U.S. Department of Energy (DOE)
Bioenergy Technologies Office (BETO)

2019 Project Peer Review

1.2.1.1000:
Development of a Wet Logistics System for Bulk Corn Stover

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Lynn Wendt, PI
Idaho National Laboratory

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Feedstock Supply & Logistics

Goal Statement

Design a feedstock logistics system that utilizes moisture during the residence time in storage to protect and even increase feedstock value

- Moisture management in corn stover continues to negatively impact all unit operations from the field to the reactor
- Moisture can be used to our advantage by designing logistics systems and operations that are compatible with it




Quad Chart Overview

Timeline

Development of a Wet Logistics System for Bulk Corn Stover

- Project start date: 10/01/2014
- Project end date: 9/30/2017
- Percent complete: 100%

Value-Added Preprocessing in the Supply Chain

- Project start date: 10/01/2017
- Project end date: 9/30/2020
- Percent complete: 33%

	Total Costs (Pre FY17)	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	$712K	$385K	$385K	$770K

Partners:

NREL (WBS 2.2.3.100, PI: Melvin Tucker)

LBNL (ABPDU, POC: Ning Sun)

Barriers addressed

- Ft-H. Biomass Storage Systems
- Ft-G. Quality and Monitoring

Objective

- Use the storage operation to enable cost-effective, consistent high-quality biomass supply for a biorefinery

End of Project Goals

- Design a wet, bulk logistics system that is cost-competitive with the existing herbaceous (dry bale) SOT and secures feedstock supply from fire loss and dry matter loss
- Offset feedstock costs by > $3/ton through the application of low-severity treatments over the residence time in storage that reduce recalcitrance by 30% as measured by reduced energy consumption in grinding or mechanical milling (i.e. preprocessing) or improved digestibility in pretreatment

Project Overview

Define costs and quality of biomass in a wet logistics system (FY2015-2017)

- Less than 40% of corn stover in the U.S. meets the 20% moisture threshold at the time of baling according to analysis at ORNL (Oyedeji *et al*., 2017)
- Corn stover with >20% moisture is at risk of significant degradation (Darr and Shah, 2012)
- A wet, bulk system solves multiple logistics problems
  - Reduces dry matter loss due to microbial degradation
  - Mitigates catastrophic loss of bales to fire
  - Reduces losses in handling and transportation
  - Reduces preprocessing losses at biorefinery
  - IMPACT TO BETO: Wet feedstock that meets the size spec will lead to higher reliability and operability, higher yield in conversion, and meeting cost goals of $2.50/gallon

Define opportunities for value-add (FY2018-2020)

- Utilize the residence time of storage to begin to break down biomass
  - In-storage treatments can reduce costs and energy consumption of mechanical preprocessing and pelletization, chemical pretreatments, and enzymatic hydrolysis of complex carbohydrates
- 2017 Peer Reviewers suggested the project look beyond storage for stability and explore recalcitrance reduction

Management Approach

Engage diverse national laboratory capabilities through collaboration

- Measure cost impacts through INL Feedstock Supply Chain Analysis project
- Measure impacts of storage treatments in multiple conversion approaches through collaboration (e.g. NREL, LBNL)

Meet aggressive goals via framework of Quarterly, Annual and Go/No-Go Milestones

- End of Project Milestone (completed 9/30/16)
  - Define costs of a wet, bulk logistics system that preserves corn stover and quality
- Go/No-Go milestone (due 3/31/19)
  - Quantify potential for value-added processes to occur in storage

Interaction with BETO promotes relevance to DOE and industry

- Annual Operating Plans (AOPs) used to define research path and work scope
- Quarterly progress reports and milestones document step-wise progression of research
- Quarterly presentations for BETO provide framework for information sharing and feedback

Technical Approach-Wet Storage

Anaerobic storage, or ensiling, has been used for centuries to preserve high-moisture biomass for livestock

- Anaerobic conditions created mechanically and biologically
- Acid fermentation lowers pH and stabilizes biomass
- Dry matter losses of <5% possible compared to losses of 12% for bales entering storage at 30% moisture (2015 SOT)

Wet storage can compliment existing dry systems

- Dry logistics systems apply when corn stover can be baled dry
- Long-term wet storage at biorefinery used for “at-risk” material

Utilize industrial-scale storage within the biorefinery gate

- Eliminates a transportation step
- Eliminates on-site queuing (3-5 days of feedstock)

Techno-economic analysis (TEA) and life cycle analysis (LCA) informs wet logistics system selection

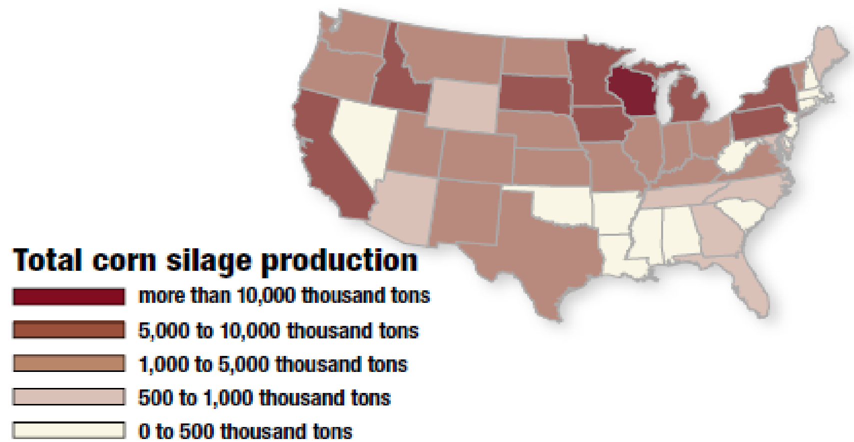
Current wet logistics infrastructure in the US

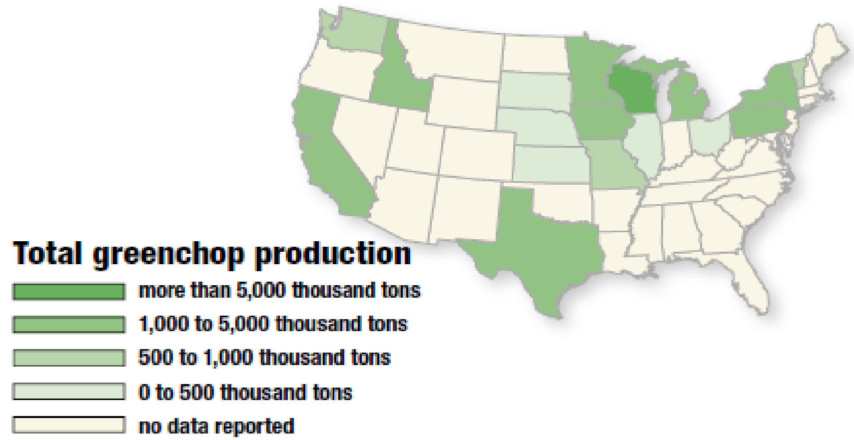
162 million US tons of high-moisture biomass harvested for livestock feed in 2016

Resources and infrastructure distributed across the US

	Million U.S. tons harvested
Corn Silage	125,670
Sorghum silage	4,171
Alfalfa haylage and greenchop	22,857
Other haylage and greenchop	9,521
Total	162,219

USDA Crop Production Summary 2016





https://www.progressivepublish.com/downloads/2017/general/2016_fg_stats_lowres.pdf

Technical Approach-Wet Storage Cont.

