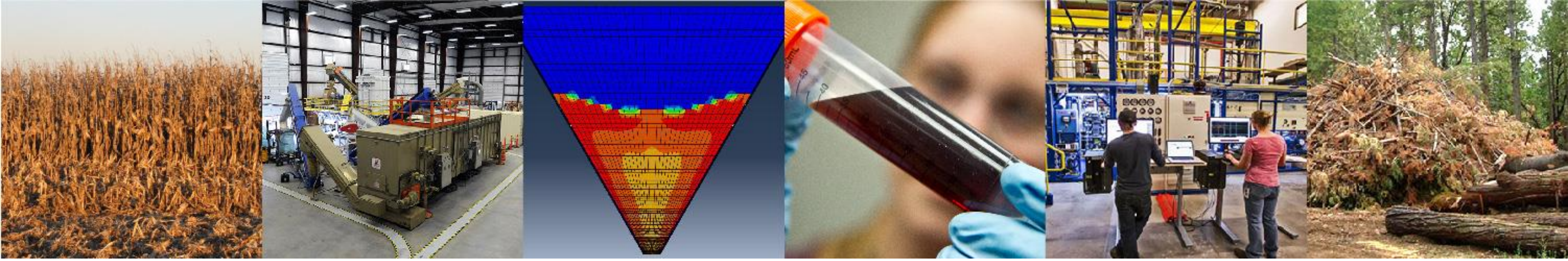


DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

Feedstock Variability and Specification Development

WBS# 1.2.2.401-408

March 7, 2019

PI: Allison Ray (INL)
A. Hoover, R. Emerson, J. Klinger, T. Westover,
L. Williams, M. Ramirez-Corredores (INL),
D. Tanjore (LBNL), T. Semelsberger (LANL),
E. Webb (ORNL), B. Donohoe, N. Nagle, E. Wolfrum (NREL),
K. Sale (SNL), J. Collett (PNNL), G. Fenske, O. Ajayi (ANL)

fcic
FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

Goal of the Consortium

Identify and address the impacts of feedstock variability – chemical, physical, and mechanical – on biomass preprocessing and conversion equipment and system performance, to move towards 90% operational reliability

Goal Statement

PROJECT GOAL

- Quantify variability in chemical, physical, and mechanical properties and supply biomass feedstocks for FY18 Experimental Baseline Runs
- Conduct fundamental characterization required to understand property impacts on performance in preprocessing and conversion

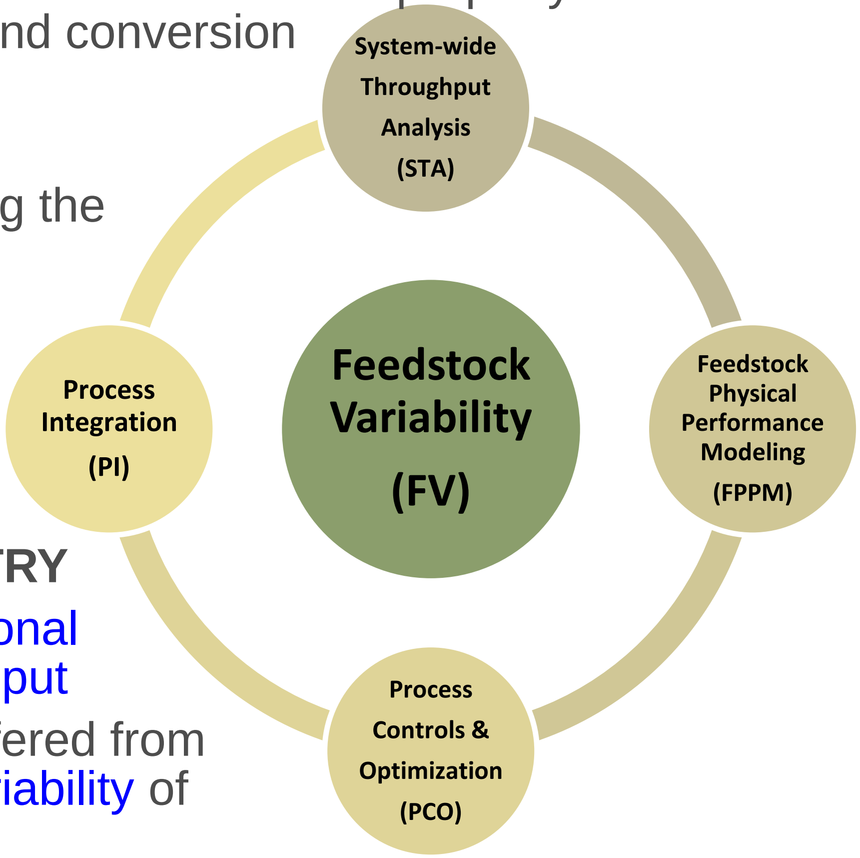
OUTCOMES

Fundamental knowledge is critical to de-risking the conversion of lignocellulosic biomass to fuels.

- Inform mitigation strategies
- Support specifications development
- Develop methods tailored to biomass

RELEVANCE TO THE BIOENERGY INDUSTRY

- Feedstock variability poses a major operational challenge to equipment uptime and throughput
- Integrated biorefinery development has suffered from failing to account for the complexity and variability of lignocellulosic biomass



Quad Chart Overview

Timeline

- Project Start Date: November 2017
- Project End Date : September 2018
- Percent Complete: 100%

	Total Costs Pre FY17**	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	N.A.		$4,368K	0
Project Cost Share*	N.A.			$

Partners: INL (61%), NREL (9%), SNL (5%), ORNL (5%), LBNL (11%), LANL (7%), PNNL (1.5%), ANL (0.5%)

Barriers addressed

- **Ct-A. Feedstock Variability**
- **Ft-E. Terrestrial Feedstock Quality, Monitoring**
- **Ft-G. Biomass Physical State Alteration and Impact on Conversion Performance**

Objective

Provide fundamental characterization data for corn stover and loblolly pine residues to identify impacts of variability on preprocessing and conversion in low and high-temperature pathways.

FY18 Project Goals

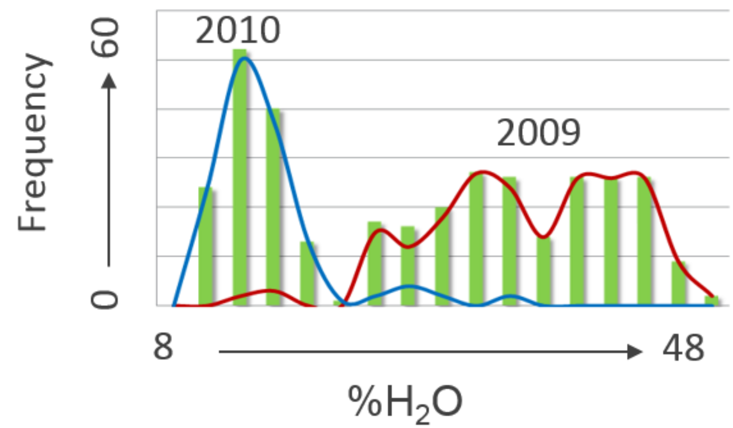
- Conduct fundamental characterization and analysis of corn stover and pine residues to
  1) Enable understanding of property-performance relationships
  2) Establish preliminary ranges of physicochemical properties
- Supply variable corn stover and loblolly pine residues for FCIC Baselines
- Facilitate data sharing
- Develop methods for biomass

1 – Project Overview

CONTEXT

- Feedstock variability cited as a major operational challenge*
- Ash, moisture, and soil contaminants* noted as critical factors that impact biomass quality, process uptime and throughput

Variability in moisture content of **corn stover**



Degradation of corn stover in field-side storage leads to dry matter loss, altering bulk composition and structural integrity.

Fundamental characterization of non-pristine biomass is needed* to understand the quality of available biomass resources for integrated preprocessing and conversion pathways.

*Biorefinery Optimization Workshop Summary Report (October 2016), USDOE EERE Bioenergy Technologies Office.

