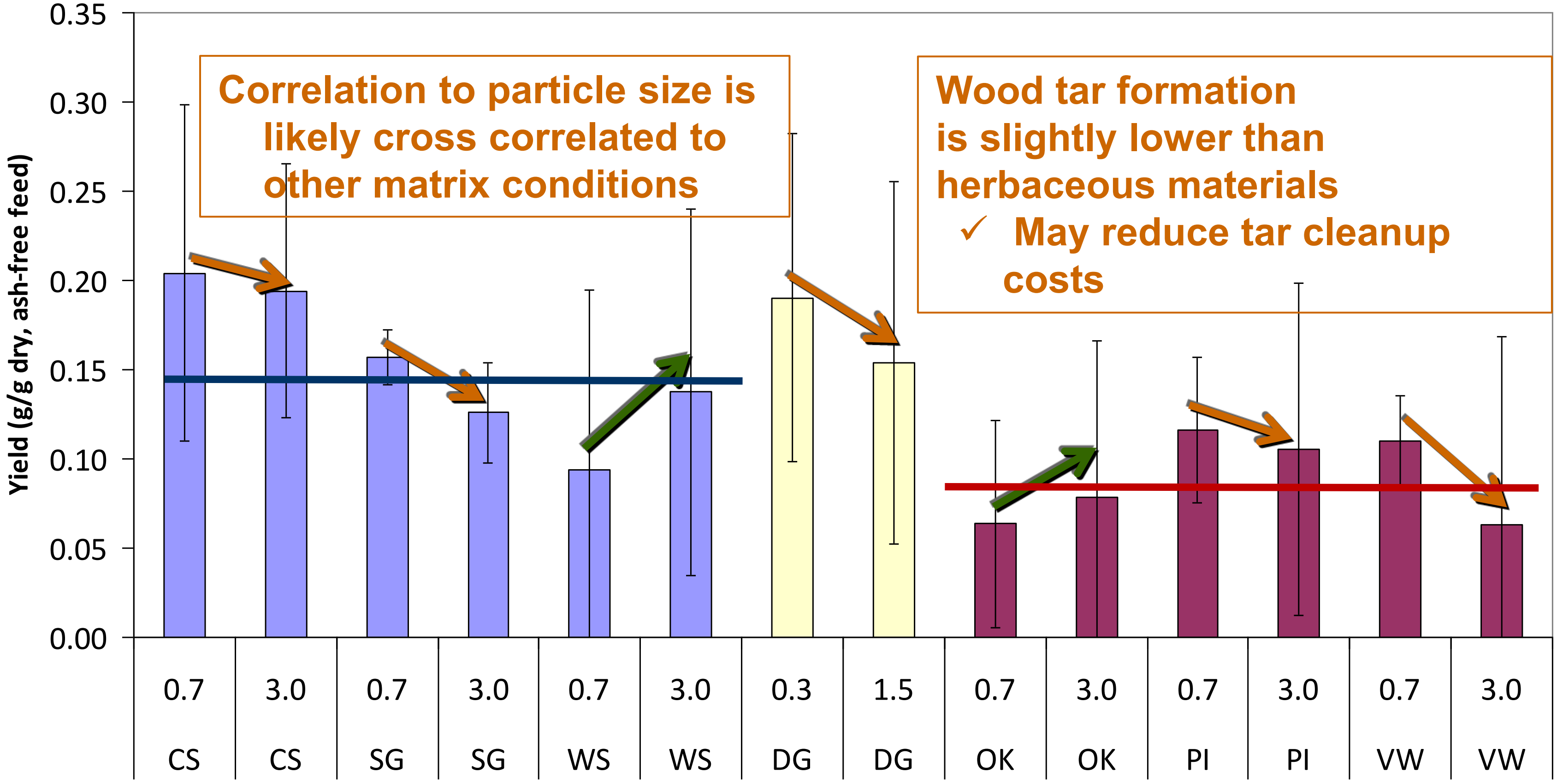
Observed Performance

Corn Stover

Idaho National Laboratory

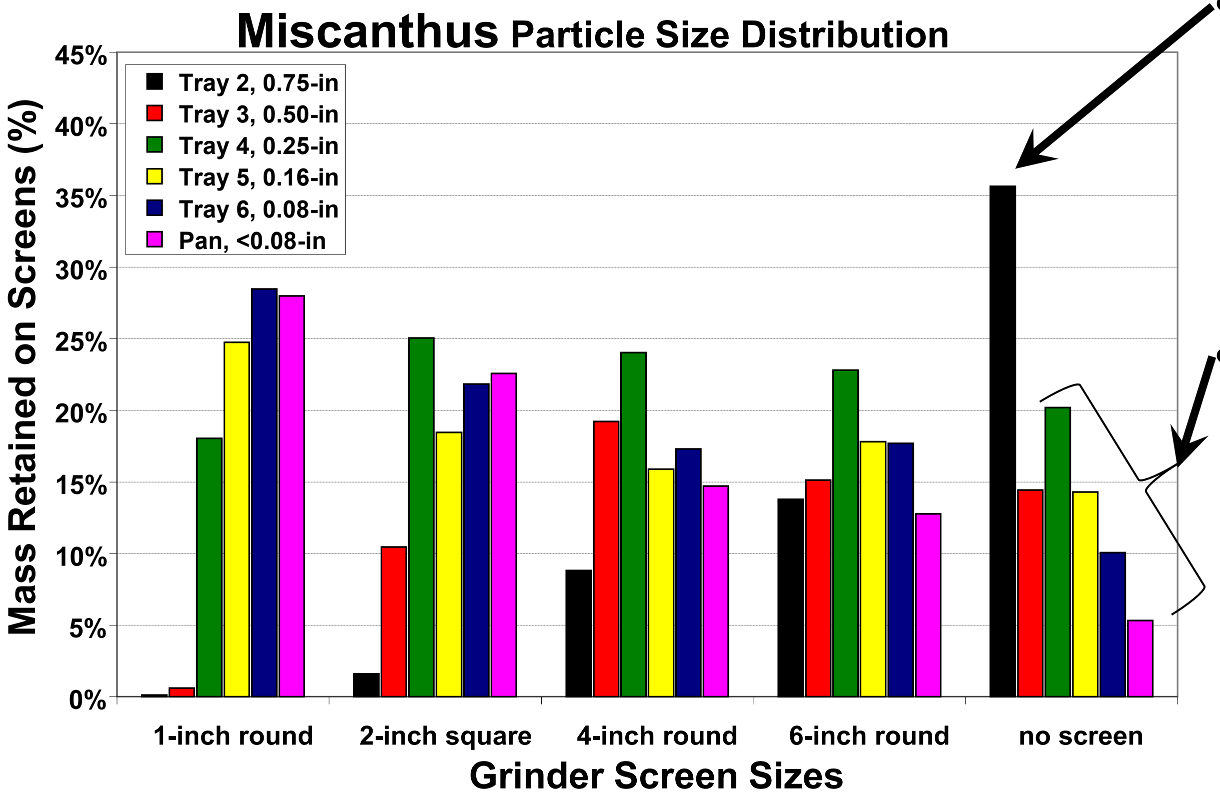
Biomass

Feedstock Particle Size Impact on Syngas Tar Composition

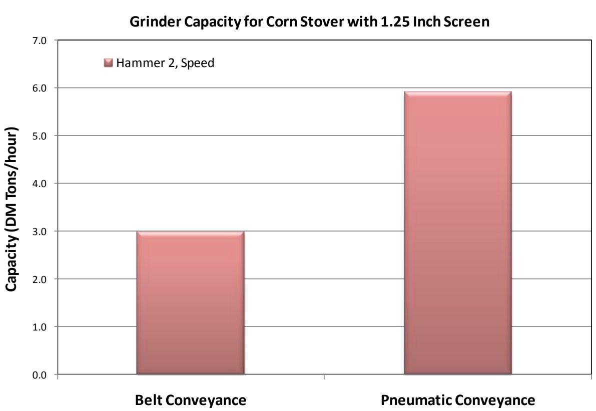


NREL data: Kim Magrini, Personal Communication, 2010

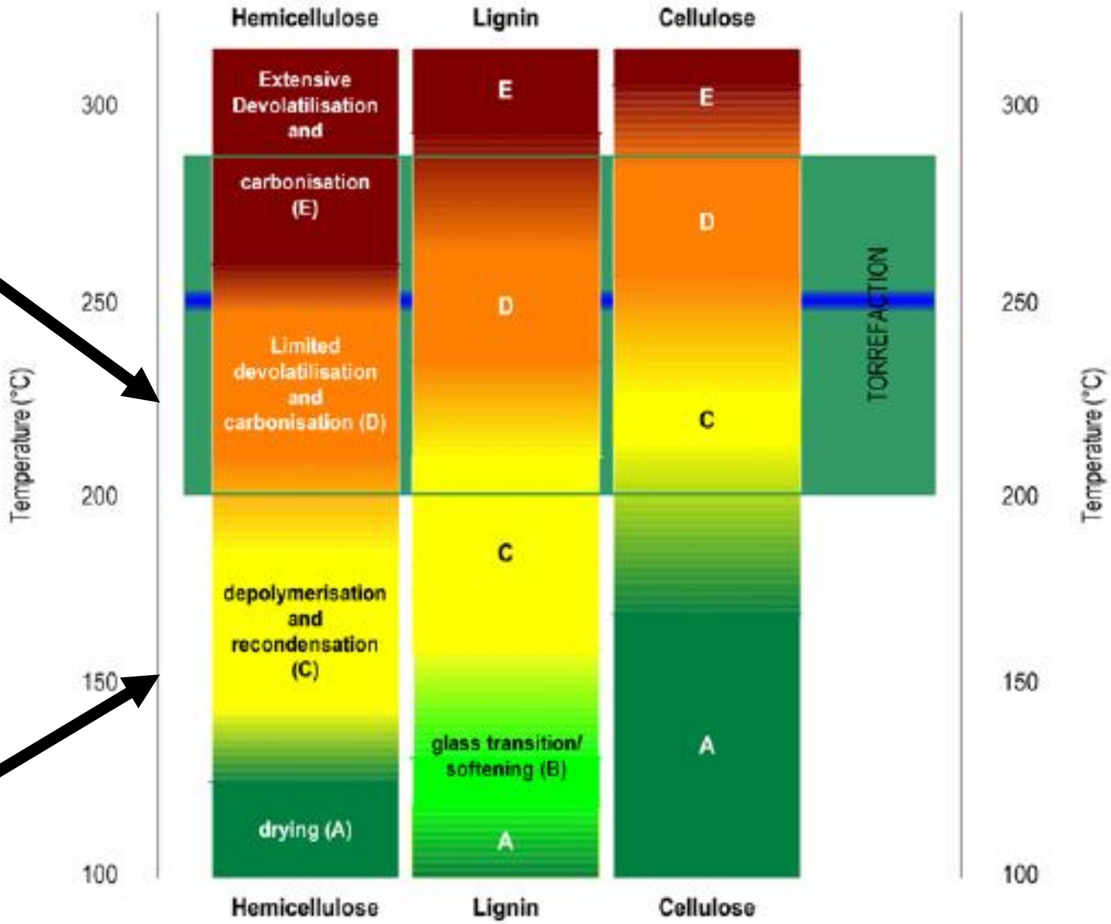
Biomass Differential or Factional Deconstruction