BACKGROUND

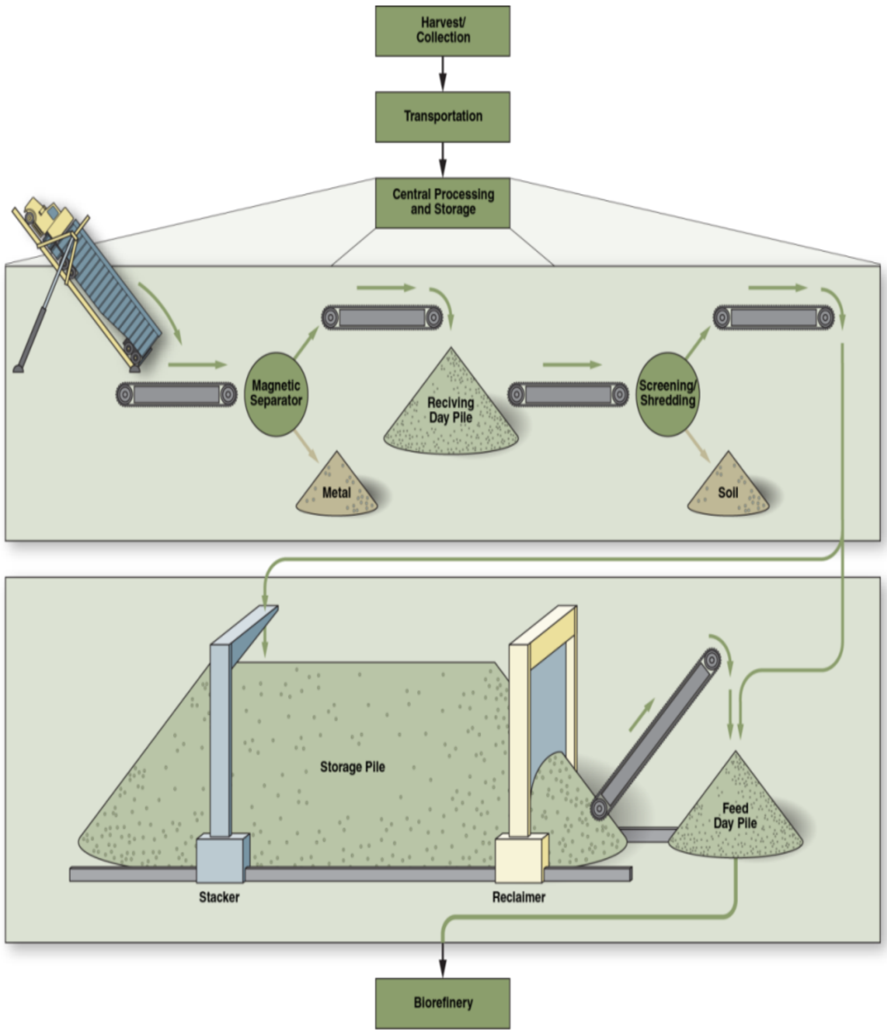
- Experimental data, TEA, and LCA suggest implications of a wet, bulk corn stover supply chain utilizing centralized storage at a biorefinery

ACCOMPLISHMENT

- Comparison of wet bulk systems to conventional bale designs
  - 10% higher total cost, 2X higher transportation costs
  - ~50% reduction in energy consumption
  - 60% reduction in GHG emission
  - Additional unidentified benefits likely

PATH FORWARD

- Assessing viability of wet logistics pathways at commercial scale
- Identifying value-added preprocessing opportunities in storage



Wendt et al., 2018, Frontiers in Energy Research

Technical Approach-Wet Storage Cont.

Goal: Assess how wet storage systems would perform at commercial scale and in commercially-relevant conversion conditions

Explore cost reductions in storage

- Understand impact of aerobic conditions to better define storage parameters
- Modeling of heat and mass transfer in outdoor storage piles
- Define opportunities of cost reduction

Assess impact of wet storage on conversion potential

- Hydrolysis of carbohydrates to monomers through pretreatment and enzymatic hydrolysis
- Dilute acid pretreatment (INL)
- Dilute alkaline pretreatment (LBNL)

Technical Approach-Value Add Project

Goal: Transform storage from a cost-center to a value-add operation

- Apply low-severity treatments during the residence time of storage
  - Agricultural residues require 3-9 months of storage to supply a biorefinery with a consistent feedstock year-round
  - Short-term storage of 3-5 days occurs at a biorefinery gate to ensure no disruptions in feedstock supply

Approach: Utilize aerobic and anaerobic storage approaches

- Biological approaches
  - Filamentous fungi: selective and non-selective lignin degraders have been documented to reduce pretreatment severity
  - Application for on-site queuing similar to “seasoning” in pulping industry
- Chemical approaches
  - Adding alkali in storage to promote chemical impregnation and lignin breakdown

Success measured by:

- Reduction of recalcitrance by 30% as measured by reduced energy consumption in grinding or mechanical milling (i.e. preprocessing) or improved digestibility in pretreatment
- Offset feedstock logistics costs by > $3/ton (dry basis)

Technical Approach

Challenges

- Transportation costs: Transporting water increases costs. A fully wet system must include these costs, but using storage for value-add can accept baled biomass that is then size-reduced at the biorefinery
- Entire supply chain is impacted by wet biomass, not just storage
- Aggressive cost and performance targets set for value-added preprocessing
- Near-term industry adoption: Preprocessing operations for corn stover at biorefineries is currently designed around dry bales

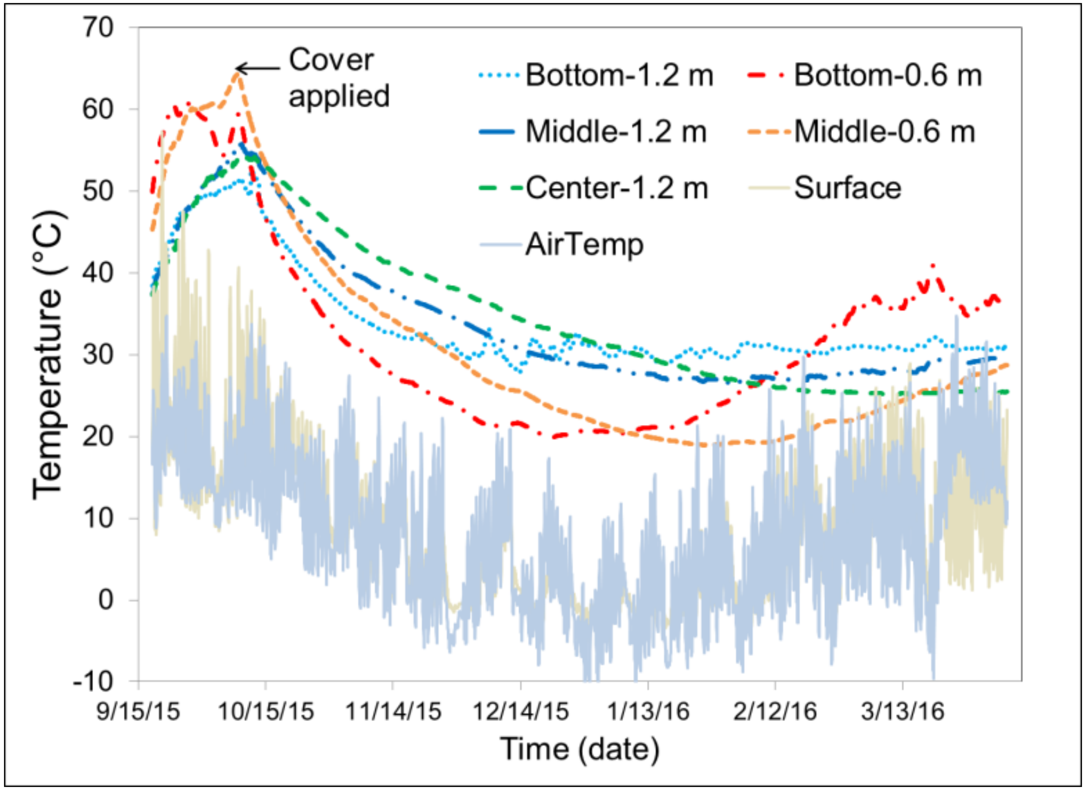
Critical Success Factors

- Cost competitiveness: TEA shows wet systems are competitive with dry systems
- Sustainable designs: analysis shows reduced energy and water consumption
- Peer-reviewed publications
- Application of bulk logistics systems for additional crops (e.g. sweet sorghum, energy cane)

Accomplishments-Field Demonstration

Goal: Utilize field storage performance data to inform pile designs at commercial scale

- 10 zones monitored in pile for temperature, gas concentration, composition



Pile temperatures over 6 months of outdoor storage

300 dry ton, covered pile

ACCOMPLISHMENT

- Increased initial self-heating prior to covering
- 5% loss after 6 months of storage
- Aerobic and anaerobic zones perform similar to laboratory conditions

