2013 DOE Bioenergy Technologies Office (BETO) Project Peer Review

1.3.1.4 Feedstock Logistics Engineering

Date: May 21, 2013
Technology Area Review: Feedstock Supply & Logistics

Presenter: Kevin L. Kenney
Principal Investigators: William A. Smith, Tyler Westover, Neal Yancey, Kevin L. Kenney
Organization: Idaho National Laboratory

Goal Statement

- Identify and develop solutions to near-term feedstock barriers facing the biomass/biorefining industry
  - Inform development of biomass-specific harvesting and preprocessing equipment
  - Develop best management practices for growers/producers
    - Harvest practices that reduce soil contamination (ash)
    - Storage practices that preserve biomass carbohydrates
  - Inform biorefinery end users

Quad Chart Overview

Timeline

- Project start date: FY-07
- Project end date: FY-17

Budget

- Funding for FY11: $2.6M DOE
- Funding for FY12: $2.2M DOE
- Funding for FY13: $1.85M DOE
- Years the project has been funded / average annual funding: 7 years, avg. funding $3.0M/yr.

Partners

- AGCO Corp.
- CNH
- DDCE
- FDCE
- IA State U
- NREL
- OK State U
- POET
- Texas A&M

Barriers

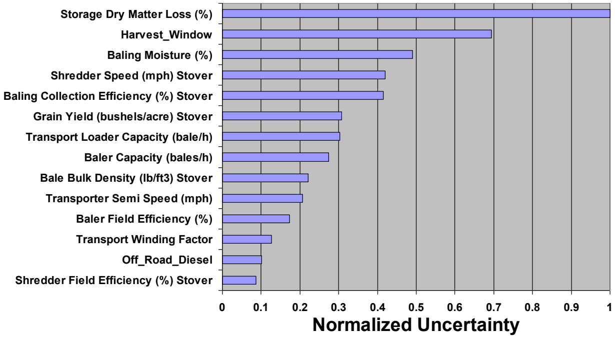
- Ft-G: Feedstock Quality and Monitoring
- Ft-H: Storage Systems
- Ft-J: Biomass Material Properties

1- Approach

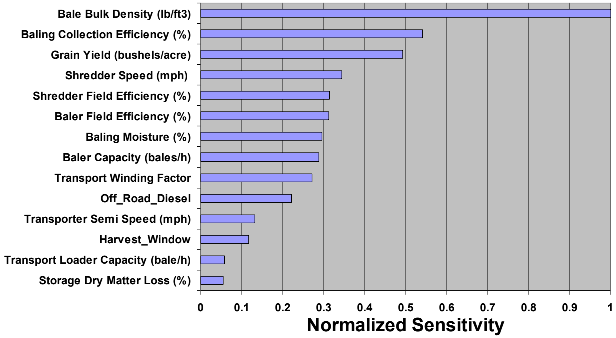
- Identify R&D barriers through modeling, supported by investigative R&D and literature reviews
- Develop Design Report
- Develop annual MYPP targets
- Develop and execute annual R&D plans to achieve MYPP targets
  - Engage external partners as appropriate
- Annually report progress/accomplishments against MYPP targets (SOT reports, Joule Milestones)
- Final demonstration of MYPP cost target