- Rind and vascular tissues hold together under impact forces and require shear / torsion forces to effectively size reduce
- Pith and other tissues rapidly deconstruct upon impact



Thermal Treatment & Stabilization Processes



[4] Bergman, P.C.A., et al., *Torrefaction for biomass co-firing in existing coal-fired power stations. BIOCOAL*. 2005. p. Size: 72 pages.

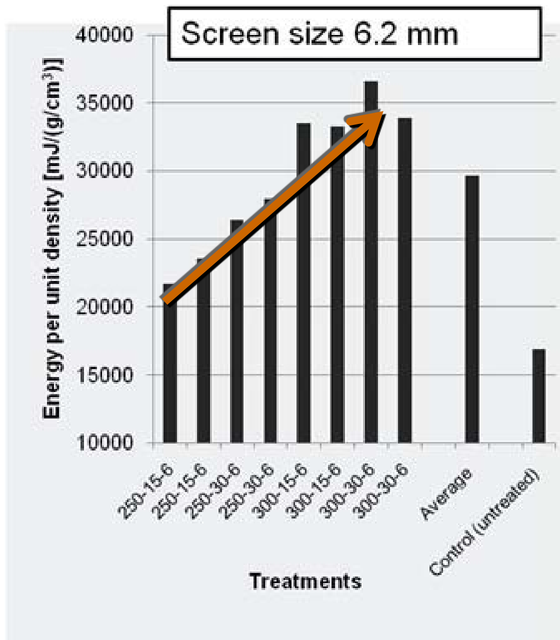
Biomass

Torrefaction and Pelletization Characterization

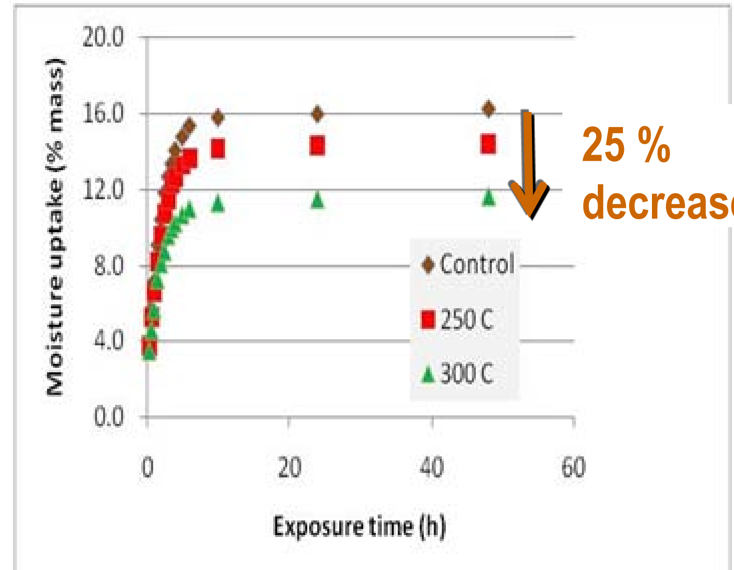
Single Pellet
Press Mill

Humidity
Chamber

ORNL data: Shahab Sokhansanj, Personal Communication, 2011



Pellets from small particles 0.8 mm



25 % decrease

- **Intermediate material energy density increased with degree of torrefaction**
- **Hydrophobicity is improved with degree of torrefaction**
  - ✓ **Decreases transportation cost**
  - ✓ **Improves storability of product**
  - ✓ **Increased energy density delivery to TC unit**