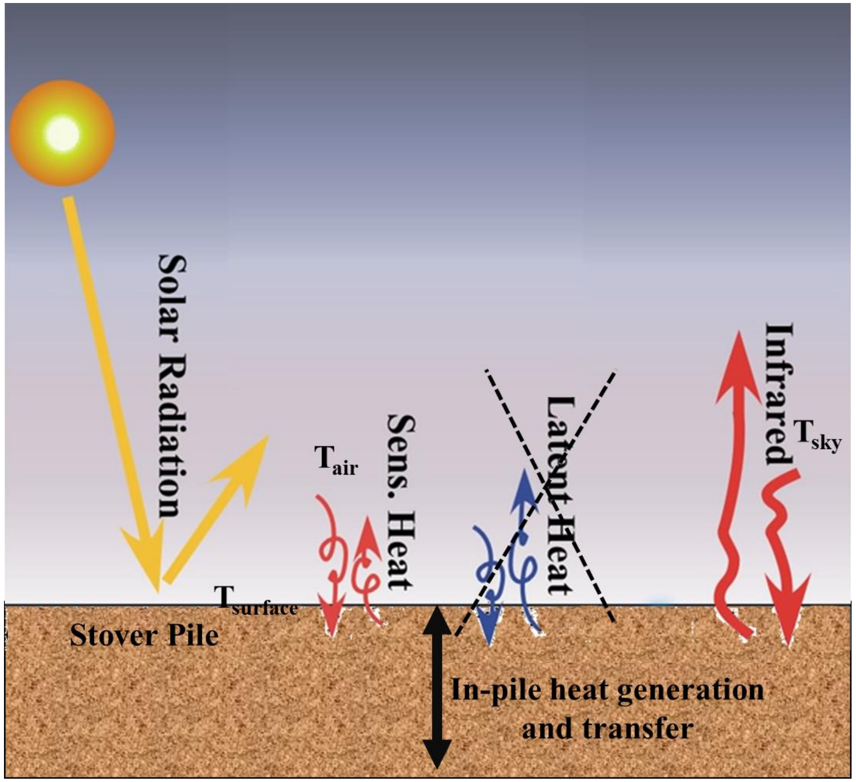
Wendt et al., 2018, Frontiers in Bioengineering and Biotechnology

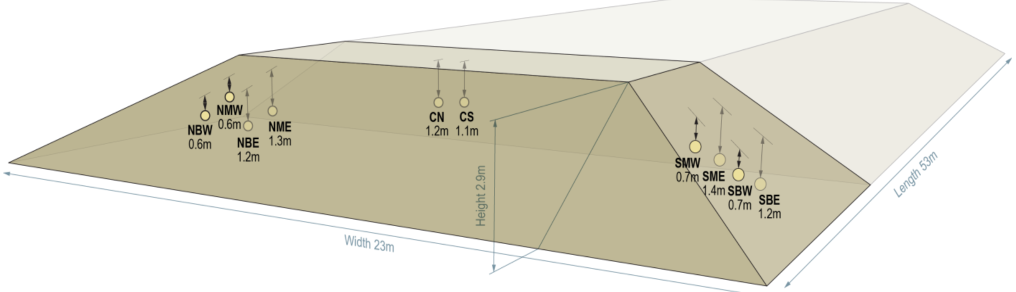
Accomplishments-Storage Model Formation

Goal: Develop a numerical model that represents the gas and heat transfer processes controlling dry matter loss and temperature in storage due to microbial respiration

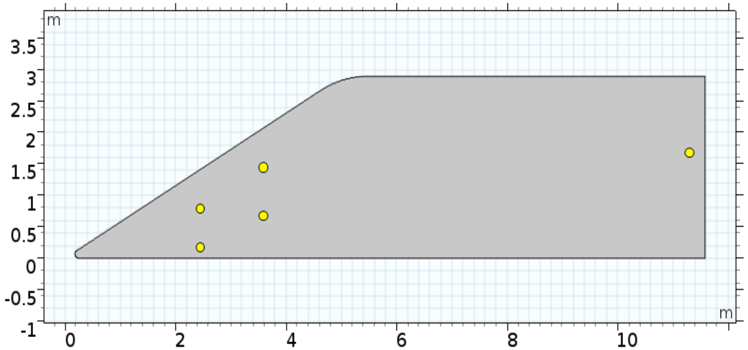
Data collected from field storage site and nearby weather station:

- Precipitation
- Solar irradiance
- Wind speed and direction
- Air temperature
- Pile surface and interior temperatures





Sampling locations in pile



Domain for the 2-D model

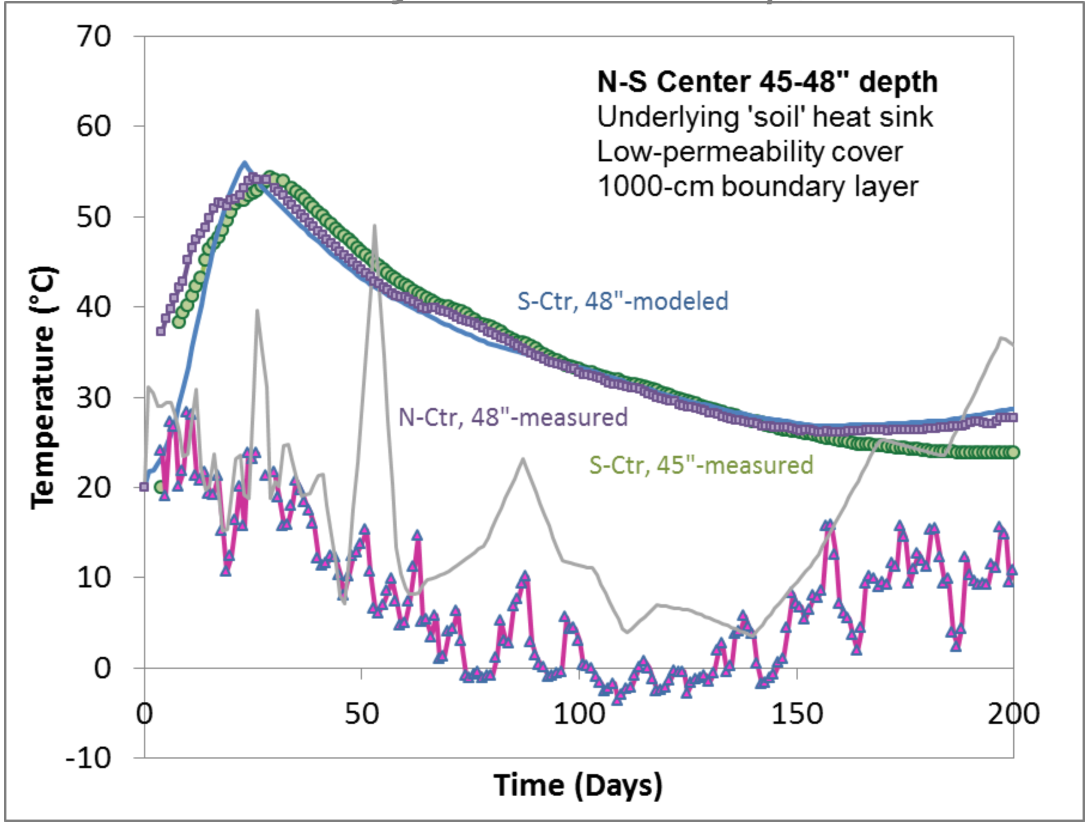
Accomplishments-Storage Model Verification

Goal: Develop a numerical model that represents the gas and heat transfer processes controlling dry matter loss and temperature in storage due to microbial respiration

- *Green = South, measured*
- *Purple = North, measured*
- *Blue = South, modeled*
- *Pink = Surface temp, measured*
- *Grey = Surface temp, modeled*

IMPACT

- Model presents similar temperature patterns observed in field at:
  - North- vs. south-facing slopes
  - Shallow and deep depths
- Model can be used to simulate degradation in pile over time and response to different variables
  - Oxygen barriers
  - Packing density
  - Permeability