Project Background

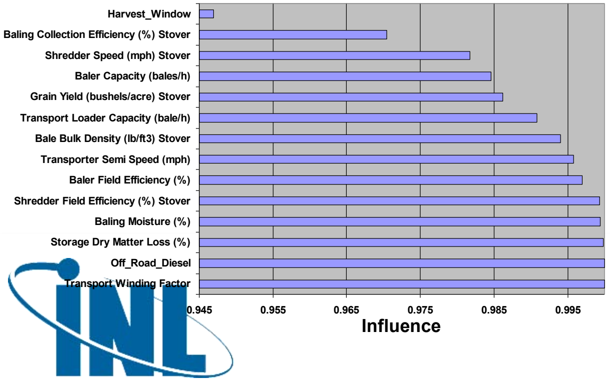
Uncertainty



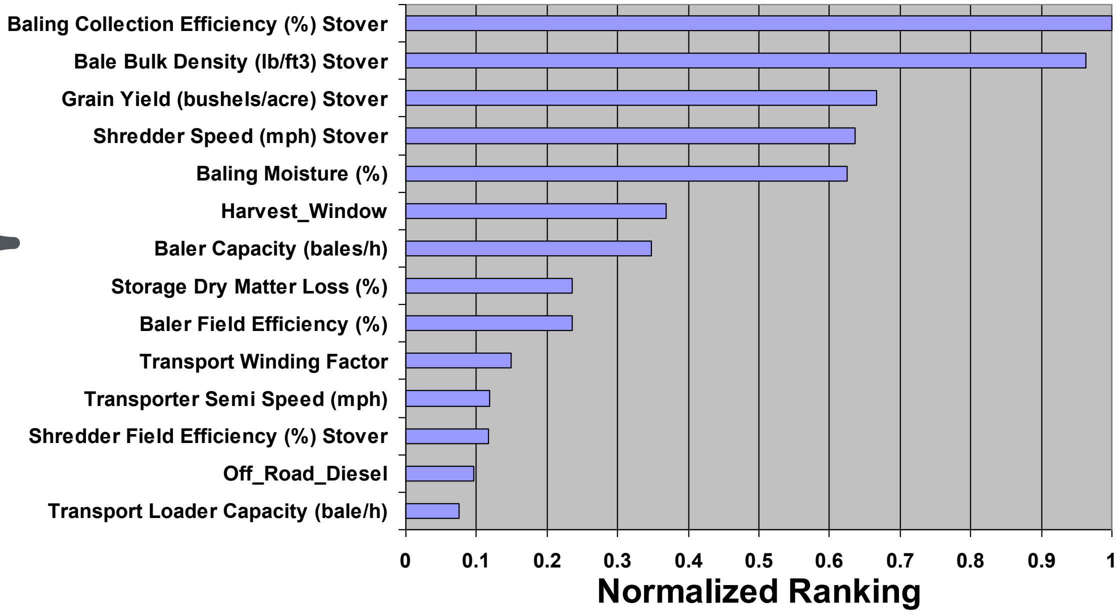
Sensitivity



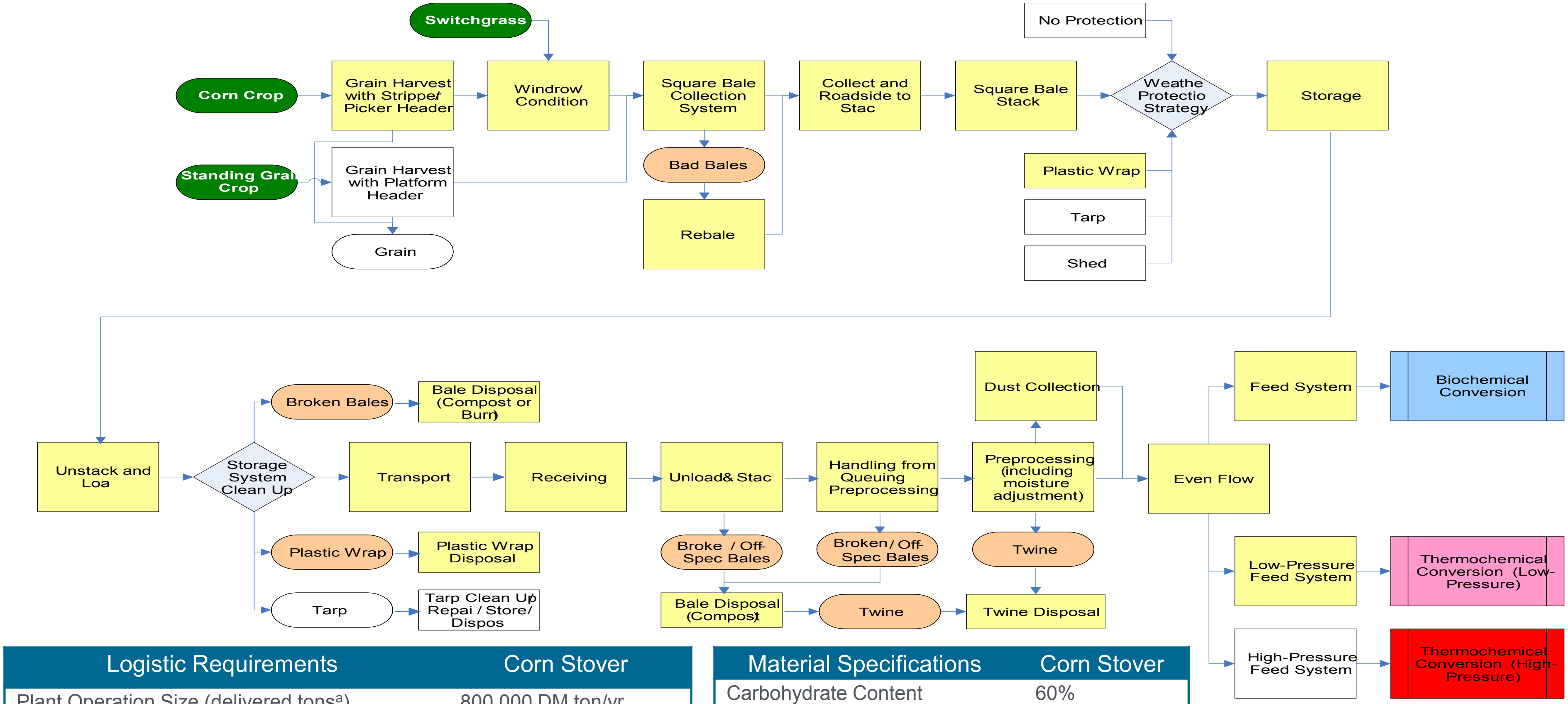
Influence



$$\text{Rank} = \frac{\text{Uncertainty} \times \text{Sensitivity}}{\text{Influence}}$$



Project Background


Switchgrass
Corn Crop
Grain Harvest with Stripper Picker Header
Windrow Condition
Square Bale Collection System
Collect and Roadside to Stac
Square Bale Stack
No Protection
Weathe Protectio Strategy
Storage
Standing Grai Crop
Grain Harvest with Platform Header
Grain
Bad Bales
Rebale
Plastic Wrap
Tarp
Shed
Broken Bales
Bale Disposal (Compost or Burn)
Dust Collection
Feed System
Biochemical Conversion
Unstack and Loa
Storage System Clean Up
Transport
Receiving
Unload& Stac
Handling from Queuing Preprocessing
Preprocessing (including moisture adjustment)
Even Flow
Plastic Wrap
Plastic Wrap Disposal
Broke / Off-Spec Bales
Broken/ Off-Spec Bales
Twine
Low-Pressure Feed System
Thermochemical Conversion (Low-Pressure)
Tarp
Tarp Clean Up Repair / Store/ Dispos
Bale Disposal (Compost)
Twine
Twine Disposal
High-Pressure Feed System
Thermochemical Conversion (High-Pressure)

Logistic Requirements	Corn Stover
Plant Operation Size (delivered tons[a])	800,000 DM ton/yr
Feedstock Harvested Annually[b]	868,600 DM ton
Acres Harvested Annually	527,000
Participating Acres	50%
Acres Available for Contract	1,054,000
Cultivated Acres	2,107,000
Feedstock Draw Radius[c]	45.8 miles