1 – Project Overview

HISTORY

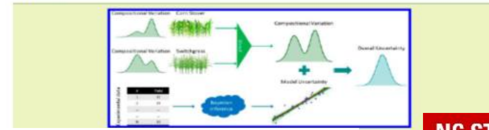
- **2006:** INL and NREL initiated the feedstock conversion interface project
- **~2011:** INL, NREL, LBNL, SNL, PNNL partnered and identified sources and impacts of feedstock variability on conversion

ACS Sustainable Chemistry & Engineering
Research Article

Understanding the Impacts of Biomass Blending on the Uncertainty of Hydrolyzed Sugar Yield from a Stochastic Perspective

Longwen Ou, Guanqun Luo, Allison Ray, Chenlin Li, Hongqiang Hu, Stephen Kelley, and Sunkyu Park
Department of Forest Biomaterials, North Carolina State University, 2820 Faucette Drive, Raleigh, North Carolina 27606, United States
Idaho National Laboratory, 2525 Fremont Avenue, Idaho Falls, Idaho 83415, United States

Supporting Information



frontiers in Energy Research
ORIGINAL RESEARCH
published: 19 June 2018
doi: 10.3389/fenrg.2018.00054

OPEN ACCESS

Impact of Drought on Chemical Composition and Sugar Yields From Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Miscanthus, a Tall Fescue Mixture, and Switchgrass

Amber Hoover[1], Rachel Emerson[1], Allison Ray[1], Daniel Stevens[1], Sabrina Morgan[1], Marnie Cortez[1], Robert Kallenbach[2], Matthew Sousek[3], Rodney Farris[4] and Dayna Daubaras[1]*

NC STATE UNIVERSITY

Idaho National Laboratory

Contents lists available at ScienceDirect
Bioresource Technology
journal homepage: www.elsevier.com/locate/biortech

Predictive modeling to de-risk bio-based manufacturing by adapting to variability in lignocellulosic biomass supply

Akash Narani[a,b], Phil Coffman[a,b], James Gardner[a,b,1], Chenlin Li[a,c], Allison E. Ray[c], Damon S. Hartley[c], Allison Stettler[a,b], N.V.S.N. Murthy Konda[b], Blake Simmons[d,2], Todd R. Pray[a,b], Deepti Tanjore[a,b,*]
[a] Advanced Biofuels Process Demonstration Unit (AB-PDU), Lawrence Berkeley National Laboratory, Berkeley, CA, United States
[b] Biological Systems and Engineering Division, Lawrence Berkeley National Laboratory, Berkeley, CA, United States
[c] Energy and Environmental Science and Technology, Idaho National Laboratory, Idaho Falls, ID, United States
[d] Biofuels and Biomaterials Science and Technology, Sandia National Laboratory, Livermore, CA, United States

BERKELEY LAB

AB PDU

HIGHLIGHTS

- Feedstock blending can enable nationwide production of biofuels.
- Predictive model can identify ideal blend ratios to achieve high sugar yields.
- A low ratio of high-quality feedstock can substantially improve sugar yields.

GRAPHICAL ABSTRACT

Bioresource Technology
Volume 271, January 2019, Pages 218-227

Simultaneous application of predictive model and least cost formulation can substantially benefit biorefineries outside Corn Belt in United States: A case study in Florida

Akash Narani[a, b], N.V.S.N. Murthy Konda[b], Chyi-Shin Chen[a, b], Firehiwot Tachea[a, b], Phil Coffman[a, b], James Gardner[a, b, 1], Chenlin Li[a, c], Allison E. Ray[c], Damon S. Hartley[c], Blake Simmons[d, 2], Todd R. Pray[a, b], Deepti Tanjore[a, b]

CREATIVE ADVANTAGE

- Fundamental approach coupled with interdisciplinary, multi-laboratory team
- Team offers diverse expertise in analytics, biology, chemistry, engineering, materials science, and physics

Feedstock Variability Project Team: Representing a Network of 8 National Labs

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FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM


Ed Wolfrum, Ph.D.


Bryon Donohoe, Ph.D.


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George Fenske, Ph.D.

Argonne NATIONAL LABORATORY


Tyler Westover, Ph.D.

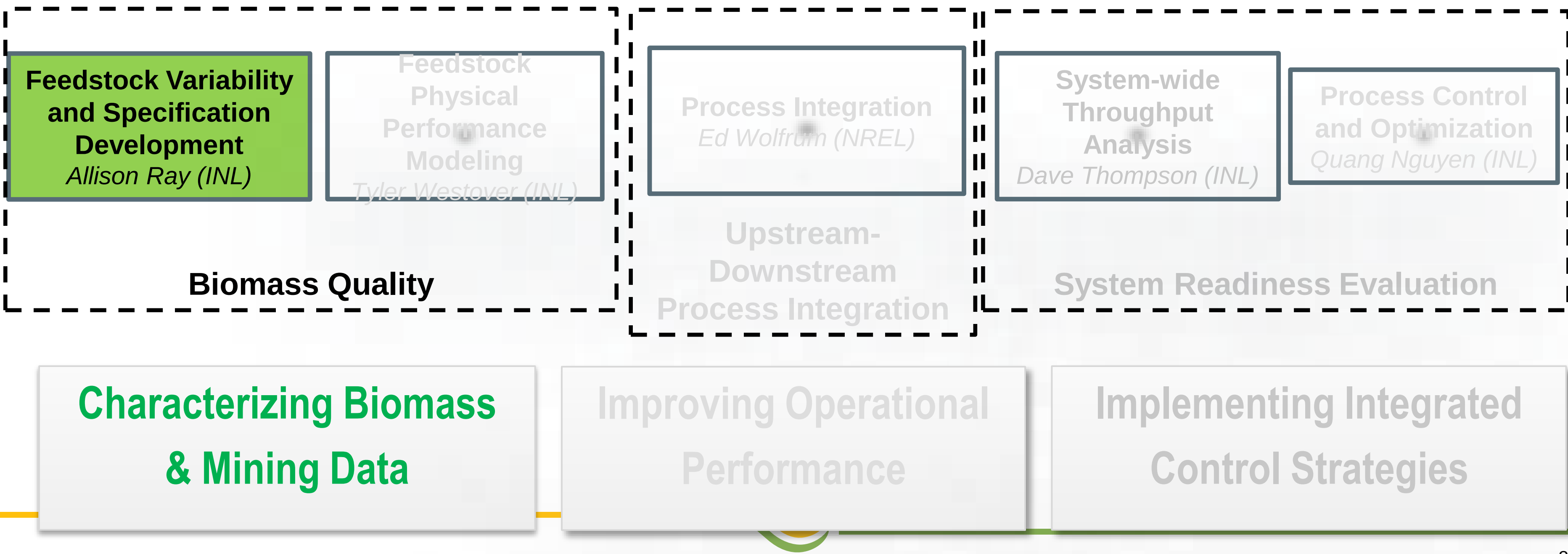

Jordan Klinger, Ph.D.

INL Idaho National Laboratory

1 - Project Overview

OBJECTIVES

- Perform fundamental, physicochemical characterization and analysis to quantify property impacts on preprocessing and conversion in low and high-temperature pathways.
- Feedstock supply for FCIC projects.
- Data sharing and management for FCIC, facilitated through BFL.
- Methods development for physical and mechanical properties of biomass.



2 - Approach - Management

- Bi-weekly coordination with **Process Integration** for planning and execution of Baseline Runs
- Engaged with **Industry Advisory Board** for recommendations on FCIC biomass supply
- Bi-weekly **Feedstock Variability** team calls
- Weekly FCIC, all-hands calls
- Joint milestones with **Feedstock Physical Performance Modeling**, including one Annual (SMART) milestone
- Facilitated sample/data sharing and management through **Bioenergy Feedstock Library**

Feedstock Variability (FV) Structure

Task Title	Task Lead
Task 1. Baselining, Data, Corn Stover and Pine Resource Management	A. Ray, A. Hoover, R. Emerson, E. Wolfrum INL, NREL, SNL, PNNL
Task 2. Feedstock Quality Analysis	E. Webb (ORNL)
Task 3. Characterize biomass variability and establish property ranges for physical and mechanical preprocessing	A. Hoover (INL)
Task 4. Characterize biomass variability and establish property ranges for Low-Temperature Conversion	D. Tanjore (LBNL) LANL, INL, NREL, SNL
Task 5. Characterize biomass variability and establish property ranges for High-Temperature Conversion	L. Williams (INL)
Task 6. Physical and Mechanical Method Development and Characterization of Biomass (Tightly coupled to 1.2.2.50X *Feedstock Physical Performance Modeling*)	T. Westover (INL) ANL

2 - Approach - Technical

TECHNICAL APPROACH:

- Defined conditions required for Baseline Runs with **Process Integration**
  - ‘High’ and ‘low’ moisture
  - ‘High’ and ‘low’ ash/inorganics content
- Acquired **~30 tons of corn stover** and **~45 tons of pine residues** for low- and high-temperature baselines working with industry and academic partners
- Developed screening and sampling plans for supply and execution of Experimental Baselines with **Process Integration**
- Quantified variability in **physicochemical properties**
- Developed and implemented methods tailored to biomass
- Provided data inputs to **Process Integration, Feedstock Physical Performance Modeling, Process Controls and Optimization,** and **System-wide Throughput Analysis** for analysis of property-performance relationships
- Developed the ‘FCIC Primer’ for vocabulary and methods harmonization