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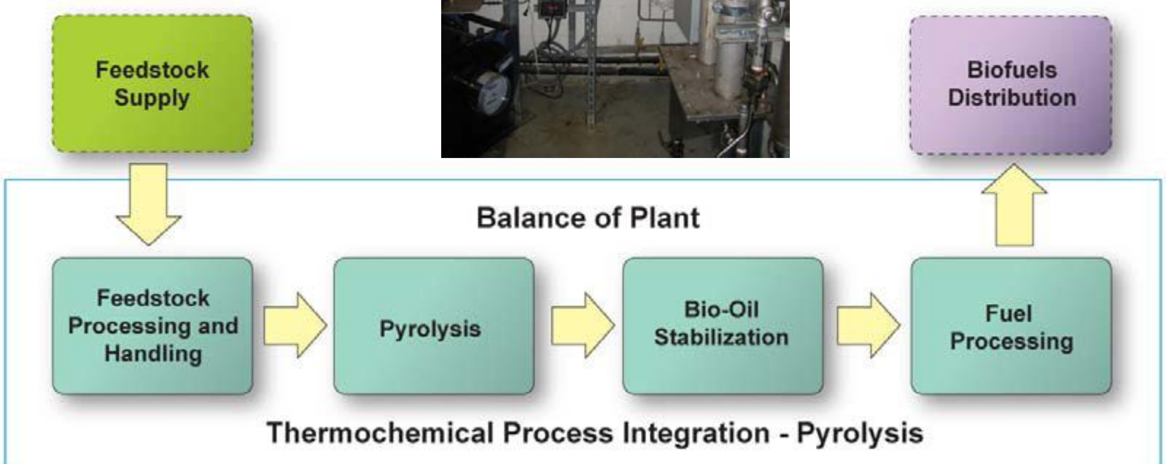
Torrefied vs Untorrified Woody Biomass Pyrolysis Screening

- **Raw white oak sawdust versus torrefied material (220 °C and 270 °C)**
- **Particles ground to < 2 mm minus**
- **Pyrolysis conditions, ~1 kg/hr, 500 °C, residence time ~0.8 sec.**

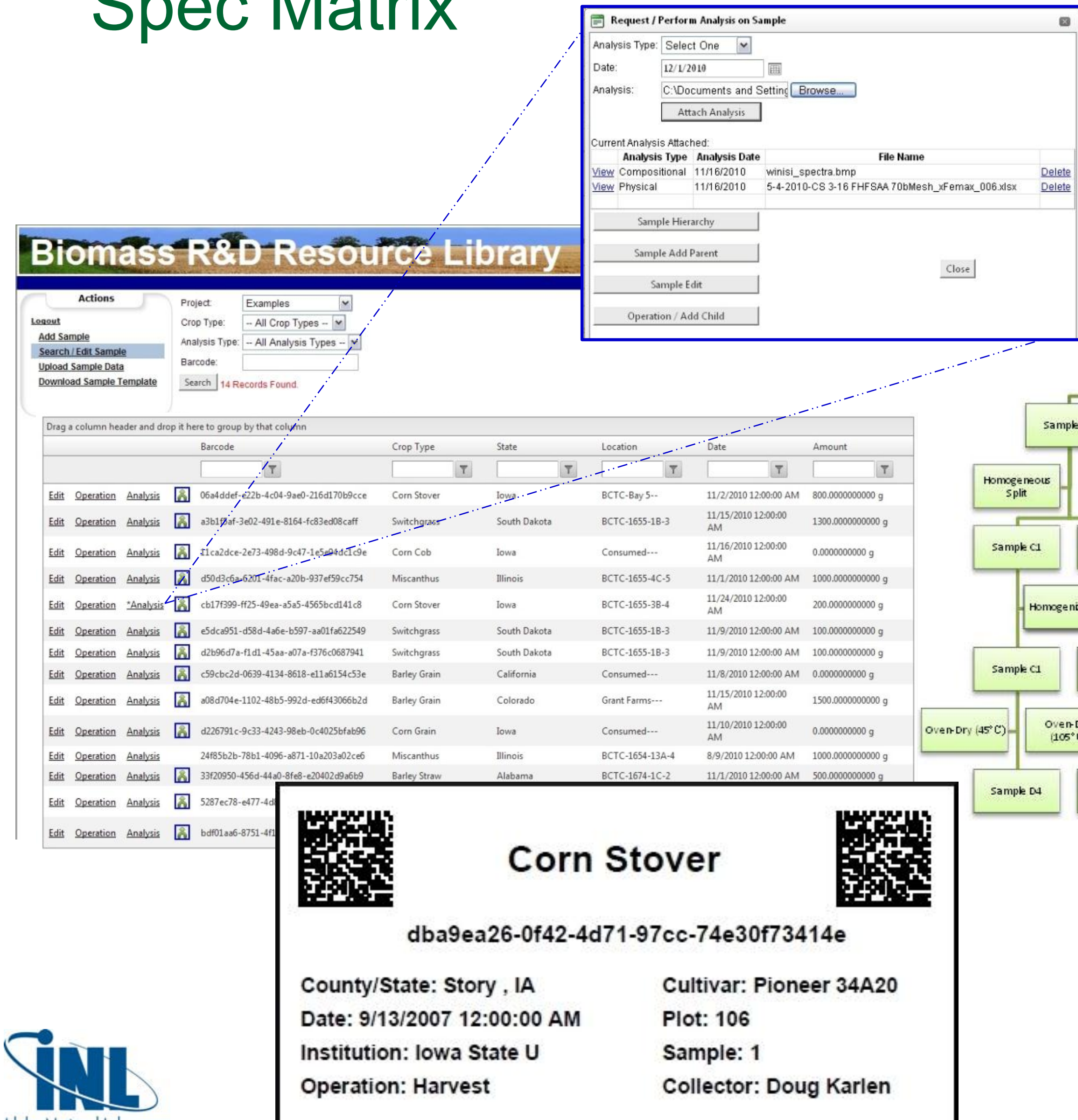
Fluidized-Bed Pyrolysis Reactor Setup 2-inch diameter, 3-ft axial