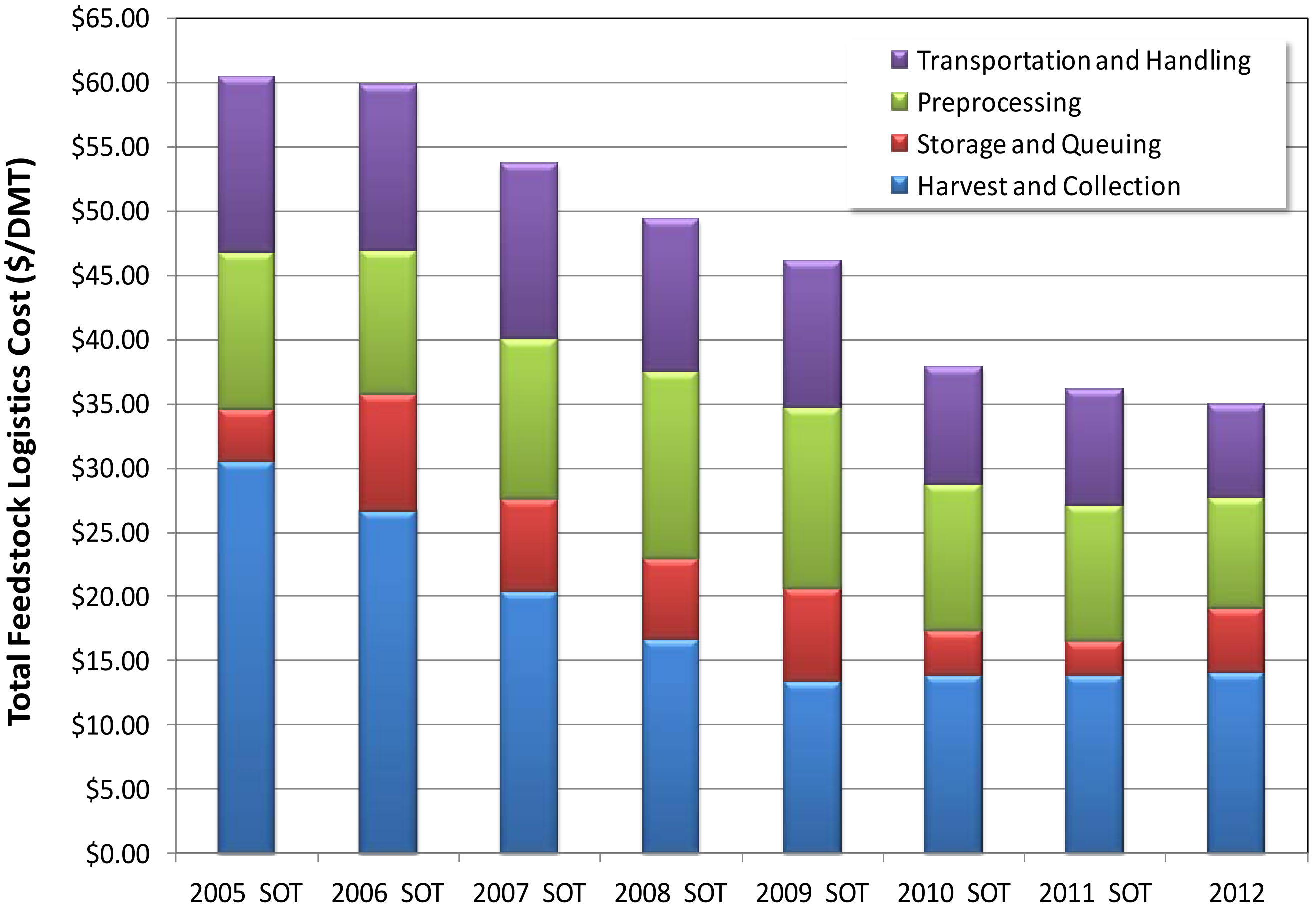
a. short ton = 2,000 lb.
b. Extra tonnage harvested to account for supply system losses.
c. Assume an equal distance distribution of acres throughout the draw radius.

Material Specifications	Corn Stover
Carbohydrate Content	60%
Moisture Content	12%
Particle Size	¼ minus
Ash Content	5-6%

Sustainability Limiting Factors
Soil Organic Carbon
Wind/Water Erosion
Plant Nutrient Balance
Soil/Water Temperature Dynamics
Soil Compaction
Off-Site Environmental Impacts

Project Background

Feedstock Cost Improvement Pathway (2007 $) to Support Cellulosic Ethanol Pathway



Transportation/Handling – Indirect gains due to improved bale density and reduced losses (shrink)

Preprocessing – direct improvements in grinder efficiency and capacity

Storage/Queuing – Lower cost storage methods, and reduce uncertainty of storage losses (e.g., preserve the 60% carbohydrate target)

Harvest/Collection – Improved Harvest/collection efficiency (i.e., a yield component) while not violating sustainability limits, and biomass quality (namely ash) targets

Harvest and Collection Accomplishments

- 2006: wheel rake, est. 43% collection efficiency, ~17% ash, $26/ton
- 2012 Demo: stalk chopper, 38% collection efficiency, 12% ash, $14/ton
- Successes:
  - 46% cost reduction
  - Reduced uncertainty with collection of machinery performance data
  - R&D showed equipment is capable of collecting sustainably available stover
  - Achieved > 65% collection efficiency with range of harvest equipment
  - Residue Removal Tool informs increased removal rates
  - Identified potential for harvesting systems to greatly impact biomass ash content
  - Best Management Practices to mitigate soil contamination associated with increasing collection efficiencies

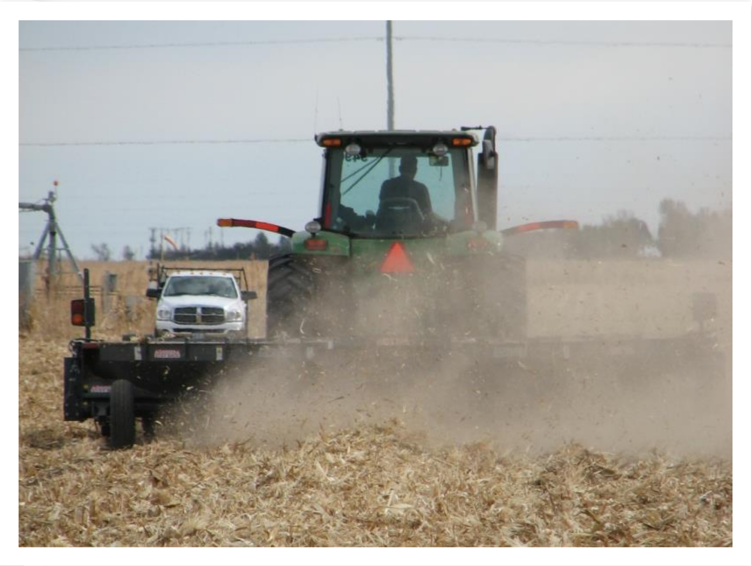
Collection Efficiency – the ratio of biomass collected to the amount available in the field

Biomass Quality

- Of the numerous biomass quality factors to consider, ash seems like the low hanging fruit.
- Ash is easily understood as:
  - Physiological ash (beyond this groups control)
  - Entrained ash (soil; added during biomass handling)
- Our harvest processes affect ash content, but by how much?
- What is the impact of this easily altered quality factor?