2 - Approach - Technical

CHALLENGES

- Difficulty in locating corn stover post-harvest
- Lack of complete datasets for relevant biomass resources
  - Inorganic speciation
  - Loblolly pine residues
  - Physicochemical, surface properties
  - How properties vary as a function of moisture content, degradation state, etc.
- Lack of available methods—existing methods from other industries are not tailored to biomass

CRITICAL SUCCESS FACTORS

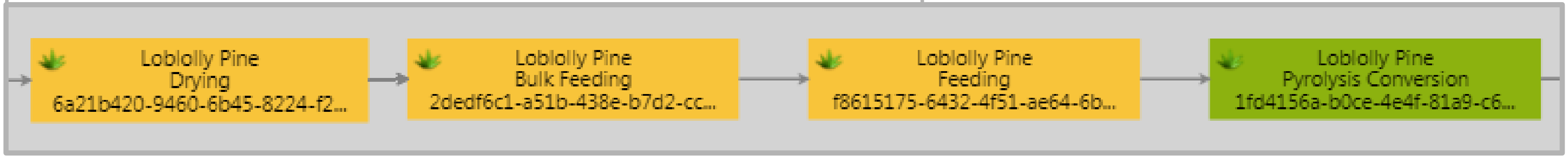
- Expansive datasets capturing variability in biomass from field through conversion
- Fundamental understanding to address technical risks associated with scale-up and the integration of preprocessing and conversion technologies
- Industry acceptance

3 - Technical Accomplishments: FCIC Sample and Data Management

- Supported objectives to integrate and share data across the FCIC
- Tracked ≥ **5000** FCIC Baseline samples using Bioenergy Feedstock Library (BFL)
  - Sample sizes: up to 20 tons
  - Barcode system for tracking
  - Biomass & intermediate samples
  - Characterization data

IMPACT: Comprehensive datasets were compiled for baseline runs and shared across the FCIC.

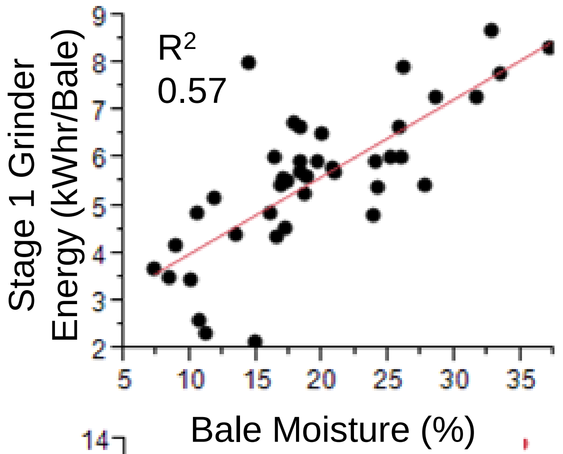
BFL sample tracking for baseline unit operations:

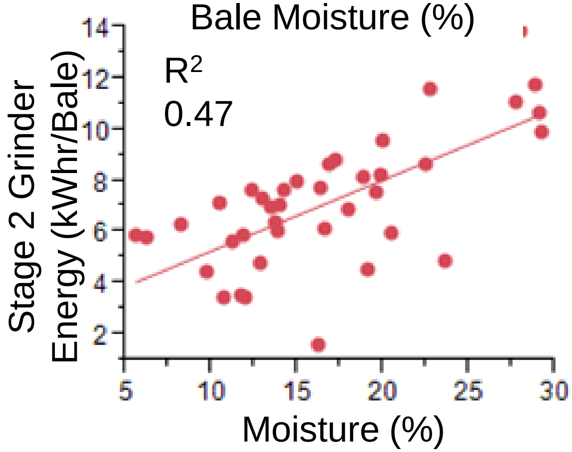


Analysis of Historical Data in Bioenergy Feedstock Library to Identify Knowledge Gaps

- Analysis of historical data (moisture, particle size distribution, etc.) and Biomass Feedstock National User Facility (BFNUF) PDU process data to identify gaps for FCIC
- Grinder energy evaluated as a function of bale moisture
  - Process data from BFNUF PDU
  - Bale moisture from BFL

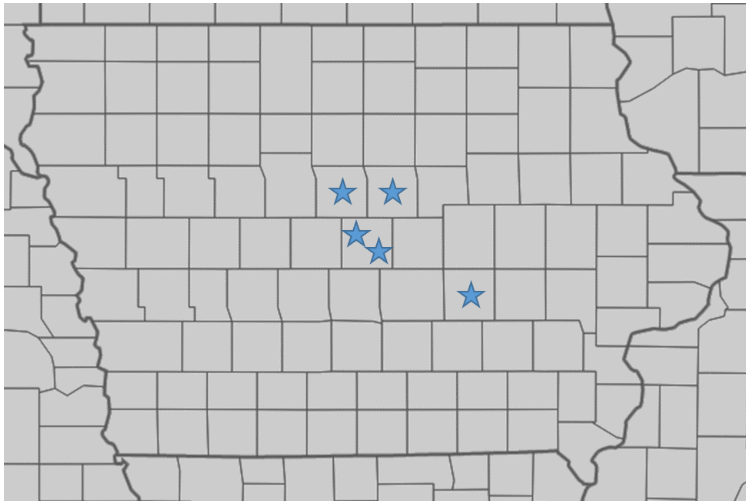
IMPACT: Moisture explains some but not all variability in process efficiency (grinder energy).



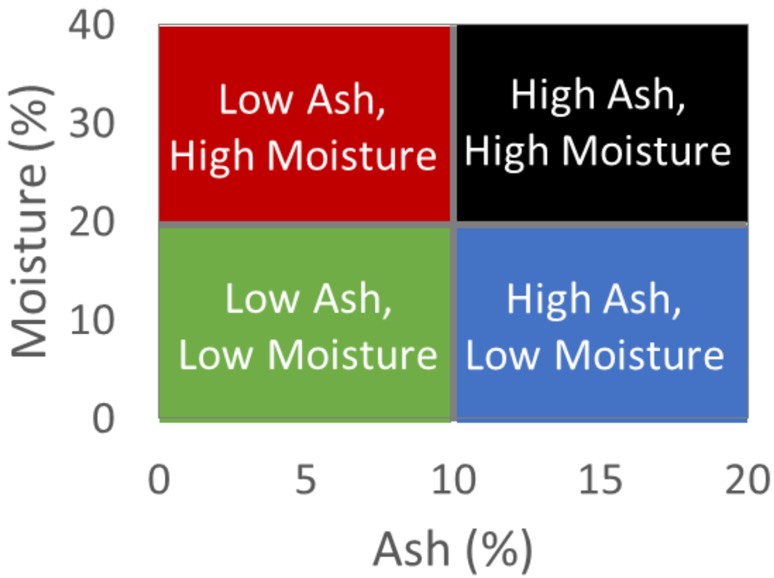


3 - Technical Accomplishments: LT FCIC Baseline Supply: Corn Stover

- **~30 tons** commercially-harvested stover in IA
- Represents biorefinery supply shed (5 sites)
- Coordinated with DuPont & Iowa State Univ.



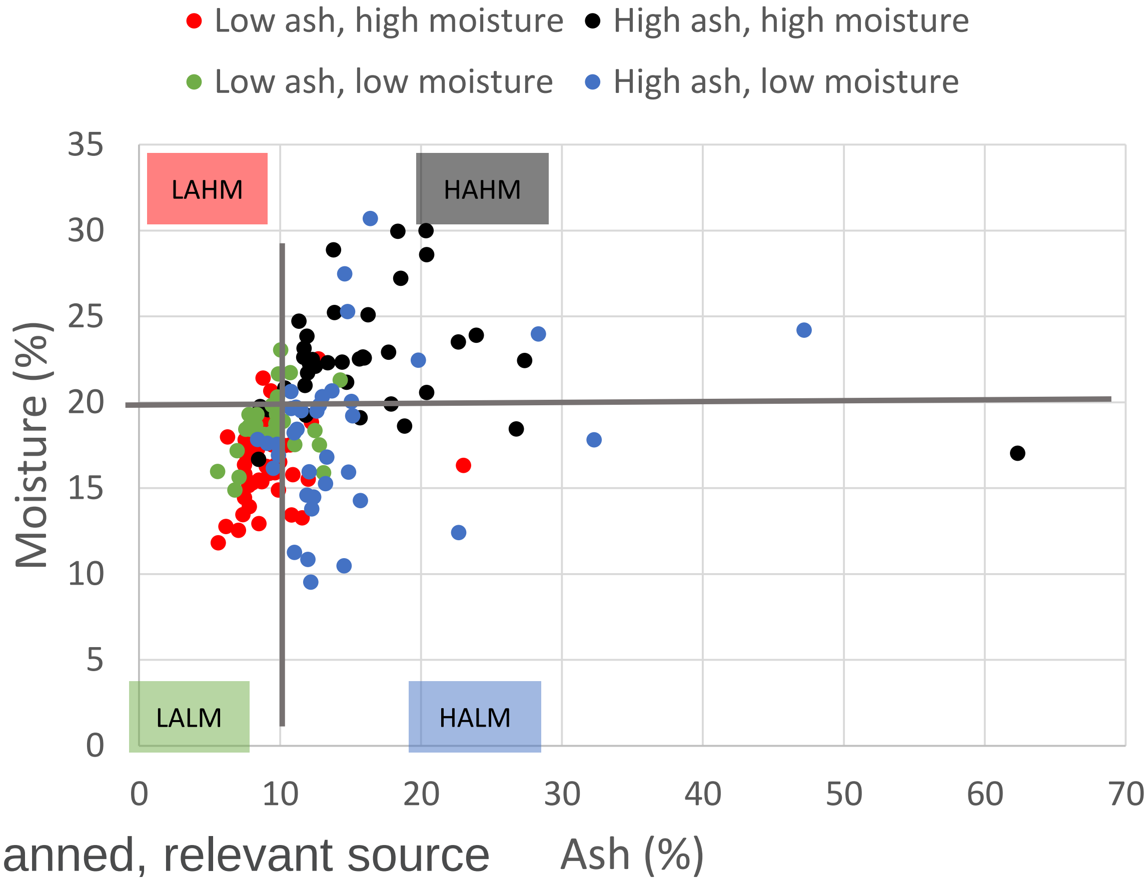
Targeted ash and moisture conditions:



Bale Characterization and Selection for FY18 Experimental Baseline Runs

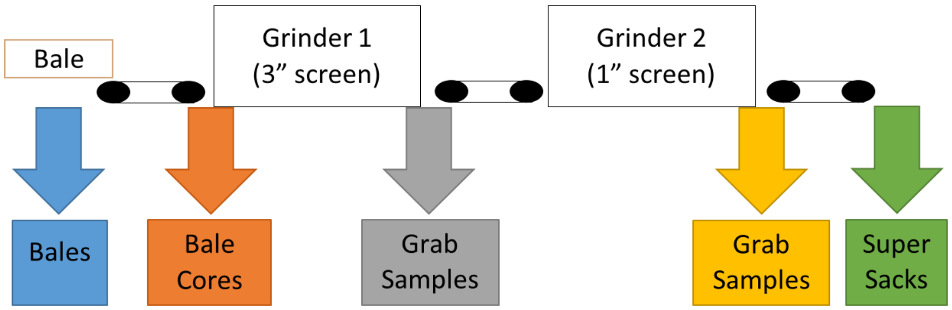
- Bales characterized via preliminary screening (3 cores/bale)
- Bales selected
  - 4 baseline runs
  - 6 bales/run
  - 9 cores/bale (216 total)
- Within-bale variability too high for target classification
- Some 'high-moisture' bales did not fit category well
  - Self-heated during field-side storage
  - Self-heating was an unplanned, relevant source of variability captured by the baseline runs

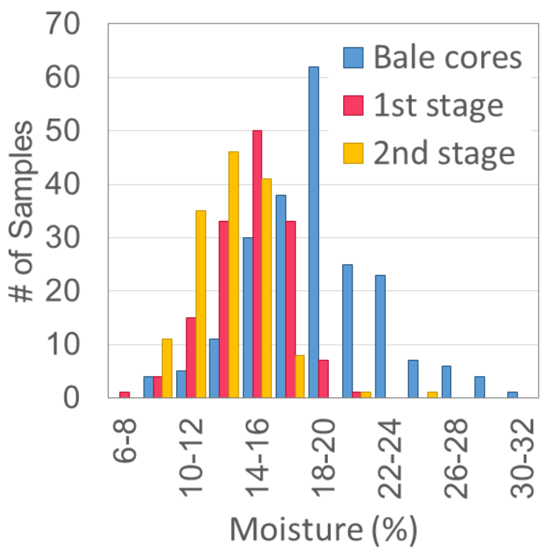
Bale cores corresponding to samples selected for LT baseline runs at NREL.

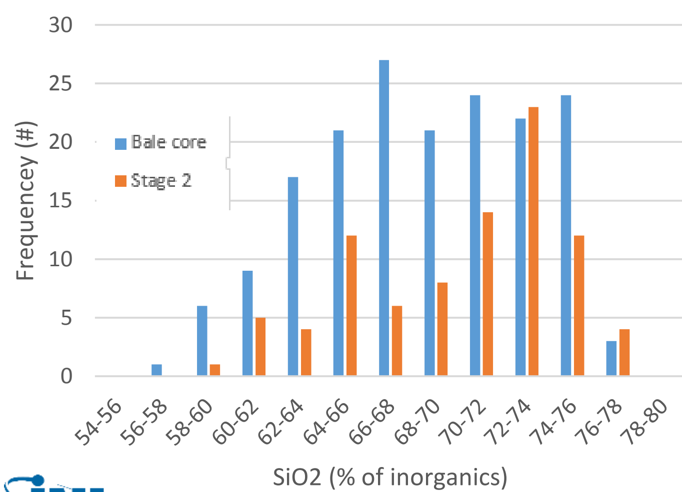


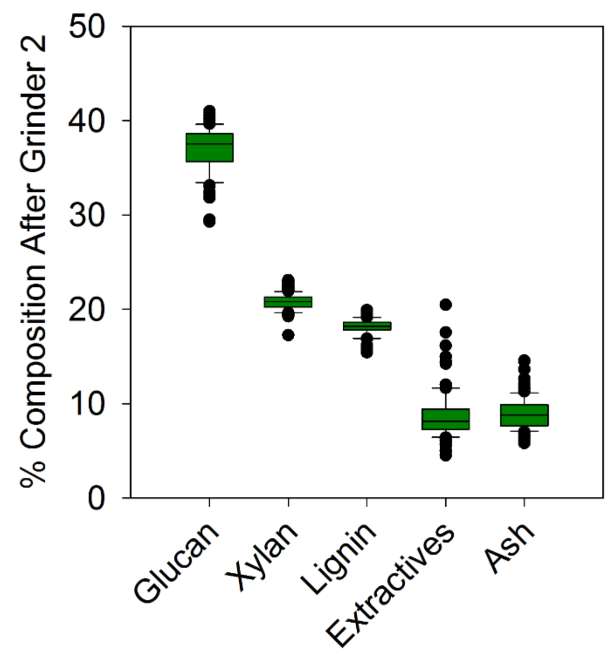
Characterization Across Preprocessing Operations for Low-Temperature Baseline Runs

- Variable corn stover across and within baseline runs
- Characterization:
  - Bale dimensions/weight
  - Inorganics (speciation & total): Ca, K, Na, Mg, Si, Al, S, P
  - Organic composition
  - Particle size distribution
  - Moisture
- Provided data to PI and STA





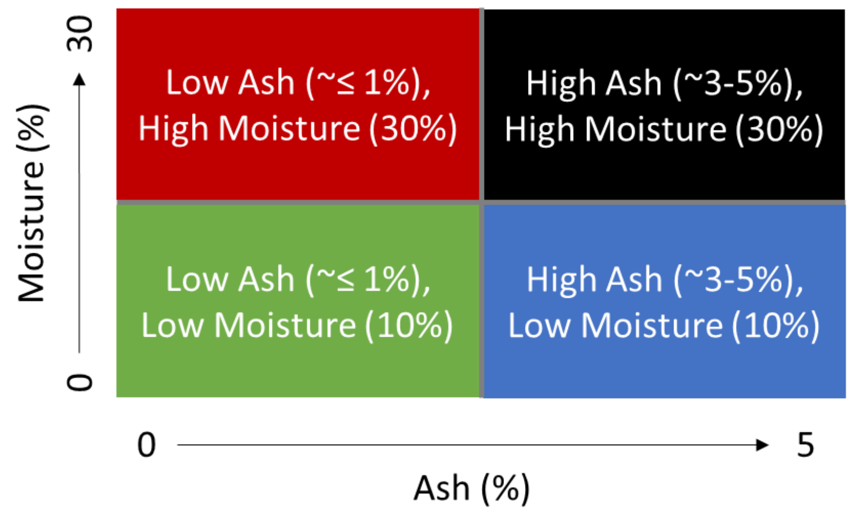


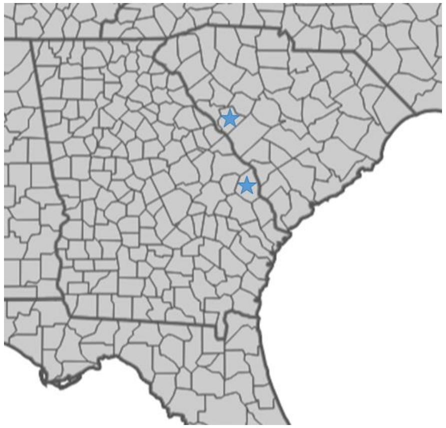


3 - Technical Accomplishments: HT FCIC Baseline Supply: Loblolly Pine

- Residues from SC & clean chips from GA
- Harvested of 11-25 yr. old trees
- **45 wet tons** at ~50% m.c.
- Dried to variable moisture to evaluate particle size effects in HT pathway
- ‘Low’ & ‘high’ ash represent distinct anatomical fractions
- Residues accumulate extrinsic ash, ash speciation expected to vary