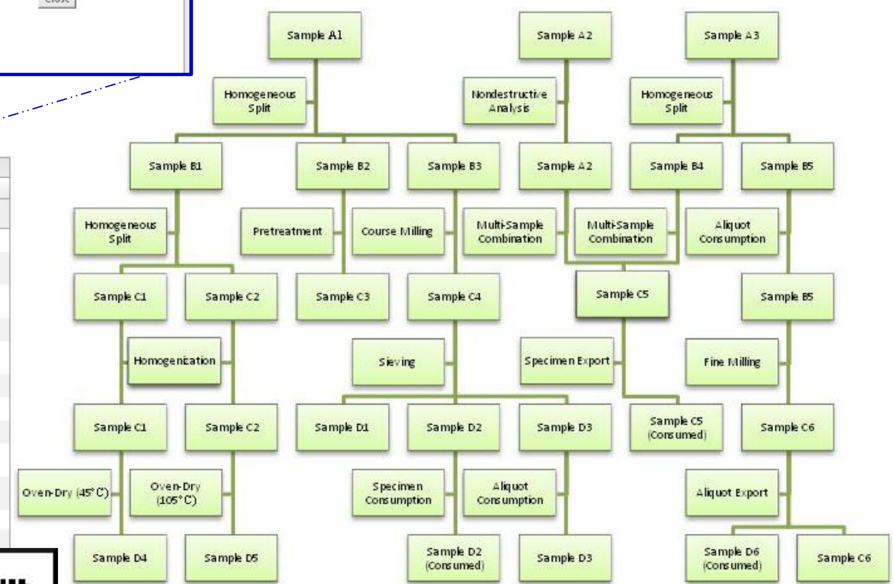
Preliminary test outcomes:

- ✓ Torrefaction enables a consistent pulverized feed to be produced with less energy
- ✓ Percent of feed going to non-condensable gas from each of the three tests were similar
- ✓ Percent of feed going to char increased with increasing torrefaction temperature
- ✓ As expected, water in the product oil decreased with increasing torrefaction temperature
- ✓ When calculated on a "dry" feed basis, the percent of feed ending up as organic product liquid is only slightly different between the baseline and 220 °C.
- ✓ Acid number appeared to increase slightly at 220 °C but decreased at 270 °C

Biomass Resource Library – To Sort Out the Spec Matrix



Sample Hierarchy



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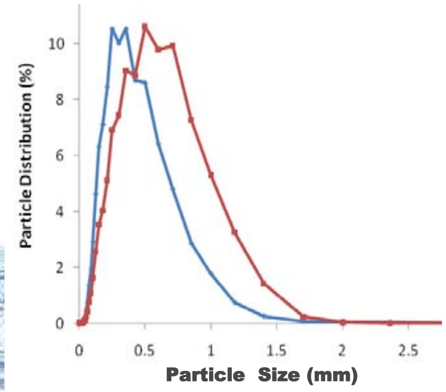
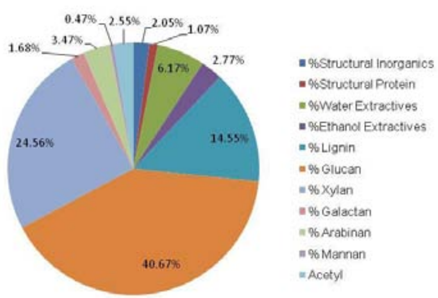
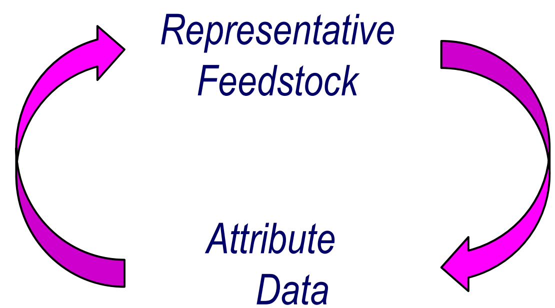
Library Physical Materials Archive & Storage