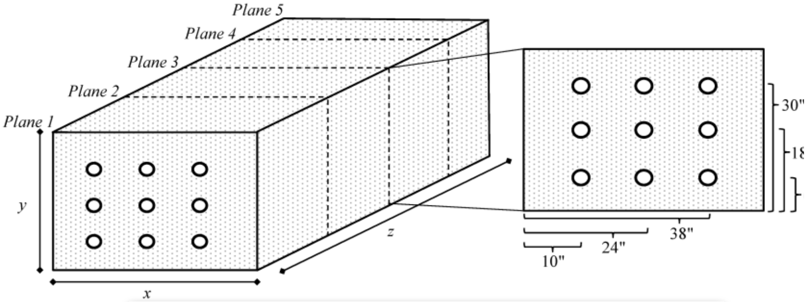
2011 Harvest - Kansas

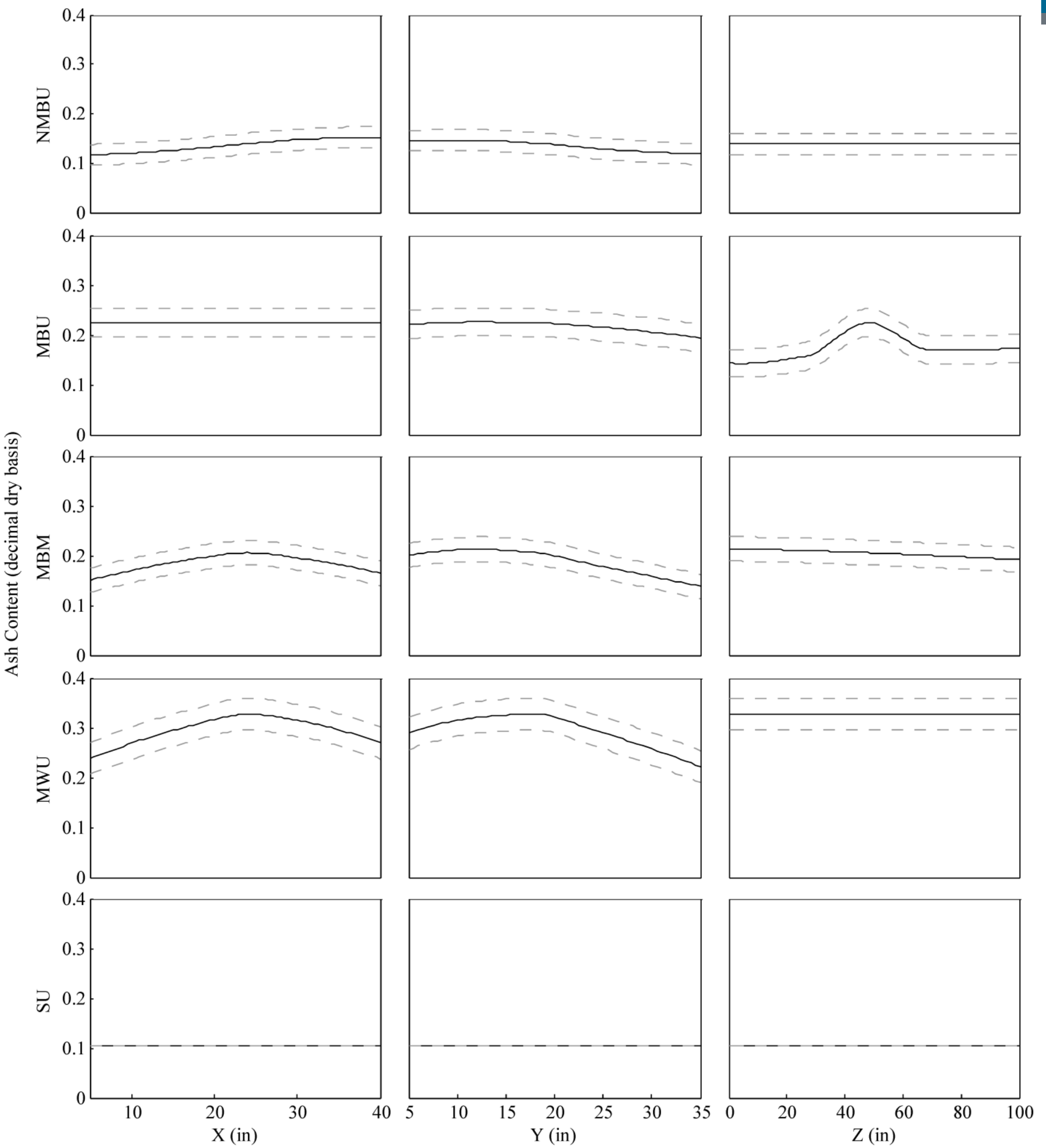
- 1230 Core samples collected and analyzed
- Purpose:
  - What is the variability of ash within a bale
  - How does collection equipment influence both the bulk ash content, and where the ash appears.