Targeted ash and moisture conditions:





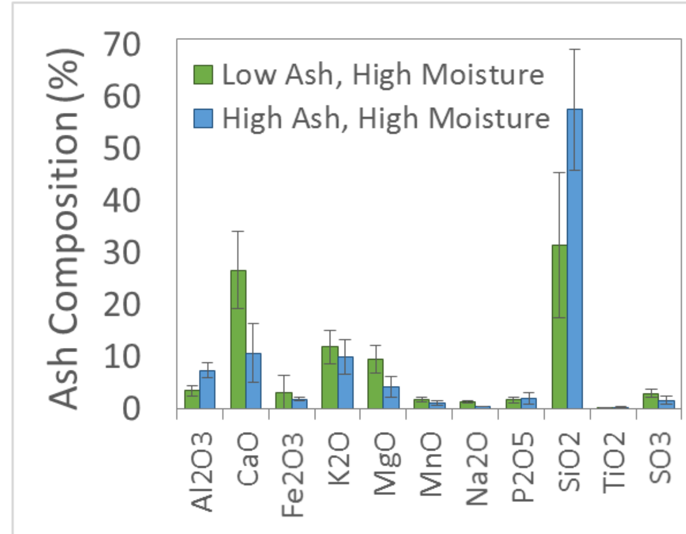
Clean chips: debarked stems of pulpwood-sized trees

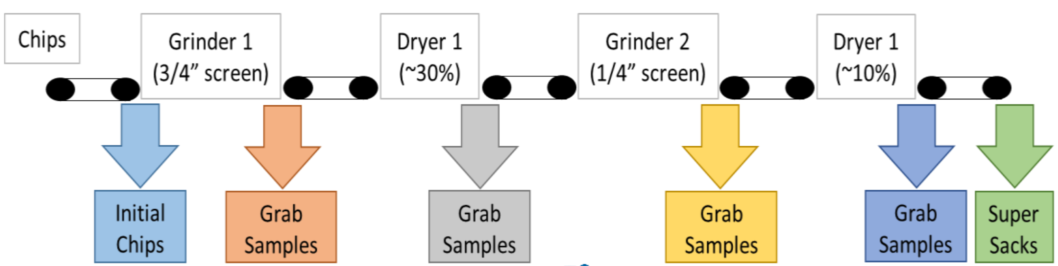
Residues: branches, needles, and bark from trees

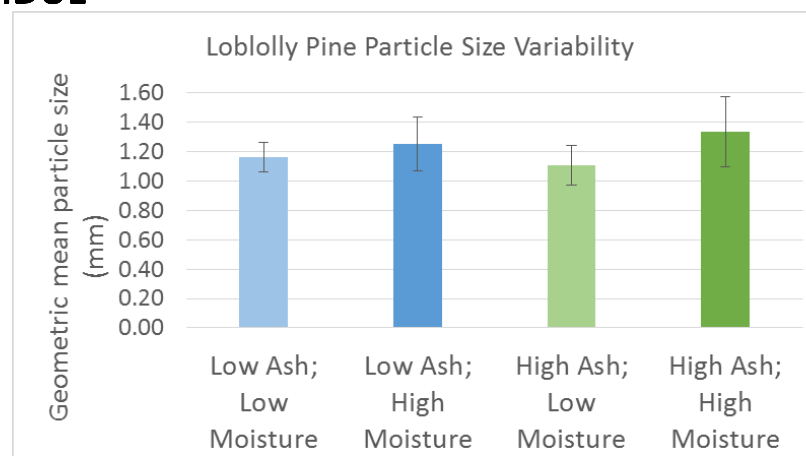
Characterization Across Preprocessing Operations for High-Temperature Baseline Runs

- **Loblolly Pine Analyses:**
  - Inorganic speciation
  - Proximate/ultimate
  - Particle size distribution
  - Moisture
  - Ash

- Inorganic speciation varied by pine fraction
- Provided data to PI and STA

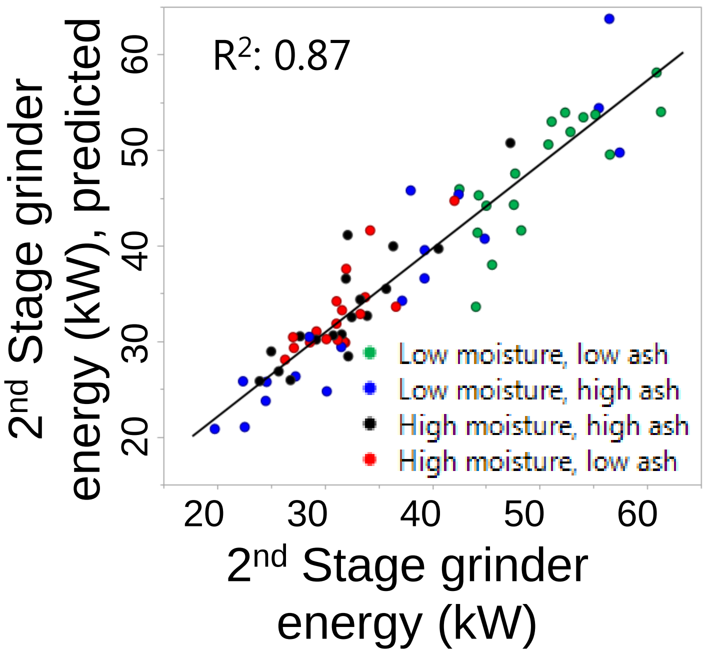






Impact of Biomass Properties on Preprocessing for LT and HT Baselines

- Regressions developed to explain variability in low-temperature (LT) & high-temperature (HT) baseline runs for throughput and grinder energies
- All characterization data collected was considered
- *Explanatory variables for LT regressions:* infeed belt speed, bale density, moisture, ash, mass flow, geometric mean particle size
- *Explanatory variables for HT regressions:* moisture, ash, mass flow