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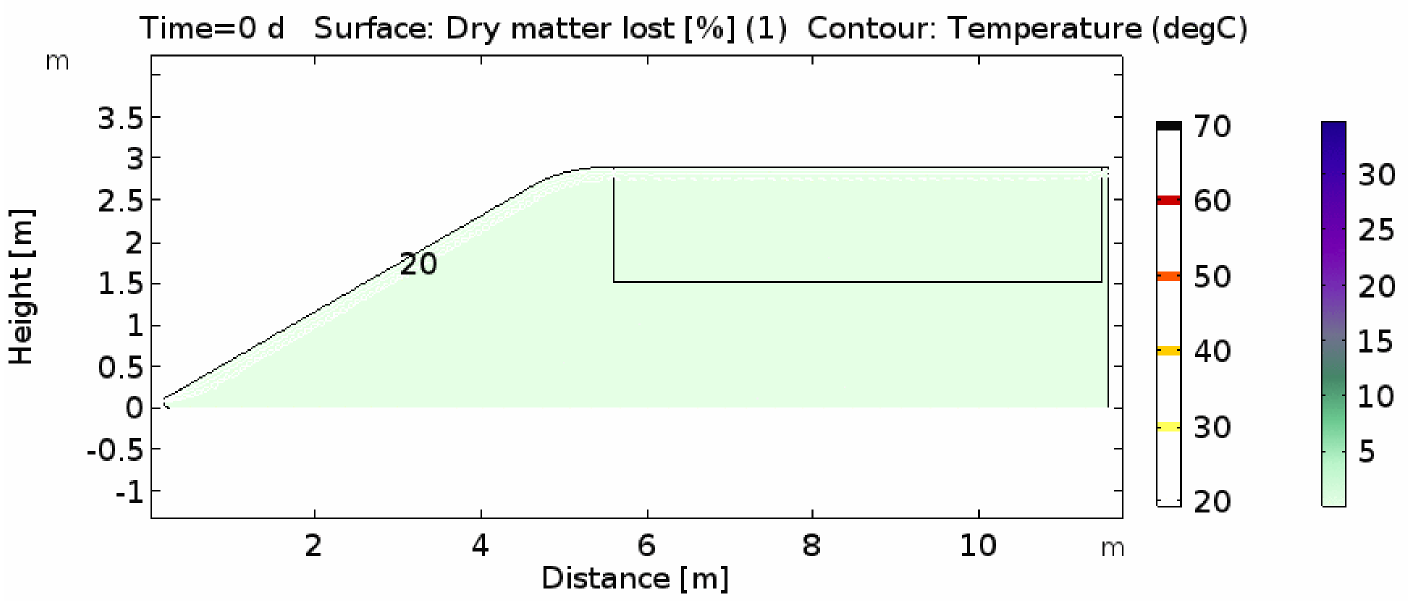
Accomplishments-Storage Modeling Results

Goal: Assess potential for degradation in uncovered pile

ACCOMPLISHMENT:

- Uncovered pile simulation shows that the outer portion of the pile will suffer >30% loss after 200 days but <5% loss in anaerobic zones
  - Agreement with laboratory reactor performance data
- Predicted 15% loss of total pile after 200 days
- Increasing the pile height 3-fold while keeping surface:volume ratio constant reduces total pile loss to <5%, even in uncovered piles

IMPACT: Model predicts optimal pile dimensions at commercial scale



Accomplishments-Impact on Composition

Goal: Identify the impact of wet storage on composition and conversion potential

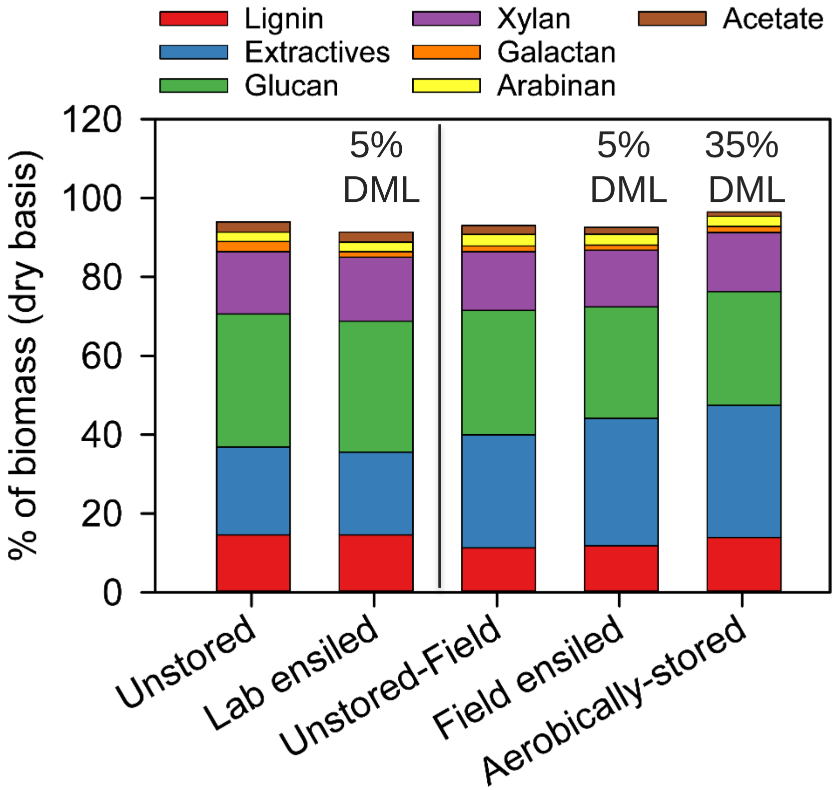
ACCOMPLISHMENT

- Laboratory ensiling: 5% DML after 100 days and no change in composition
- Field storage: 5% DML after 200 days; glucose reduced, glucan preserved
- Laboratory aerobic storage: 35% DML after 3 months; xylan and arabinan decreased; lignin enriched

IMPACT

- The anaerobic conditions created during ensiling preserve dry matter and quality, even after short term self-heating in the field

Composition of corn stover as a result of storage



Modified from Wendt et al., 2018, Frontiers in Bioengineering and Biotechnology

Accomplishments-Impact on Sugar Yields

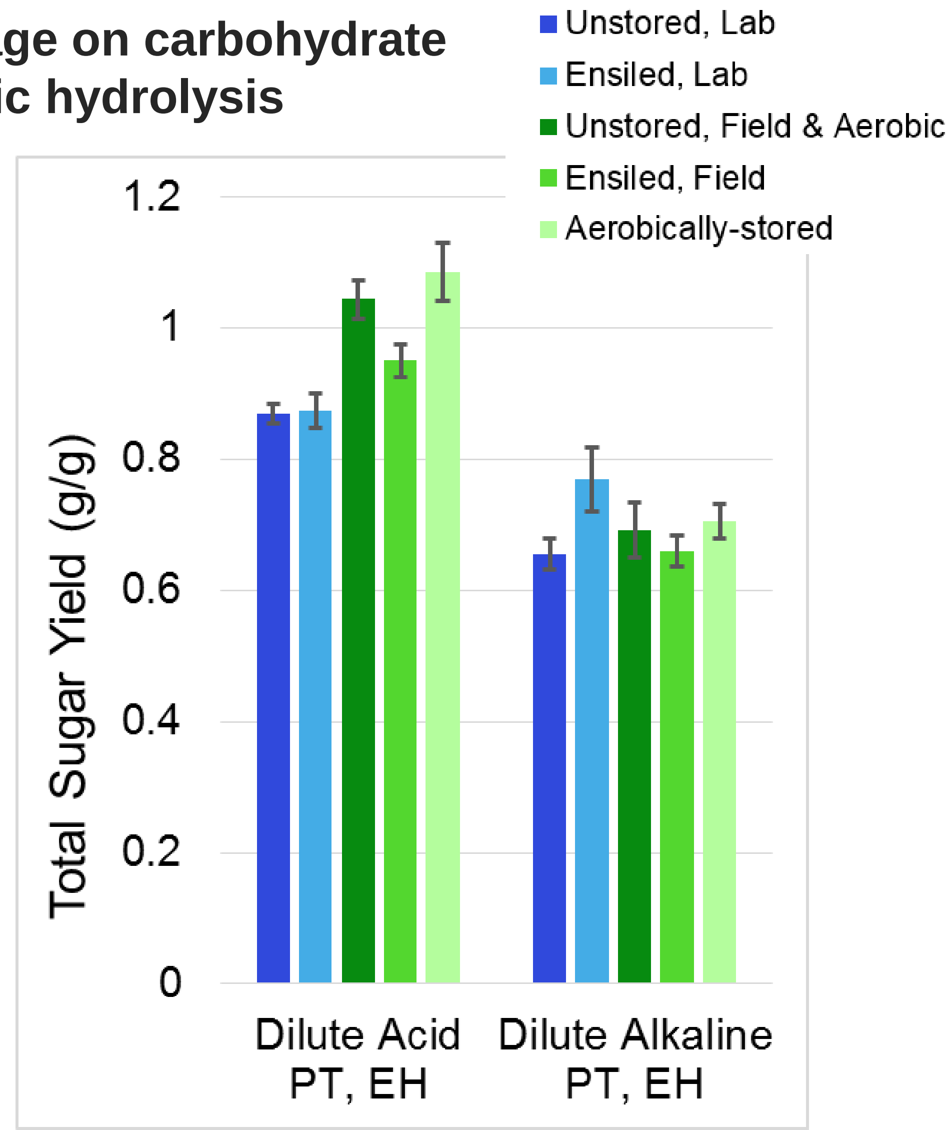
Goal: Identify the impact of wet storage on carbohydrate release in pretreatment and enzymatic hydrolysis