2011 Harvest - Kansas

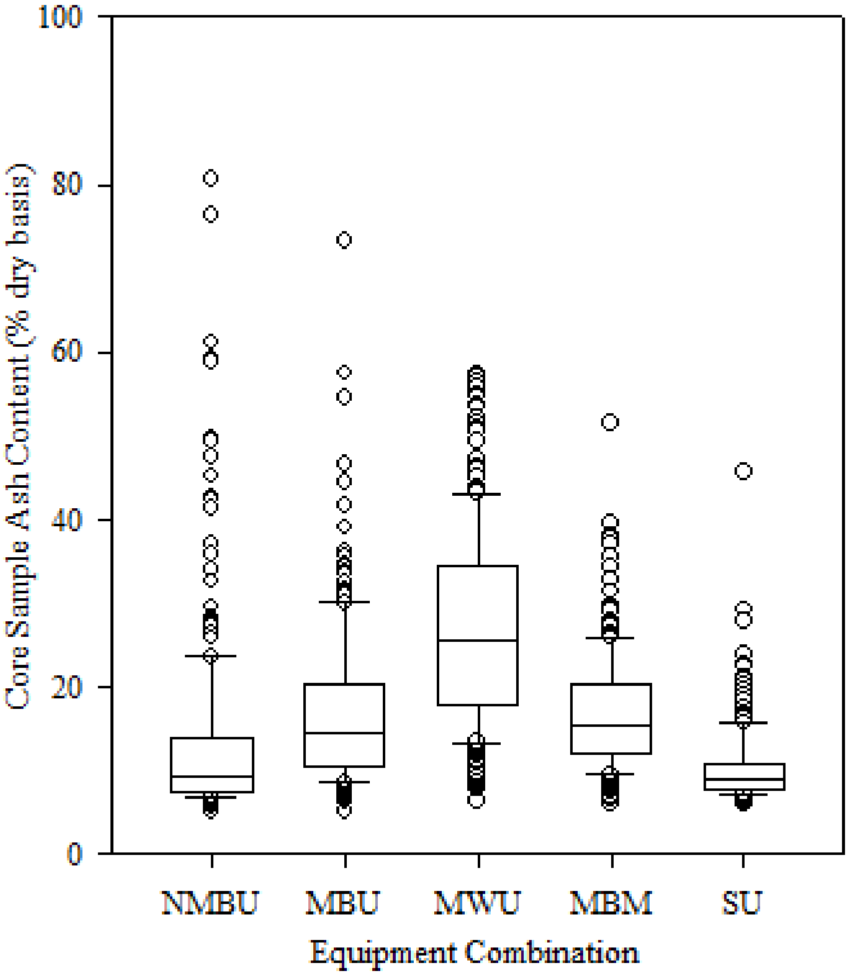
- Spatial distribution of ash within bales.
- Some patterns, but overall not significant.
- No magic "representative" sampling location.





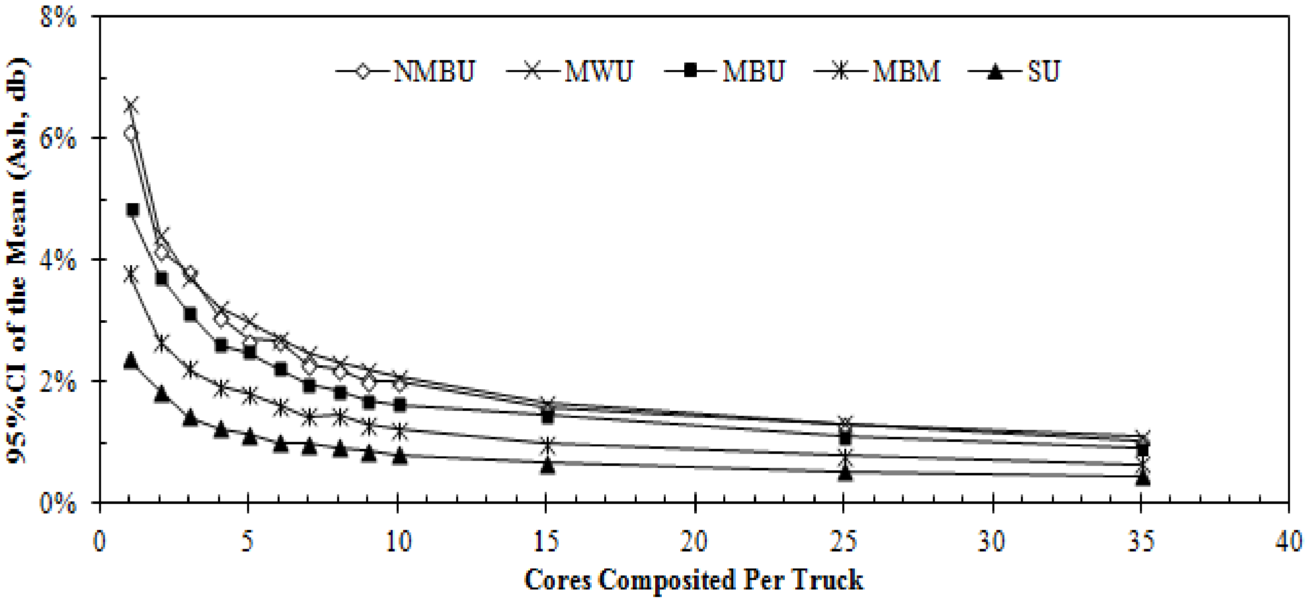
2011 Harvest - Kansas

- Core sample results
- Extreme variability based on equipment choice.
- Why?
  - Ground & material disturbance



2011 Harvest - Kansas

- What did we learn from this?
- Clearly a difference between collection methods in the same location.
- How can we accurately capture the variability within bales?
  - Simulated compositing shows decreasing uncertainty



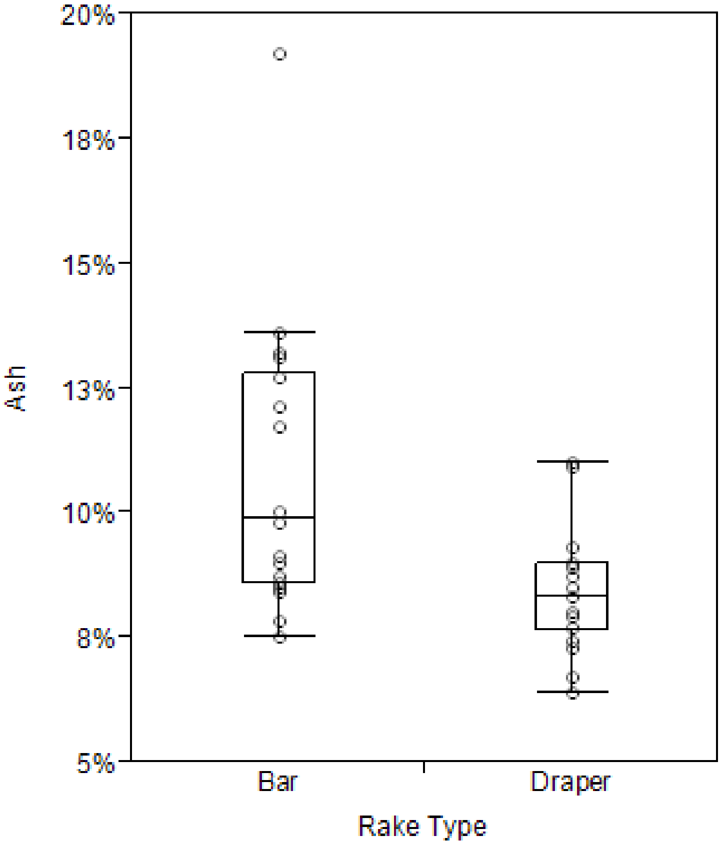
2012 Harvest - Iowa

- 360 cores per treatment (v. 270 in 2011), but composited into 18 samples (20 cores per composite).
- Focus on *bulk* ash content instead of localized.
- New state, new soil, some of the “same” equipment.