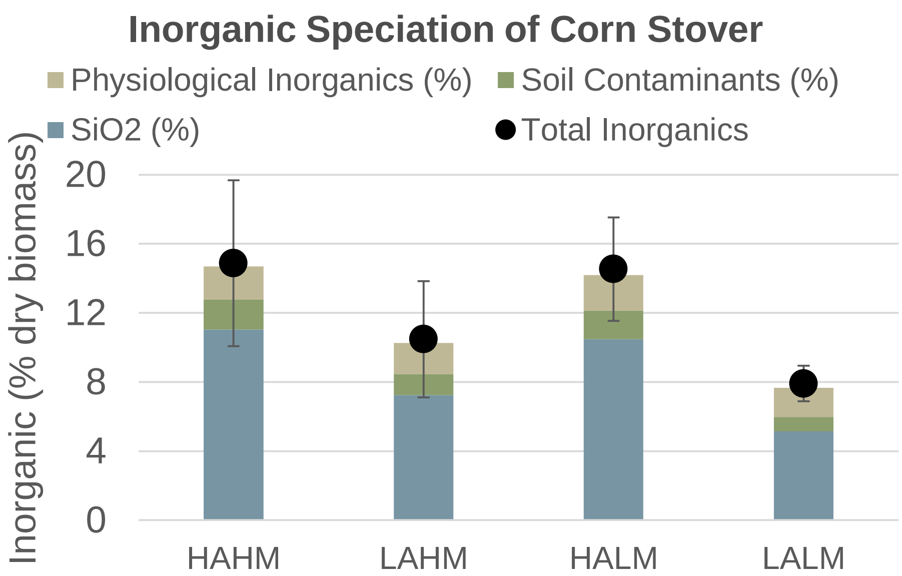
LT 2nd Stage Grinding Model Factors

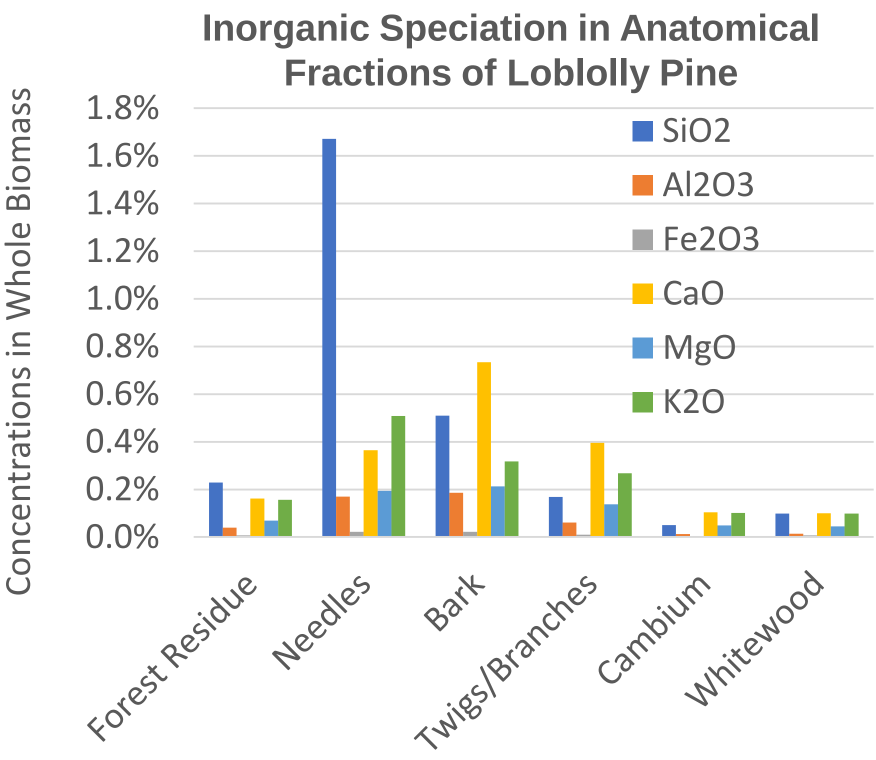
- Infeed belt speed
- Moisture
- Mean particle size
- Mass flow *x* Infeed belt speed
- Moisture *x* mass flow

<u>IMPACT</u>: Identified properties and property interactions will be used to inform characterization and experiments needed for mechanistic understanding as part of FCIC 2.0.

Inorganic Speciation in Corn Stover and Loblolly Pine

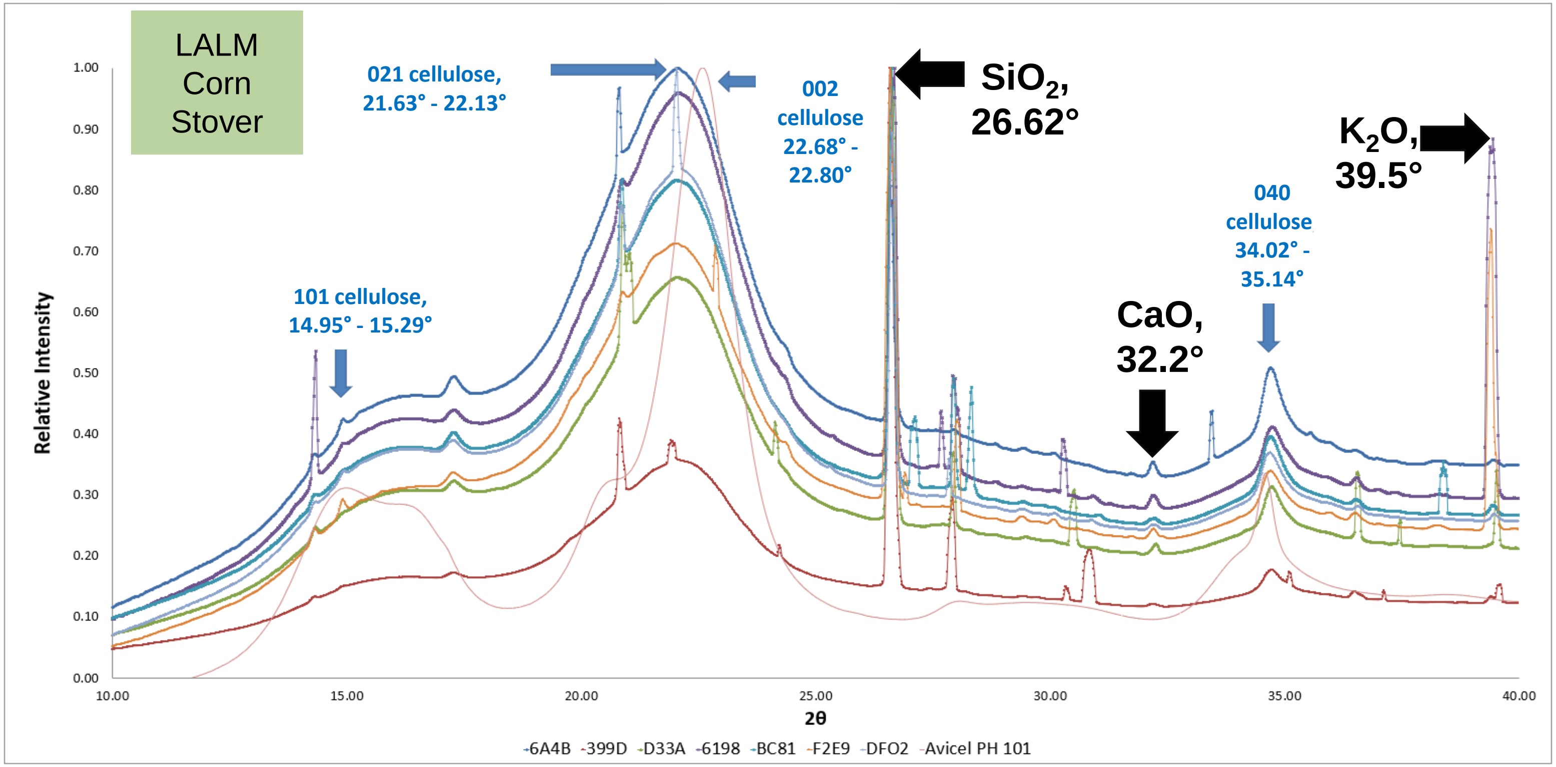
- Quantified inorganic speciation (n=312) for FCIC baseline runs
- Analyses of FCIC baselines contribute significant data on variability of inorganic species





IMPACT: Variable inorganic content and speciation in anatomical fractions vs. bulk samples will guide development of selective preprocessing.

XRD Allows for Quantification of Crystallinity and Identification of Inorganic Species

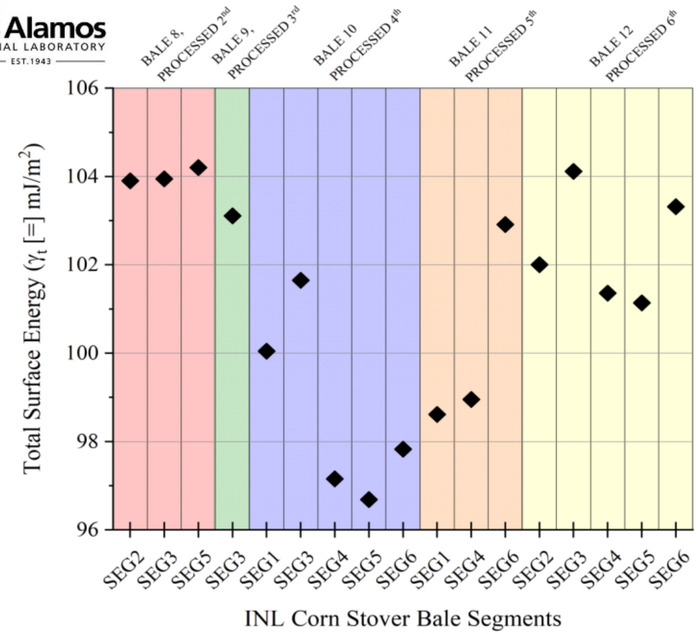


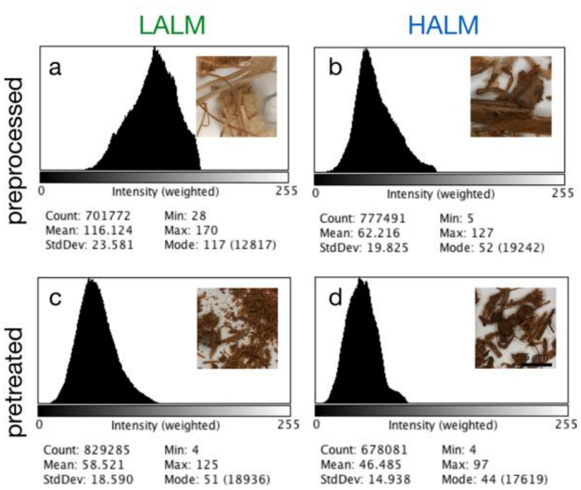
IMPACT: Variation of inorganic content and speciation will guide the development of analytical methods that discriminate between physiological and extrinsic inorganics, and experimental design in FCIC 2.0. Crystallinity data may further elucidate the effect of physical and chemical alterations on corn stover cellulose by milling and pretreatment.