ACCOMPLISHMENT

- Major impacts to sugar release not observed after storage, even after 3 weeks of self-heating in field

IMPACT

- Presence of fermentation inhibitors in dilute acid pretreatment suggest reductions in severity conditions could be tested
- Losses in dry matter remain most impactful to cost



Modified from Wendt et al., 2018, Frontiers in Bioengineering and Biotechnology

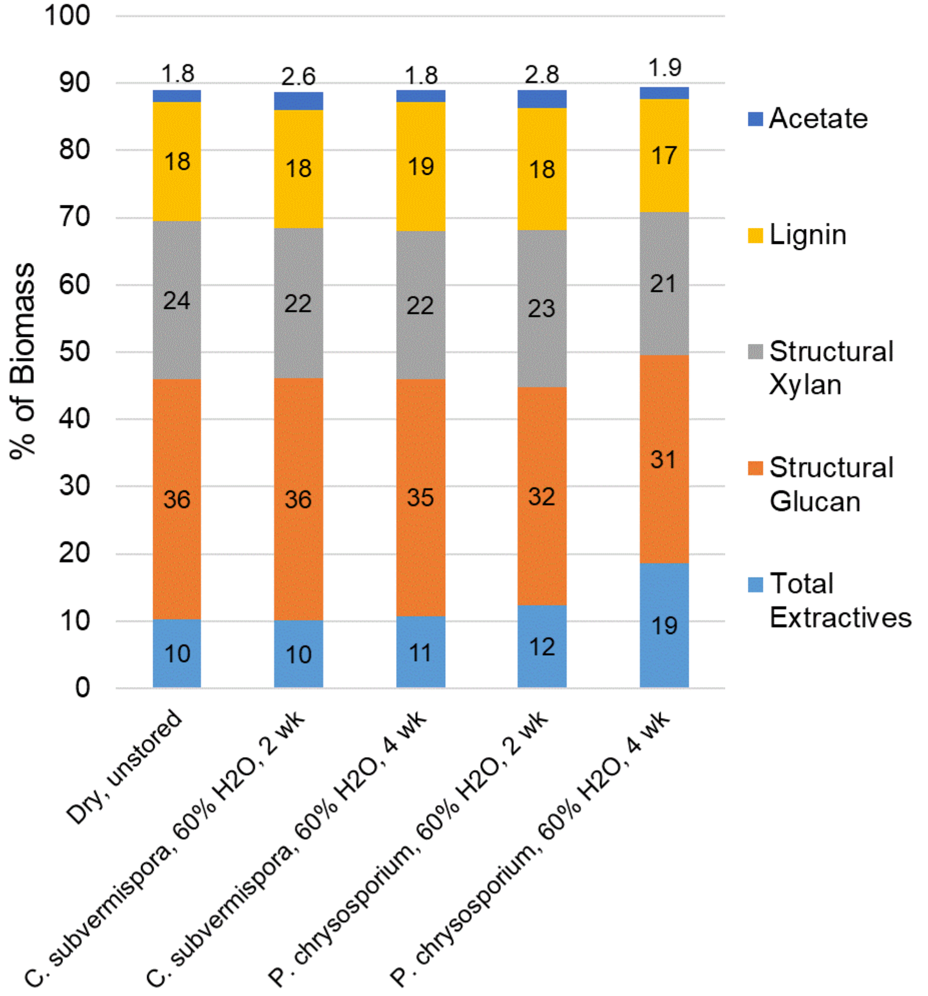
Accomplishments-Recalcitrance Reduction

Goal: Utilize fungal treatment in storage to reduce recalcitrance

– Filamentous fungi are well-documented to degrade lignin, making the cellulose more accessible to enzymes

ACCOMPLISHMENT

- *Ceriporiopsis subvermispora* (selective lignin degrader)
  - Minimal DML
  - 6% xylan solubilized
- *Phanerochaete chrysosporium* (non-selective degrader)
  - 5% DML/week
  - 10% xylan and 13% lignin solubilized
  - 85% increase in extractives



IMPACT

- Opportunity for short-term storage at biorefinery gate to reduce recalcitrance

Accomplishments-Recalcitrance Reduction Cont.

Goal: Combine alkali treatment with storage to increase stability and reduce recalcitrance

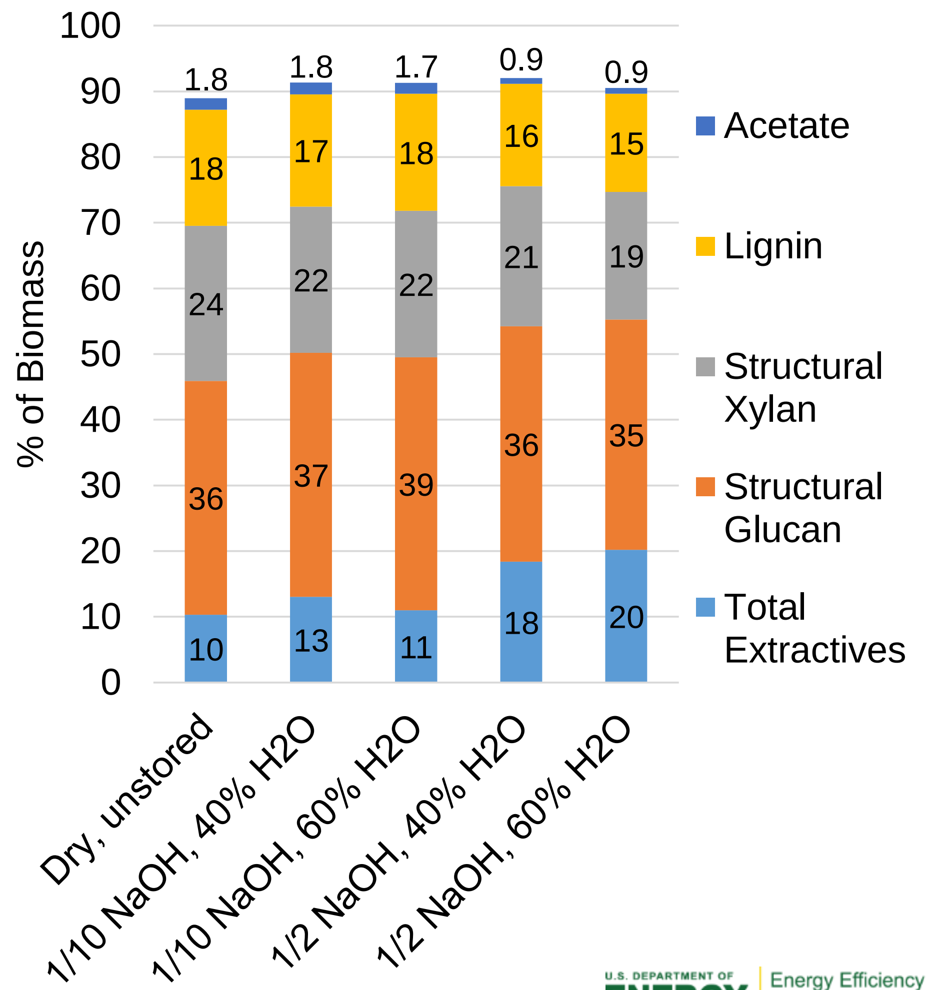
- NaOH loaded at 1/2 and 1/10 of what is used in deacetylation, stored 4 weeks