2012 Harvest - Iowa

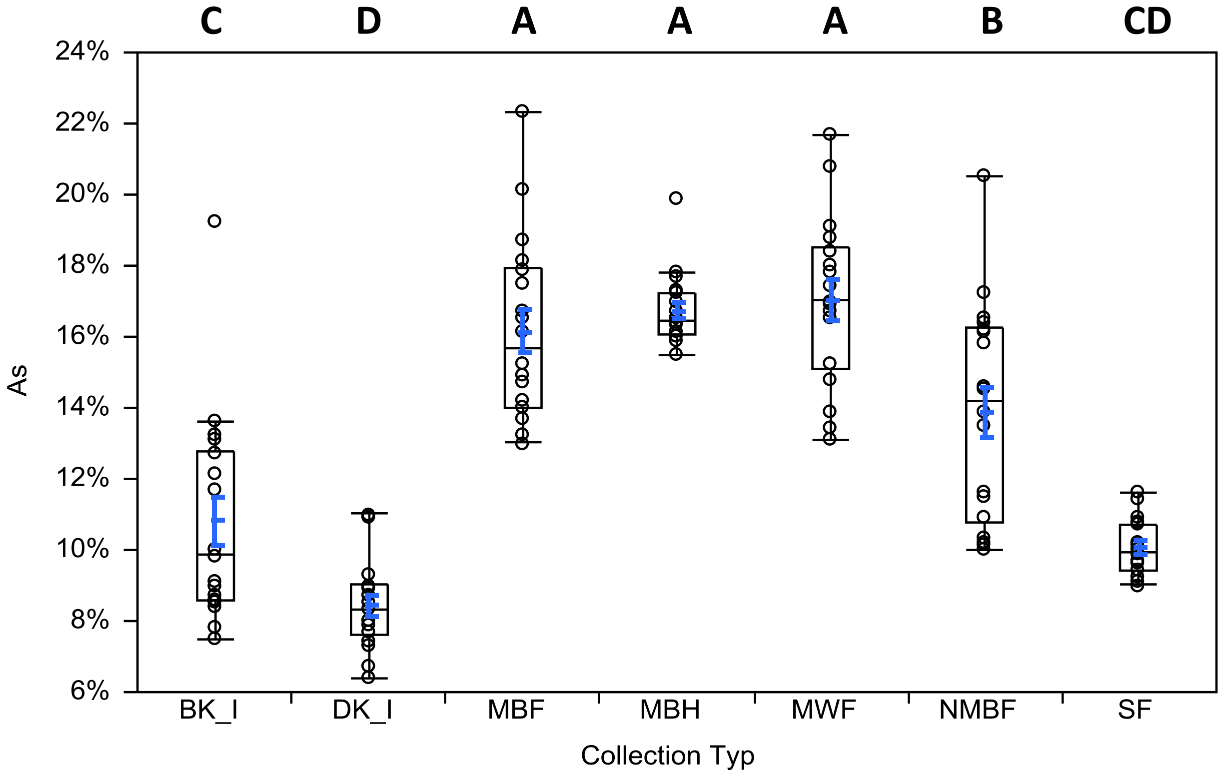
- Drastically reduced range and standard deviation
- Naturally tight confidence interval, no need for extreme data manipulation.
- Still one relatively far-off sample
  - Odds of collecting high ash cores can still provide misleading composite results

	Mean	Std Dev	Lower 95%	Upper 95%
Bar	10.80%	2.90%	9.40%	12.30%
Draper	8.40%	1.20%	7.80%	9.00%



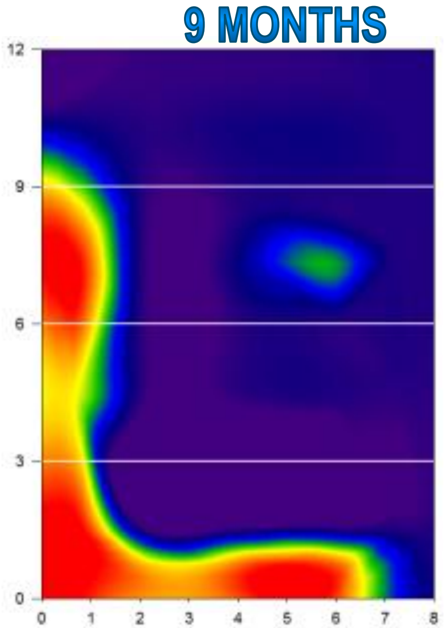
2011 & 2012 Harvest

- How can we compare the 2011 to 2012 results?
- Simulated compositing of the 2011 samples



Storage & Queuing Accomplishments – Stability (DML)

- 2006: wrapped storage, < 20% moisture, est. 7.9% dry matter loss (DML), $9/ton
- 2012 Demo: tarped storage, 24% moisture, 7.7% DML, $5/ton
- Successes:
  - 44% cost reduction
  - Research-based recommendation for tarped storage over wrapped storage
  - Understanding dry matter losses - difficult to quantify due to inability to accurately quantify post-storage moisture content
  - Understanding the dynamic nature of moisture within a storage system has informed best management practices
  - Improved procedures for bale sampling for measurement