Bulk Materials **Process Intermediates** **Unmodified**

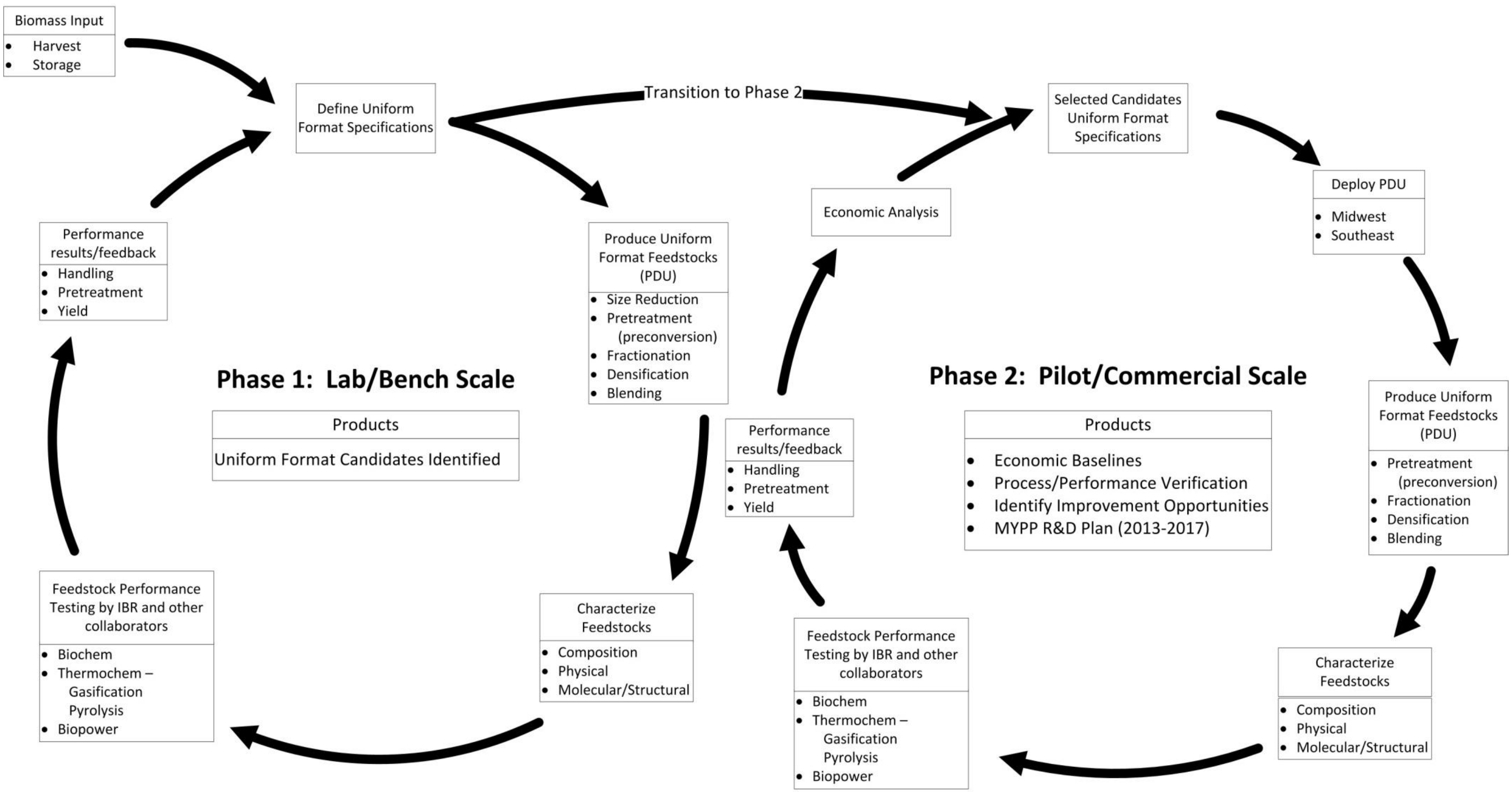
The Uniform Format Research Path

Conventional Designs Priorities

- Efficiency/Capacity
- Dry Matter Losses
- Operational Windows

Uniform Format Designs Priorities

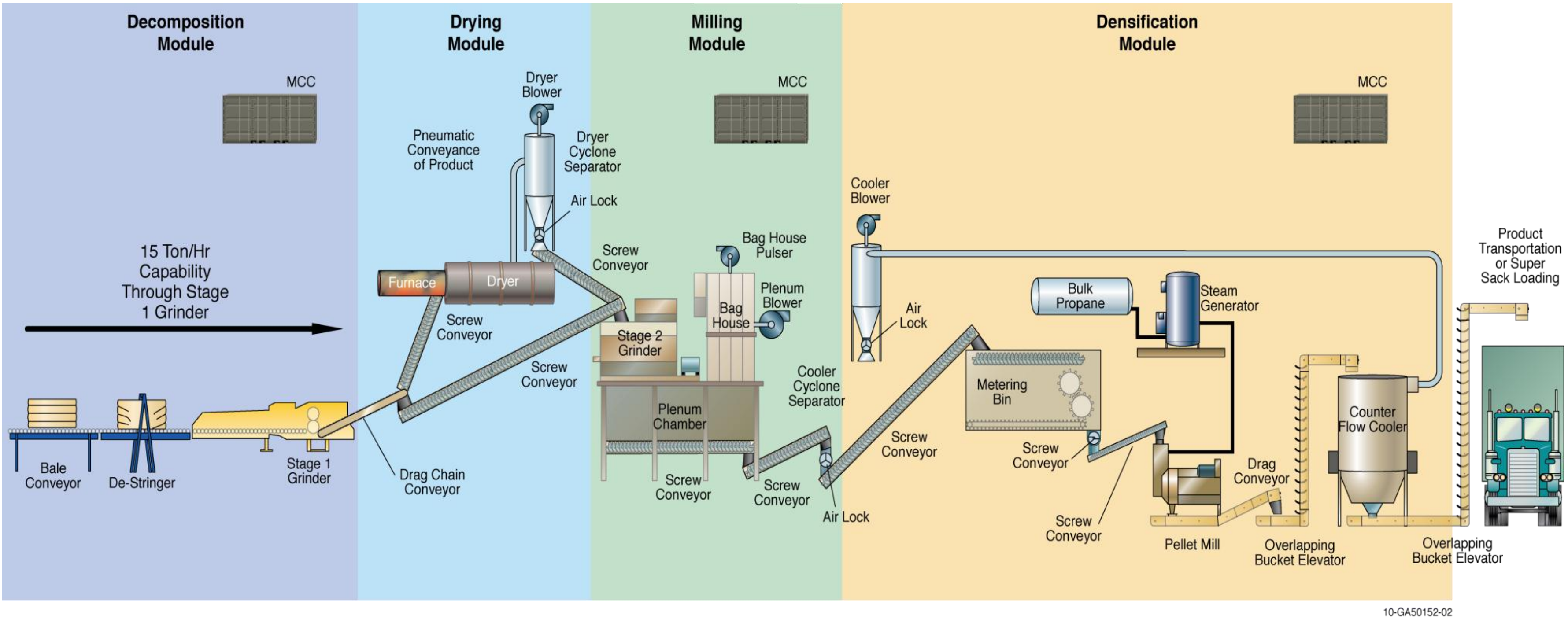
- Altering Material Properties
- Stabilization
- Densification



Depot Preprocessing to Uniform Format Products

- **Thermochemical Biofuels and Heat/Power Market:**
  - **Preprocessing and blending for ash, moisture and rheological properties**
  - **Commodity has grades same as corn or coal (e.g., #1, 2, 3….)**
- **Biochemical Biofuels and Products Market:**
  - **Preprocessing and segregation for specific conversion process**
  - **Commodity similar to wheat (e.g., blend within species/variety) .**
- **Petroleum Refinery Market:**
  - **Energy density and feedstock stability are key characteristics (e.g., Liquid Format)**

PDU Modular Design



Modules are designed to operate individually or in any combination and alternate equipment can replace one or more modules.

PDU – Instrumentation, Controls, and Data Systems

- Modular in hardware and software design and implementation.
- Designed to accommodate any type of measurements required for research data without major modification/redesign.
- Local and remote control of modules.
- Local safety system implementation.
- National Instruments Labview software for quick development and modification.
- Control Trailer provides networked process control, archival storage and data analysis capability.
- Control Trailer also serves as a documentation library and tool crib for maintenance on the PDU.