ACCOMPLISHMENT

- Alkali treatments in storage result in 50% reduction of acetate and ~20% reduction of xylan and lignin
- Anaerobic storage significantly reduced DML (2.6-7%) over 1 month compared to aerobic storage (7.5%-13%)

IMPACT

- Utilizing storage residence times improves alkali impregnation
- Screening at INL of optimal treatment conditions (FY18-19) facilitates assessment at NREL (FY19) for potential mechanical refining energy reduction



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Future Work-Storage scale up

Scale-up of corn stover experiments necessary to provide sufficient material for conversion and deconstruction studies

- *P. chrysosporium* inoculation using 100 L storage simulators over 2 weeks of storage
  - Control with no inoculum used to compare self-heating profiles
  - Temperature data will be assessed in microbial degradation model to design optimal storage pile parameters

- *C. subvermispora* inoculation over 2 weeks of storage
- Alkali storage treatments for 2 weeks at 3 alkali sources

Initial results suggest a wide range of impacts

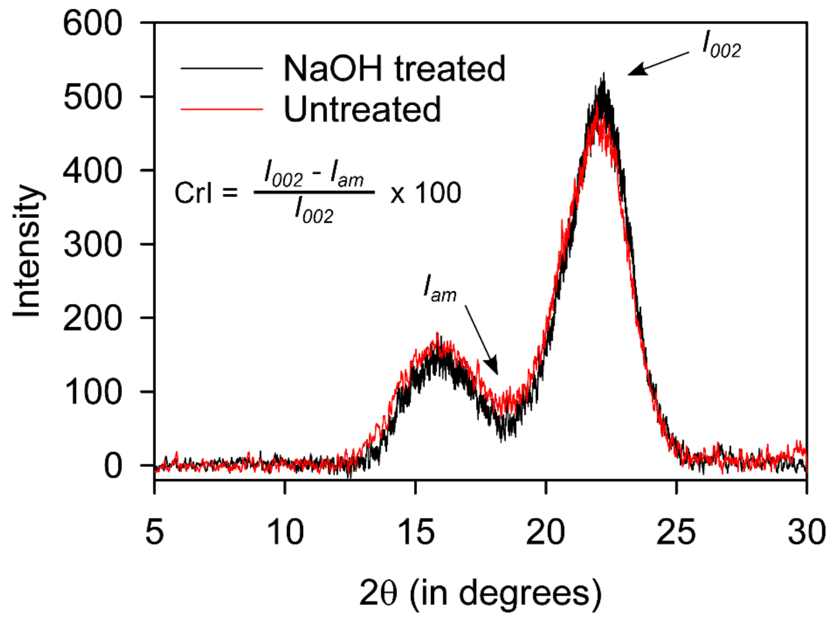
Fungal strain, storage duration	% Dry Matter Loss
***P. chrysosporium*, 1 week**	5.4% ± 0.3%
***P. chrysosporium*, 2 weeks**	22.1% ± 1.2%
***C. subvermispora*, 2 weeks**	10.5% ± 0.9%

Alkali source	% Dry Matter Loss
Sodium hydroxide	4.3% ± 1.6%
Sodium carbonate	1.9% ± 1.3%
Magnesium hydroxide	6.8% ± 4.9%

Future Work-Assessing Recalcitrance

Gain fundamental understanding of impacts of treatments on lignin

- Assess cellulose crystallinity through x-ray diffraction
  - Crystallinity index increased by 9-12% due to removal of amorphous fractions (hemicellulose and lignin)
- Assess lignin structure through NMR and FTIR
- Characterize lignin oxidation products
  - Water extraction of alkali-treated samples indicates lignin solubilization
  - Lignin oxidation products (e.g. ferrulic acid, coumaric acid, vanillic acid)



Water extracts of treated corn stover

Future Work-Assessing Recalcitrance Cont.

Identify impact of sugar yield as a result of storage treatment

- Small-scale screening experiments to select optimal treatment
  - Enzymatic hydrolysis
  - PFI mill plus enzymatic hydrolysis
  - Low-severity pretreatment plus enzymatic hydrolysis
- Collaboration with NREL to determine energy consumption in disk refining
  - 12” disk refiner using 1 kg corn stover

Corn stover without storage and treated with *P. chrysosporium* for 1 and 2 weeks (left to right)

Go-No Go Milestone (3/31/19)

- A Go decision will be determined by attainment of either a relative 30% reduction in pretreatment severity requirements compared to untreated biomass from the same harvest with similar sugar yield after enzymatic hydrolysis, OR a relative 30% increase in sugar release in enzymatic hydrolysis after mechanical milling compared to untreated biomass from the same harvest

Future Work – Screw Feeder Testing

Assess feeding of storage treatments in screw feeder

- Compare to untreated corn stover to assess ability of treated material to flow
- Low-pressure feeding conditions can mimic screw feeder
  - Applicable to deacetylation and disk refining pretreatment approach for biochemical conversion
- High-pressure feeding conditions aim to mimic plug screw feeder
  - Applicable to dilute acid pretreatment approach for biochemical conversion

4” Plug Screw Feeder in INL’s Biomass Feedstock Process Development Unit

Future Work - Techno-Economic Analysis

Use techno-economic analysis to identify costs

- Annual milestone (9/30/19)
  - Present TEA of pathway for value-add in the corn stover supply chain that reduces feedstock costs by $3/ton
  - Assists in meeting BETO's cost goals of $2.50/gallon
- Annual milestone (9/30/20)
  - Transform storage from a cost center to a value-add operation by offsetting feedstock costs by > $3/ton through the application of low-severity treatments over the long residence time in storage that reduce recalcitrance by 30% as measured by reduced energy consumption in grinding or mechanical milling (i.e. preprocessing) or improved digestibility in pretreatment

Use life cycle assessment to identify sustainable pathways

Relevance

Wet logistics systems can reduce risk of loss in the supply chain

- ~5% loss in anaerobic storage, compared to 12% loss in 30% moisture corn stover (SOT) (demonstrated in laboratory and field storage)
- Contributes to BETO MYPP targets and strategic goals
- Reduces feedstock loss in the supply chain, compatible with high-moisture portion of Billion Tons

Storage can be refocused to become a value-add instead of a cost by utilizing the residence time to perform slow chemical transformations

- Recalcitrance reduction possible though biological and chemical approaches
- Impact can be seen in reduced preprocessing and pretreatment requirements, resulting in energy, chemical, and/or cost savings
- Compatible with multiple conversion approaches

Relevance Cont.

Impact of Wet, Value-Added Storage Operations on Bioenergy Industry and Marketplace

- Performing fundamental research on alternative storage approaches that can reduce overall costs for DOE Bioenergy Technologies Office and bioenergy industry
- Provides alternative pathways to manage year-round supply risks
- Compatible with existing logistics operations and conversion technology, leading to quick market entry
- New profit opportunities for equipment manufacturers: Informs selection of equipment and new design
- New and improved profit opportunities for feedstock producers: Enables double cropping and increased profit; delivers biomass at peak conversion value for optimum feedstock payment

Industrial adoption is underway: Verd Company is currently demonstrating a value-add approach in wet storage systems using energy crops

Summary

Overview

- Design a wet storage system that utilizes the residence time in storage to increase feedstock value

Relevance

- Wet logistics systems protect feedstock from loss to degradation or fire and can be used to reduce recalcitrance

Approach

- TEA informs designs, validated by lab and field data

Progress

- Anaerobic storage reduces dry matter loss to 5%
- TEA shows that a wet bulk logistics system for corn stover is competitive with existing bale logistics systems meanwhile reducing energy and water use
- Recalcitrance reduction demonstrated with biological and chemical treatment

Future Work

- Assessing cost:benefit ratio storage treatments through laboratory and cost modeling efforts
- Application of approaches to high-yield, high-moisture crops as available

Acknowledgments

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John Lucas

Additional Slides

Publications, Patents, Presentations, Awards, and Commercialization

Publications

Wendt LM, Murphy JA, Smith WA, Robb T, Reed DW, Ray AE, et al. Compatibility of high-moisture storage for biochemical conversion of corn stover: storage performance at laboratory and field scales. Frontiers in Bioengineering and Biotechnology. 2018;6(30).