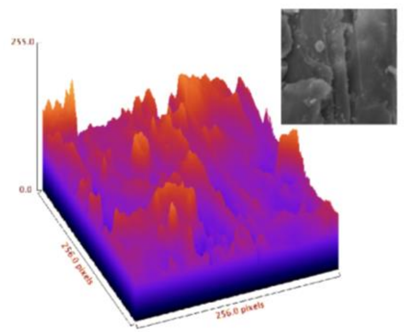
Quantifying Fundamental Physical Properties of Biomass: Surface Energy & Particle Morphology

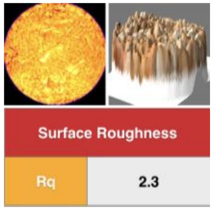
- Developed and verified method for measuring surface energy of corn stover
- Surface energy quantifies intermolecular forces that give rise to wettability and cohesion that influence flow behavior and conversion
- Significant differences in surface energy (>5mJ/m^2) were measured in LT baseline samples
- Analysis of particle morphology and size, luminance, surface topology and roughness

Los Alamos NATIONAL LABORATORY EST. 1943





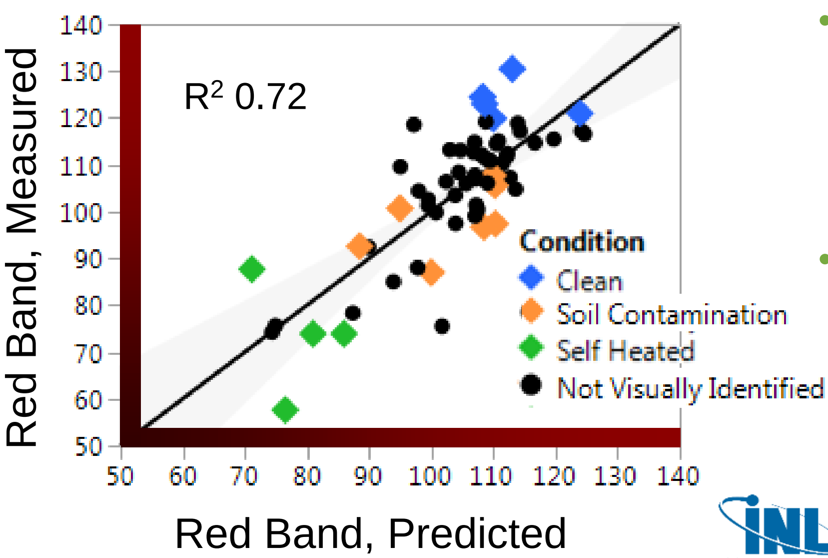




NREL NATIONAL RENEWABLE ENERGY LABORATORY

IMPACT: Integrated analysis of surface mapping and surface energy enables a multi-mode approach to examine cellular and molecular-level properties and to elucidate impacts on deconstruction and conversion.

Image Analysis of Corn Stover: Quality Assessment in Visible, RGB space

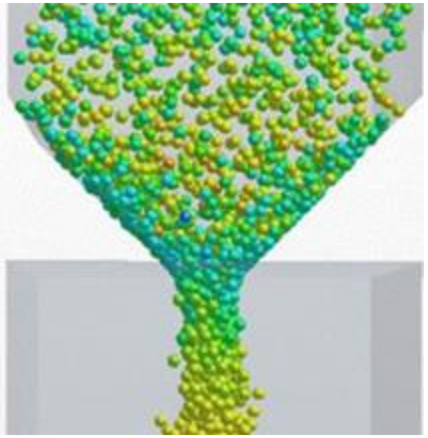


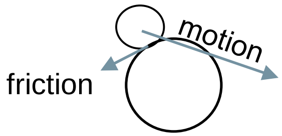
- Analysis of red band from core images differentiates observational sample quality
  - Clean (low ash, no self-heating), Soil-contaminated, and Self-heated
- 72% variability in red band explained by SiO_2 and glucan contents

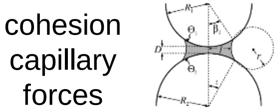
IMPACT: Results show promise for development of a rapid screening tool that could be deployed for in-field or in-line process measurement.

Particle-Particle Friction-Cohesion

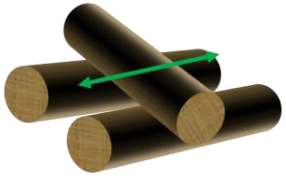
- Method Development for Physical and Mechanical Characterization of Biomass for Bin/Hopper/Feeder Flow
- Argonne activity focusing on particle-particle friction/cohesion properties in bins & hoppers



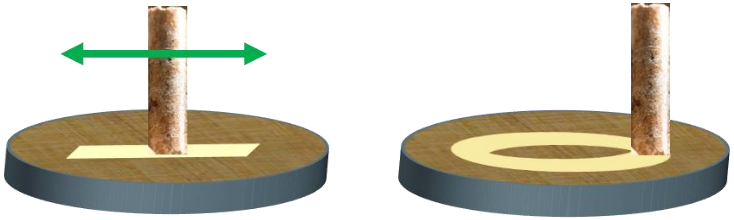




- Concept definition
- Reciprocating motion



- Reciprocating/unidirectional pin-on-flat/disc



Fundamental characterization inputs to 1.2.2.50X, *Feedstock Physical Performance Modeling*

Argonne NATIONAL LABORATORY

4 - Relevance

PROJECT GOALS

- Quantify variability in chemical, physical, and mechanical properties of biomass feedstocks for FY18 Experimental Baseline Runs
- Conduct fundamental characterization required to understand property impacts on performance in preprocessing and conversion

PRODUCTS AND OUTPUTS

- Established data management for **≥ 5000 samples** using BFL; generated data on chemical analysis (n=360), ash speciation (n=312), PSD (n=482), and mechanical properties to enable understanding of property-driven impacts for FY18 Experimental and Modeled Baselines for low and high-T pathways.

CUSTOMERS

- FCIC project teams are current customers. Future customers include biomass producers, process and equipment designers, plant engineers, and investors.

RELEVANCE TO BIOENERGY INDUSTRY

- Informs the science of scaling, integration of handling with conversion, development of mitigation strategies, fundamental models, and specifications through identification of critical factors that affect reliability.
- Fundamental knowledge from this project supports quality-based valuation that is required to mobilize domestic, biomass resources for an emerging bioeconomy.

Summary

1. **Overview:** Quantify variability of the physicochemical and mechanical properties of biomass, and how they affect reliability of process operations and integrated systems through feeding, preprocessing and conversion
2. **Approach:** Fundamental approach coupled with an interdisciplinary, multi-laboratory team
3. **Technical Accomplishments:**
   - Fundamental property characterization of corn stover and loblolly pine for FY18 Experimental Baseline Runs
   - Methods development
4. **Relevance:** Feedstock Variability generates foundational data and knowledge for FCIC to inform the science of scaling and integration of handling with conversion for development of mitigation strategies and fundamental models, and identification of critical factors that affect reliability
5. **Future work:** Employ a multi-scale approach to elucidate mechanisms by which attributes impact feeding, preprocessing, and conversion

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Response to Reviewers' Comments 2017

REVIEWER COMMENTS

- This is a very relevant project and the results will have a dramatic impact on the real-world situation of using agricultural feedstocks harvested in different geographies and different seasons. There may also be an opportunity to help direct compositions of purpose-grown energy crops.
- The in-depth analysis of feedstocks and incorporation of this data into blending profiles has extremely high potential. Widening feedstock supply locations and providing consistent composition feedstock will have a large impact on not just biorefinery operations, but also scale possibilities.

RESPONSES

- INL and NREL have complementary roles within the interface representing feedstock logistics and biomass conversion, respectively. Teams coordinate projects via monthly conference calls, yearly laboratory visits, and participation in BETO meetings; in addition, AOPs are coordinated with joint milestones. INL's feedstock supply chain TEA informs blend selection and testing based on cost. Blending can be used to dilute negative impacts of inorganic impurities.
- We have observed variation in the sugar yields and feedstock performance resulting from continuous, dilute-acid pretreatment & enzymatic hydrolysis of milled corn stover, harvested from 2007-2015, from several locations. However, preprocessing corn stover using deacetylation followed by acid impregnation resulted in reduced variation in both yield and operational feed flow, suggesting that the strategy of feedstock preprocessing can minimize feedstock differences and increase feedstock consistency.
- We agree with the reviewer, addressing the challenges faced by the existing IBR's is a critical near-term issue. In FY18 we will be re-scoping our annual operating plans (AOP's) to provide more resources for IBR issues, specifically focusing on feeding and handling biomass at the biorefinery. Integrated efforts between the laboratories will allow for both the near-term focus on IBR challenges and on achieving longer-term BETO goals and objectives.