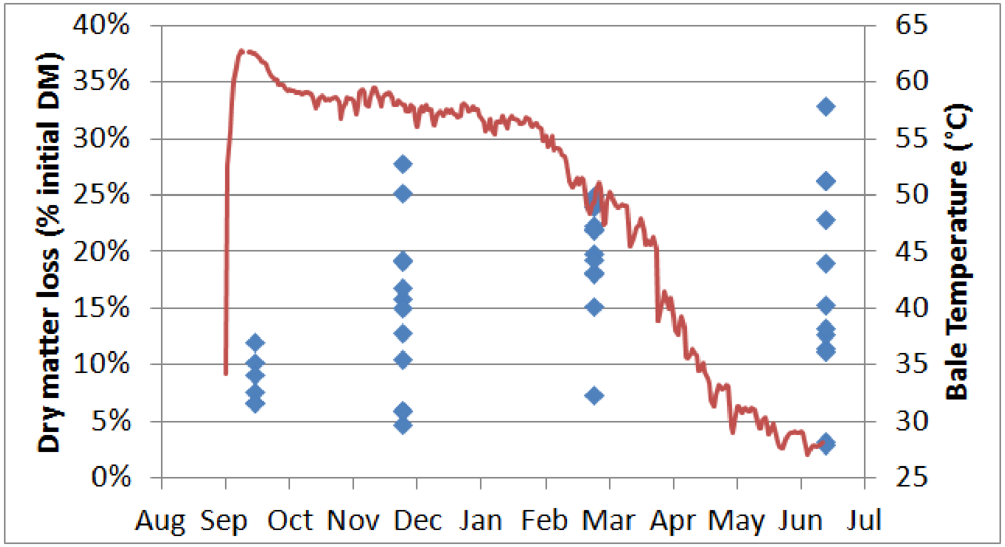


Focus of Storage R&D

- **Problem**: *Self heating is observed in the field under wet, aerobic conditions.*
  - What does this mean for us in terms of feedstock stability?
  - How do we capture data that is hard to obtain in field?

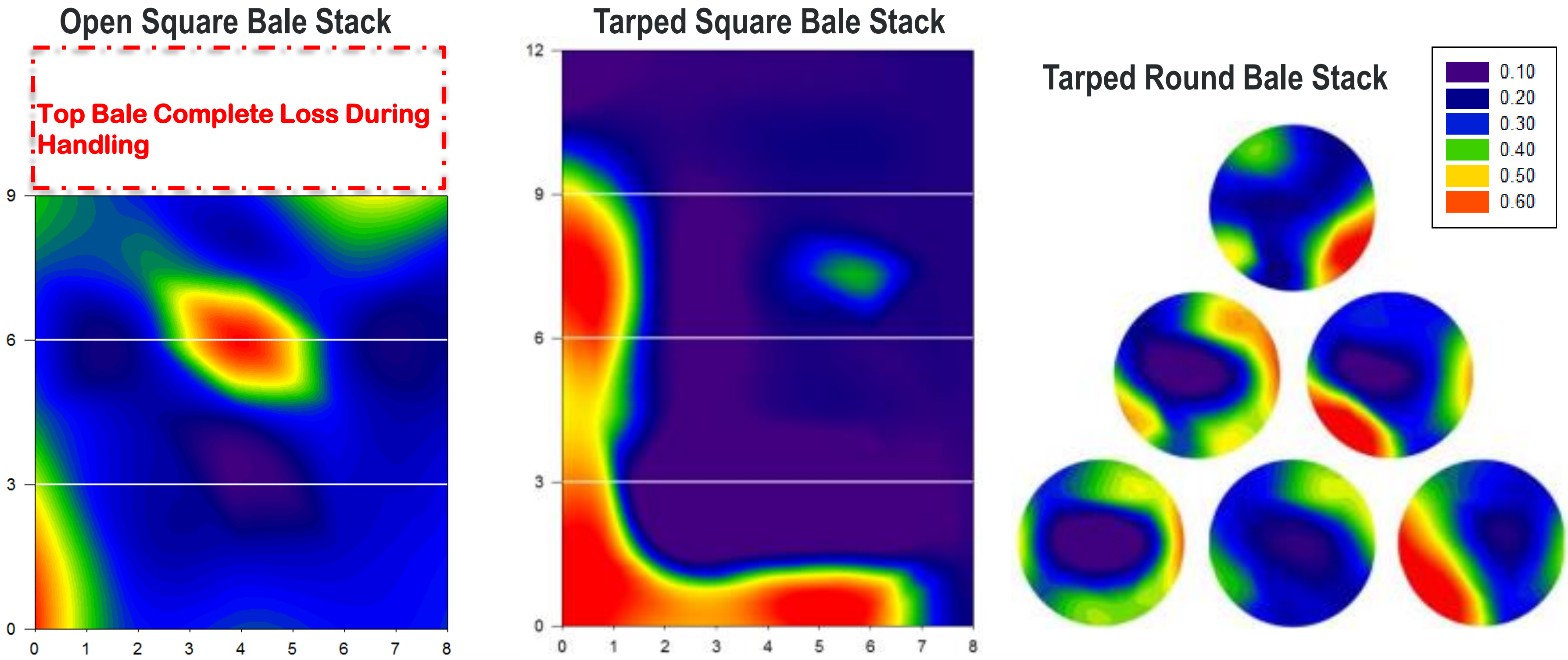
- **Experimental Approach:** *Recreate field storage conditions using relevant laboratory-scale experiments*

- **Experimental Objective:** *Define loss throughout each stage of self-heating profile*
  - Dry matter loss
  - Composition changes



Moisture Management in Dry Storage

- Conventional approach: <15% moisture content = stable dry storage
- Moisture gain and migration results in significant losses even in materials that enter “dry”
- Moisture management requires a system approach (aggregation of bale properties, stack configuration, and environmental influences)