Wendt LM, Smith WA, Hartley DS, Wendt DS, Ross JA, Sexton DM, et al. Techno-Economic Assessment of a Chopped Feedstock Logistics Supply Chain for Corn Stover. Frontiers in Energy Research. 2018;6(90).

Presentations

Wendt LM, Wahlen B, Walton M, Nguyen J, Schaller K, Nguyen Q. Alkali pretreatment of corn stover in storage. 41st Symposium on Biotechnology for Fuels and Chemicals. Seattle, WA. April 28-May 1, 2019.

Wendt LM, Smith WA, Murphy JA, Robb T. Field demonstration of anaerobic storage for high moisture corn stover. 39th Symposium on Biotechnology for Fuels and Chemicals. San Francisco, CA. April 25-28, 2017.

Wendt, LM, Murphy JA, Smith WA, Robb T, Nguyen Q, Hartley D. Cost and performance estimates of corn stover in a wet logistics system. Poster Presentation. The 38th Symposium on Biotechnology for Fuels and Chemicals, Baltimore, MD. April 25-29, 2016.

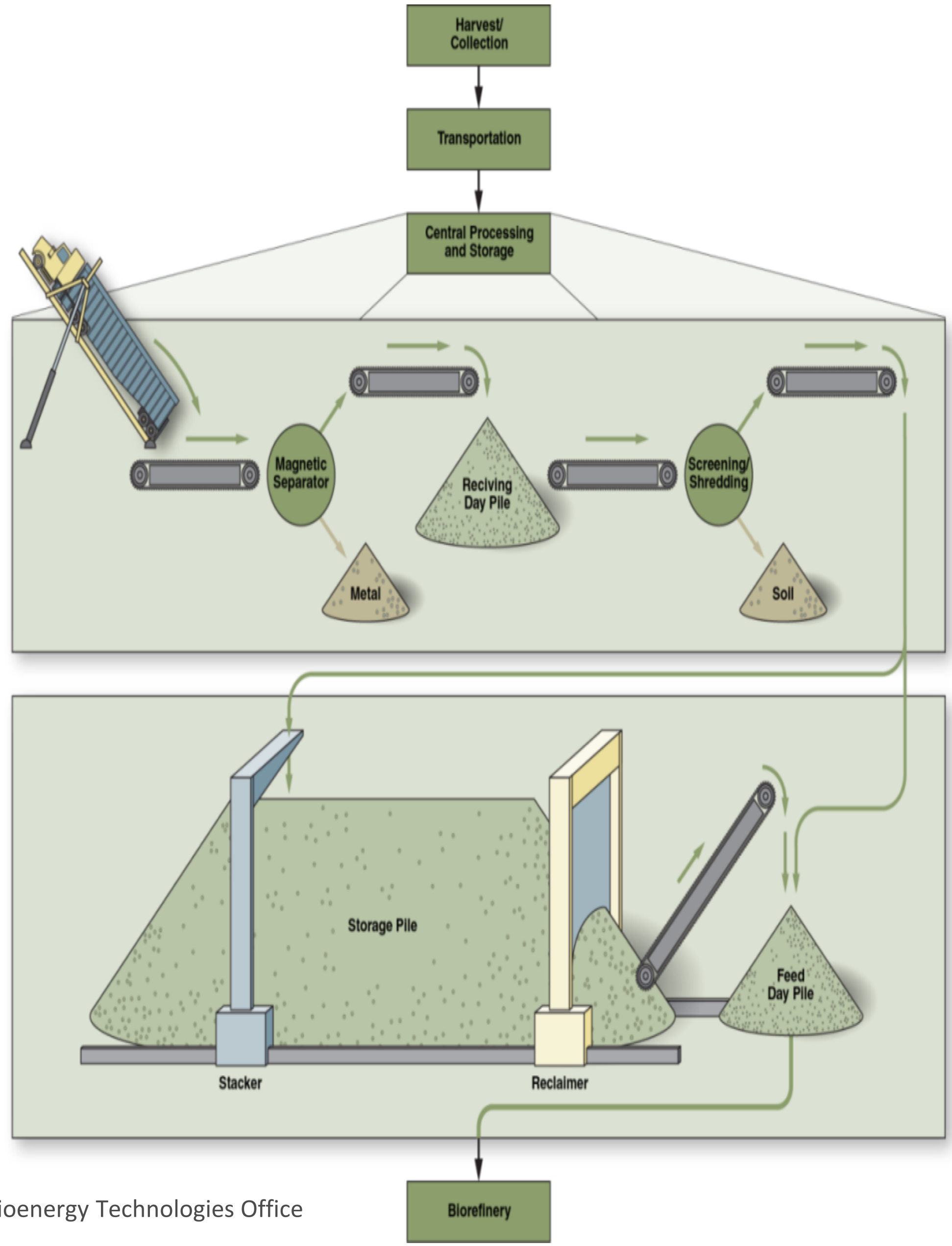
Responses to Previous Reviewers' Comments

- Reviewer: The examination of storage methods for wet biomass is a response to a suggestion in previous Project Reviews of a gap in BETO strategies, and a recognition that a significant portion of the billion ton biomass requirement result in material collected at moisture levels above 20%. This will be especially true for biomass sorghum and energycane. The examination of alternative methods and identification of the superior choice between the two alternatives examined represents significant progress. Further study is needed to get the costs down to make the system competitive with baling systems. This project is contributing to the BETO goals, and should be continued. Future work should include the following. Expand the number of crops stored to determine if the approach is equally suitable for stover, sorghum, switchgrass or energycane. The high cost of transporting chopped material from the field to storage (low DM density) is well known, so alternatives that minimize the distance traveled at low DM density, or increase the density during transport should be considered. Alternative configuration for anaerobic storage might be considered. The potential for chemical pretreatment during the anaerobic storage should be examined. Comparison of alternatives should incorporate both the logistics costs and biomass quality change during storage. This project should be a part of the FCIC portfolio.

- Reviewer: The project is focused on investigating the technical feasibility of wet storage biomass system. It has demonstrated that wet storage system has doubled the cost of conventional storage system. Although the wet storage system has some cost and technical issues, the benefits to pretreatment of biomass should be identified. The project has some potential to de-risk feedstock deconstruction issues for biochemical conversion platform.

- *Response:* We thank the reviewers for the encouraging feedback regarding this work. The focused research on wet logistics systems for corn stover has shed light on multiple opportunities for additional cost reduction to consider in the future. We have demonstrated in this project, through laboratory and field studies, that wet, anaerobic storage can successfully preserve high moisture biomass. We will continue to look for ways to lower the costs of wet logistics systems so they are competitive with dry bale systems, for example by reducing transportation costs, preserving soluble and structural sugars in storage, and realizing the potential for pretreatment during wet storage.