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ADDITIONAL SLIDES

FY18 Baseline Harmonization

- Drafted the "FCIC primer" with input from researchers across FCIC pillars, aiming to enable more effective communication among diverse technical teams and facilitate R&D.

The Feedstock Conversion Interface Consortium (FCIC) consists of five multidisciplinary project teams working together to solve key challenges to the nascent biofuels and bio-products industry. FCIC researchers and contributors have diverse expertise and backgrounds. Some FCIC contributors are very familiar with feedstock supply and logistics, and upstream preprocessing, others are more familiar with the chemical characterization of biomass feedstocks, while still others are more familiar with conversion and downstream processing.

The goal of this document is to provide a "primer" for researchers that come from multiple technical disciplines and professional experiences to enable more effective communication among the members of the FCIC team and to facilitate R&D activities. This document expands upon the established, general glossary of terms used in the U.S. DOE EERE Bioenergy Technologies Program (https://www.energy.gov/eere/bioenergy/full-text-glossary) to include terms specific to R&D activities of the FCIC.

Currently, this document is organized alphabetically. A proposed structure for organizing the key terms in several thematic subgroups is suggested below:

FCIC-specific projects

- **Feedstock Variability and Specifications Development:** Identifies fundamental chemical, mechanical and physical properties of biomass that impact reliability in low-temperature and high-temperature pathways; elucidates mechanisms by which biomass properties impact reliability; and quantifies the impact of properties on reliability to guide development of mitigation strategies and establish feedstock specifications to enable 50% improvement in reliability over FY18 Experimental Baseline.
- **Fundamental Modeling:** Develops mechanistic simulations for feeding operations, particle comminuntion, equipment wear due to abrasion, and fundamental modeling to predict product yields as functions of feedstock attributes.
- **Process Integration:** Identifies fundamental causes of process upsets, conversion yields, and equipment wear and develops cost-effective mitigation strategies to improve process reliability.
- **Systemwide Throughput Analysis:** Performs integrated analyses spanning the field-to-fuel system-wide impacts of variability in feedstock composition, moisture, and particle characteristics on cost, down time, achievable biofuel yield, and environmental sustainability trade-offs to understand requirements fo profitable operation for 1st-plant integrated biorefineries.
- **Process Controls and Optimization:** Develop process control systems and characterize relationships between process parameters in order to determine the feasibility for improving the operating reliability of preprocessing and 1st-stage deconstruction reactor systems for low-temperature and high-temperature conversion pathways in integrated biorefineries.

FCIC-specific terms

- Gap analysis
- Operational reliability
- Conversion performance

General Terms and Vocabulary

A

abrasion: Loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface[1]. (Standard Terminology Relating to Wear and Erosion, Annual Book of Standards, Vol 03.02, ASTM, 1987, p 243-250)

acetic acid: An acid with the structure of $C_2H_4O_2$. Acetyl groups are bound through an ester linkage to hemicellulose chains—especially xylans—in wood and other plants. The natural moisture present in plants hydrolyzes the acetyl groups to acetic acid, particularly at elevated temperatures[2].

acid: A solution that has an excess of hydrogen ions (H^+), with a pH of less than 7[2].

acid hydrolysis: The treatment of cellulosic, starch, or hemicellulosic materials using acid solutions (usually mineral acids) to break down the polysaccharides to simple sugars[2].

acid impregnation: The process by which a material is soaked, saturated, drenched, seeped, or otherwise permeated with a liquid, in this case an acid. In the realm of polymer chemistry, impregnation denotes the penetration of monomeric, oligomeric, or polymeric liquids into an assembly of fibers.

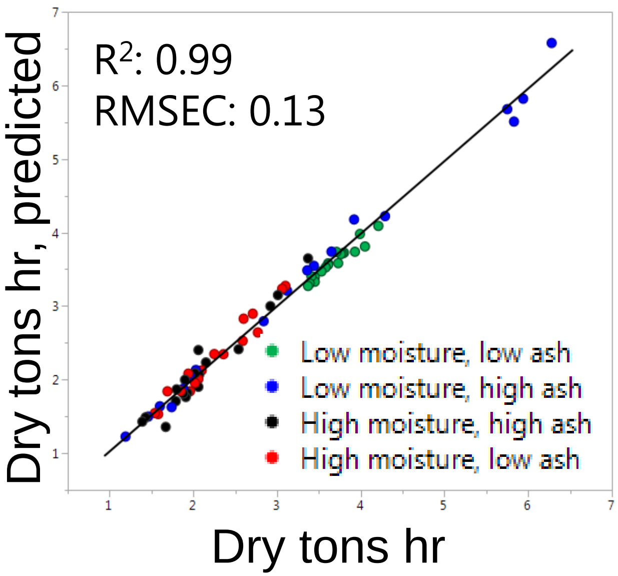
acid insoluble lignin: Mostly insoluble in mineral acids so it can be analyzed gravimetrically after hydrolyzing the cellulose and hemicellulose fractions of the biomass with sulfuric acid. ASTM E-1721-95 describes the standard method for determining acid insoluble lignin in biomass[2].

abrasion: Loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface[1] (Standard Terminology Relating to Wear and Erosion, Annual Book of Standards, Vol 03.02, ASTM, 1987, p 243-250).

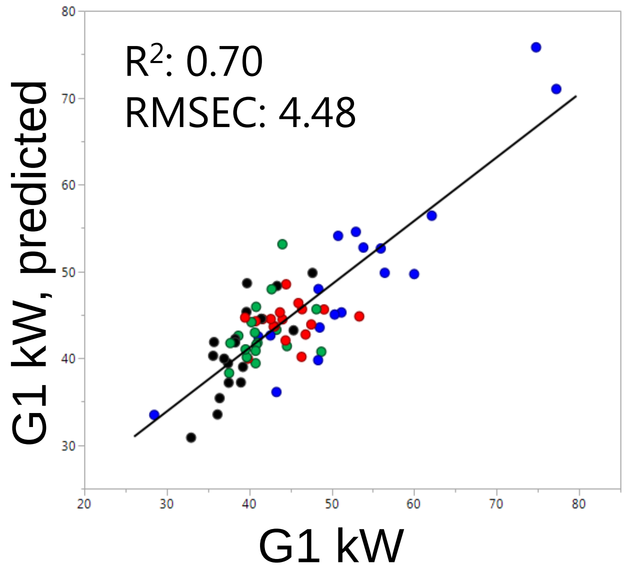
Analysis of FY18 LT and HT Preprocessing Baseline Data

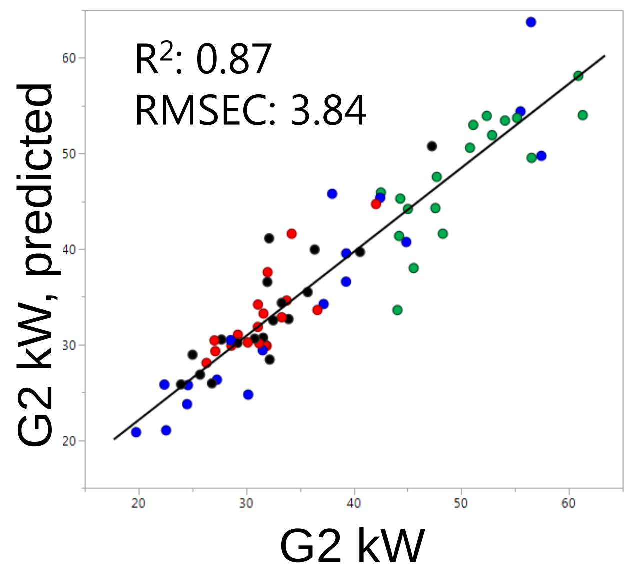
- Regressions developed to explain variability in Low Temp (LT) & High Temp (HT) baseline runs
- All characterization data collected was considered
- *Explanatory variables for LT regressions:* infeed belt speed, bale density, moisture, total inorganics, mass flow, geometric mean particle size
- *Explanatory variables for HT regressions:* moisture, ash, material amount

LT Throughput



LT Grinder Energies





Clean Pine/Residue Chip Production

fcic FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

①

Pine Plantation

②

Feller-buncher

③

Grapple skidder

④

Whole tree disc knife chipper with chain flail

Clean Pine Chips

⑤

Residue pile

⑥

Drum knife chipper

Residue Chips