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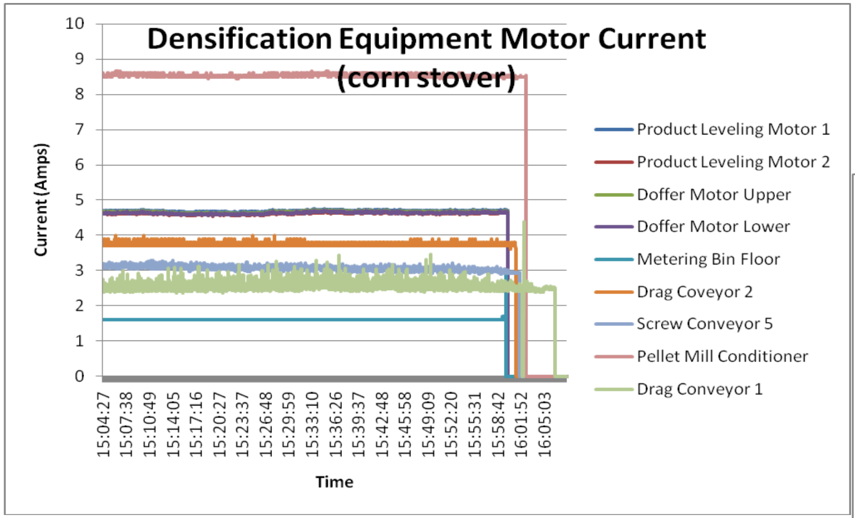
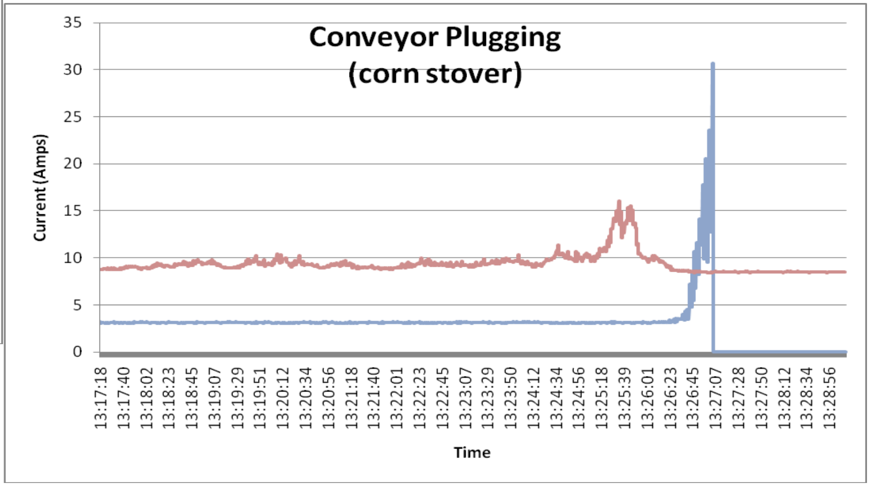
PDU – An R&D tool for Developing a Depot Preprocessing Supply System

PDU Functionality – Data Collection and Data Integration



Example above: current (amps) from multiple motors while operating PDU.

Example below: conveyor current (amps) used to prevent operation upsets.



Key Input Data Streams
- In-feed Mass Flow
- In-feed Moisture
- Steam Flow Rate
- Steam Quality
- Power Usage

Engineering Performance
- Feedstock Quality
- $/ton

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PDU - Dryer System Module

- Provides feedstock moisture reduction as needed to assist in product stabilization
- Dryer system is fully self contained for independent operation and skid mounted for easy transportation and assembly.
- Designed for research missions with:
  - Variable capacity and operating modes to accommodate multiple feedstock types, moisture, and research needs including: temperature, flow rate, fan rates, particle size, residence times, etc.
  - Provisions for insertion of component fractionation at various points in dryer process and use as a preprocessor for torrefaction and other processes.
- May be used as part of a separate research activity or in combination with other modules.

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PDU – An R&D tool for Developing a Depot Preprocessing Supply System

PDU Functionality – Portable, Modular, Reconfigurable

Rotating drum dryer (50 to 150 C) deployed to California as a single module for biomass drying studies.

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PDU – Grinder, Milling and Densification Modules

All PDU modules can be reconfigured to develop, verify and produce numerous biomass preprocessed intermediates for conversion testing

- **Accepts a variety of bale formats,**
- **input of bulk feed material into the system,**
- **component fractionation equipment.**

Hammer mill may be replaced with other types of mills

- **Pellet Mill mounted in movable containers.**
- **Steam generator and coolers may be separated and use for other processes**

PDU – Material Handling Systems

- Multiple conveyors move the material at all stages of processing from one operation to the next. All are conveyors are enclosed to prevent excessive dust generation and allow complete material balance accounting.
- Conveyors are designed to support a variety of material types, densities, and capacities.
- Modifications were made to standard conveyances to provide portability and flexibility.
  - Design allows for ease of reconfiguration of the system for testing baseline operations and alternative or new concept equipment.
  - Design provides the ability to deploy at a crop or plant location with fewer site requirements and lower setup costs.

Inside metering bin

Need for a Uniform Format Approach

- Lower productive systems can contribute (i.e. reduce stranded resources, higher resource volumes)
- Risk of obtaining a stable feedstock supply is virtually eliminated
- Feedstock supply buffer added to the system
  - Stable supply and price
  - Lower capital financing costs
  - Strategic reserves
- Consistent feedstock specifications delivered to plant gate
- Biorefinery citing and sizing can shift from resource draw constraints to infrastructure variables such as water, gas, electricity, labor, transportation systems, tax incentives, product distribution, and product demand.

The Uniform Format Research Path

Resource Coupled Supply System Design