Techno-economic analysis of a chopped system



	Wet Bulk Logistics System	Dry Bale Logistics System (30% moisture bales)
Grower Payment	$37.64 (34.15)	$37.64 (34.15)
Harvest & Collection	$15.61 (14.16)	$21.04 (19.09)
Field-Side Storage	-	$5.05 (4.58)
Transportation	$29.07 (26.37)	$15.86 (14.39)
Refinery Storage	-	$1.12 (1.02)
Refinery Handling	-	$2.06 (1.87)
Preprocessing	$46.88 (42.53)	$24.29 (22.04)
Centralized Storage		-
Dockage	$5.65 (5.13)	$18.62 (16.89)
Credits	-$0.19 (0.17)	-
Total	$134.67 (122.17)	$125.70 (114.03)

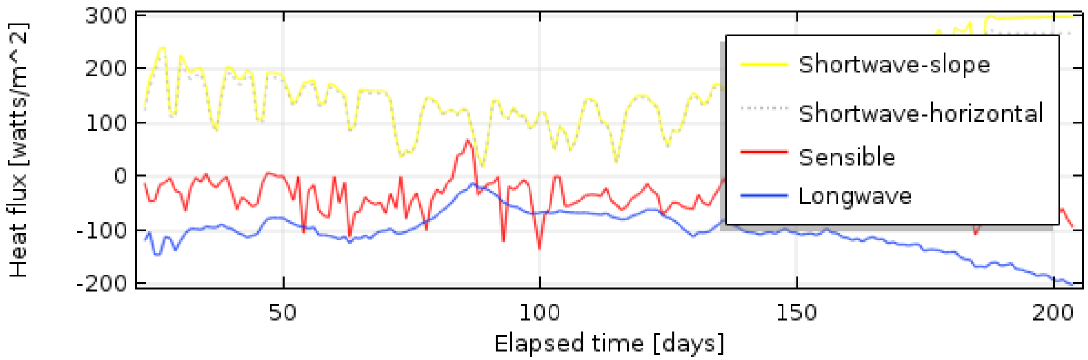
*Costs reported in 2015 dollars on a dry basis

Wendt et al., 2018, Frontiers in Energy Research

Location-Dependent Heat Flux Calculation

Goal: Create surface energy balance to understand heat exchange between the pile and the atmosphere for the Hugoton pile

- Solar radiation
  - Measured, corrected for angle of incidence
- Temperature-dependent longwave radiation, in and out
  - LW: $(1-\varepsilon_{surface})\varepsilon_{sky}\ \sigma\ T_{sky}^4 - \varepsilon_{surface}\sigma T_{surf}^4$
  - Calculated from equations relating sky temperature to 2-m air temperature and relative humidity
- Sensible heat exchange
  - $k \cdot u_{wind} \cdot (T_{amb} - T_{surf})$
  - Based on the difference between measured air temperature and calculated pile surface temperature, wind speed, and an estimated turbulent heat transfer coefficient

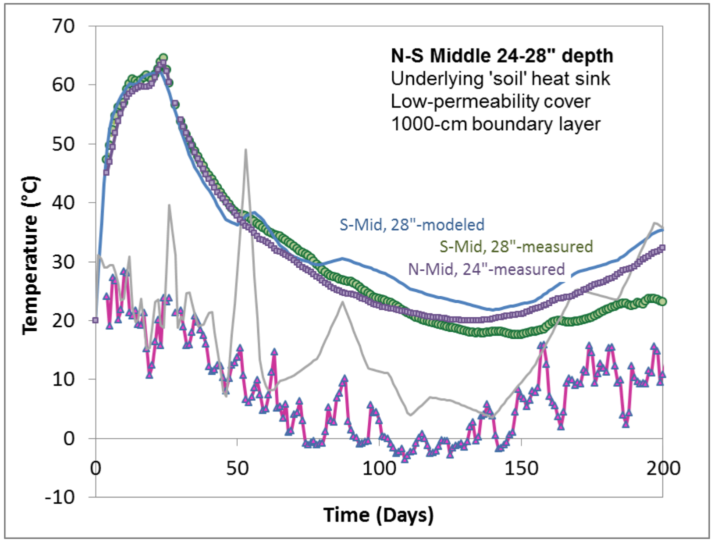


Calculated heat fluxes to the model surface for the south-facing half of the Hugoton pile

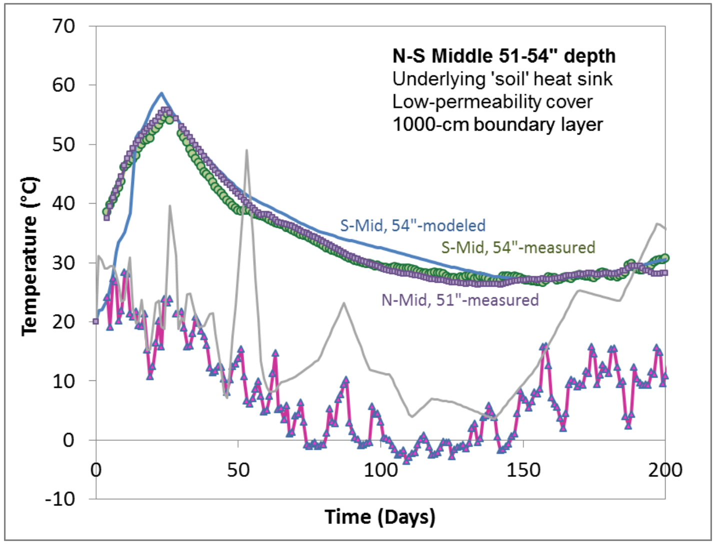
Accomplishments-Storage Model Verification

Compared the predicted vs measured
- North- vs south-facing south
- Multiple depths

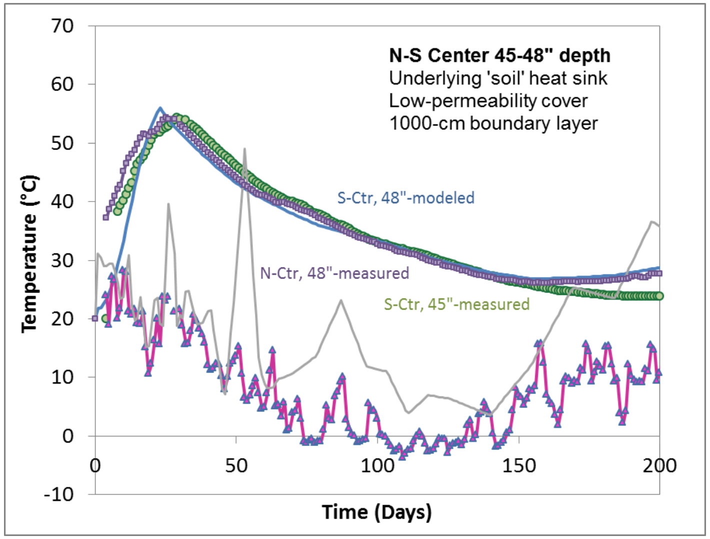
- *Green = S, measured*
- *Purple = N, measured*
- *Blue = S, modeled*



Modeled slightly higher than measured after 75 days



No N-S difference. Measured high at 100 days



Modeled similar to N-Ctr 48”. S-Ctr 45” cool at end

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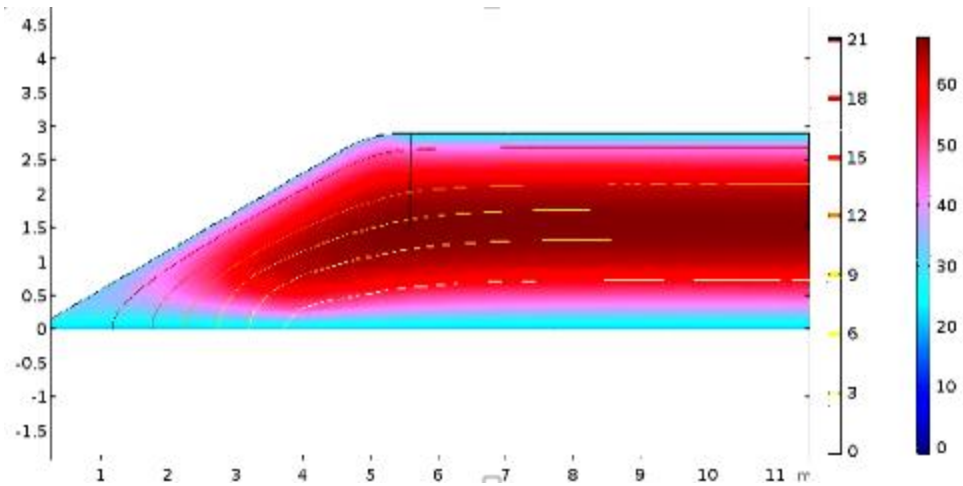
Accomplishments-Storage Modeling Results

Goal: Develop time-lapse model to predict long-term stability throughout storage

Accomplishment: Uncovered pile simulation after 200 days demonstrates that pile interior remains warm but lacks oxygen

Temperature:
Blue=Cold
Red=Hot



Oxygen Concentration:
Blue = <10% O_2
Red = >10% O_2