Open Square Bale Stack

Top Bale Complete Loss During Handling

Tarped Square Bale Stack

Tarped Round Bale Stack

- All bales < 15% initial moisture (w.b.)
- 20 gallons of water in a single bale

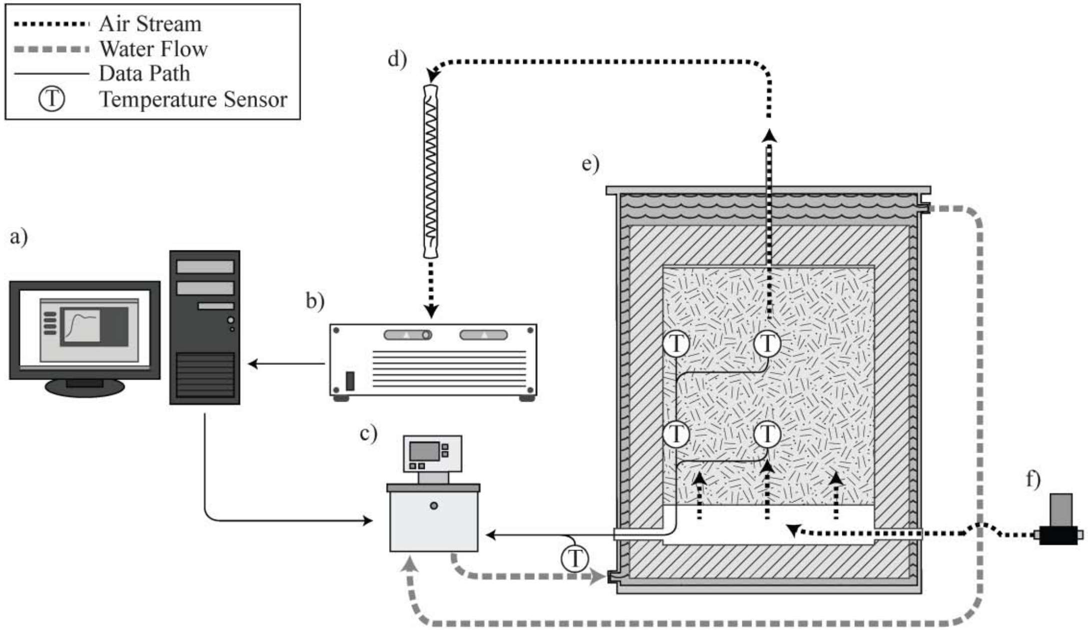
- Stacks shown at 9 months storage
- Round bales do not shed water!

Storage Simulation Reactors

- Simulate the behavior of a range of storage conditions.
  - Control: heat loss, oxygen availability, moisture content
  - Monitor: heat generation, microbial respiration, moisture change, DML, composition.

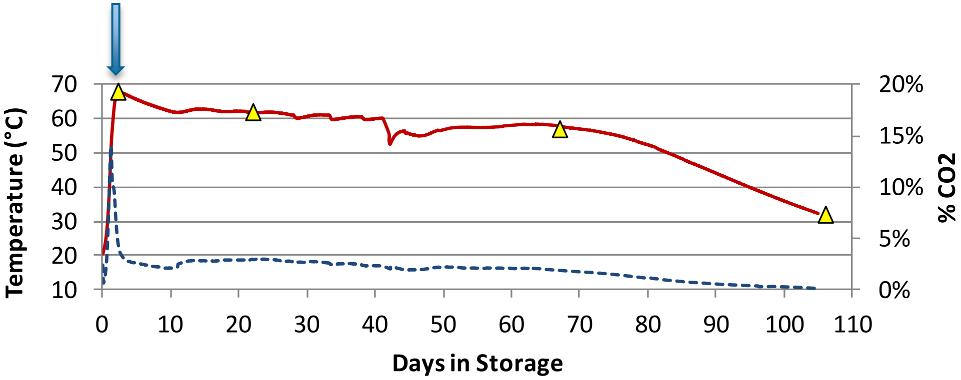
- Generate ample quantities of post-storage material with a well documented history for chemical analysis.

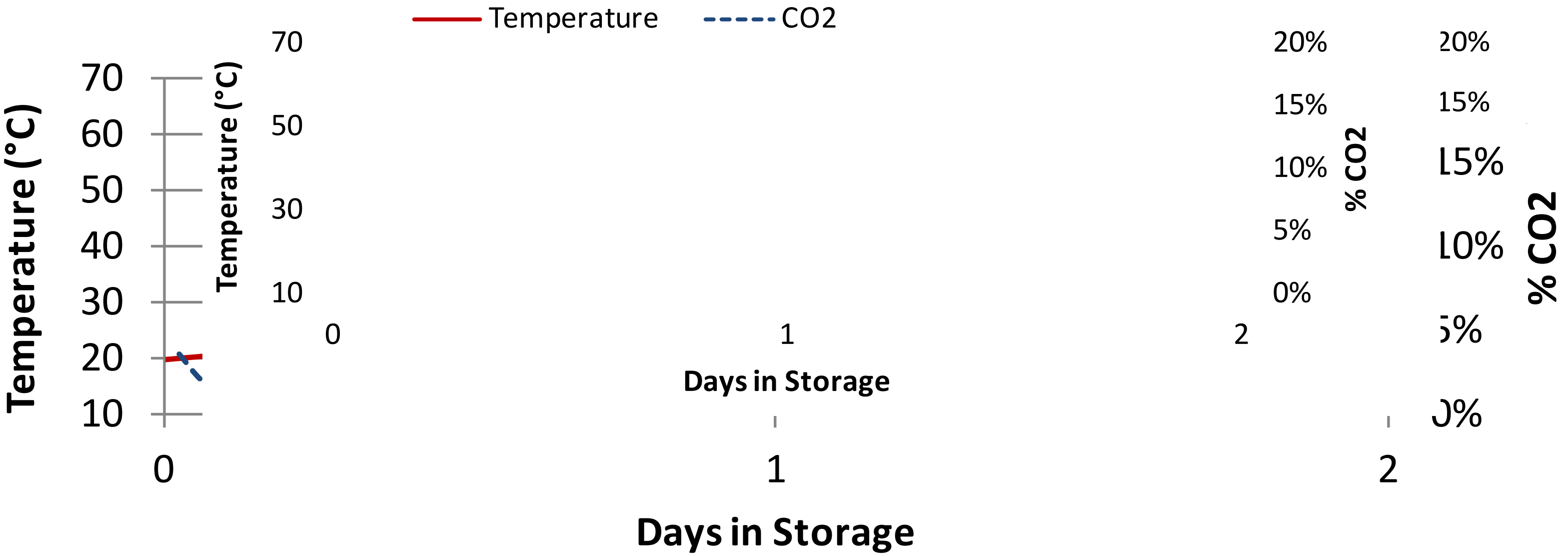
- Microbial respiration: Gas exiting the reactor is analyzed for CO_2 production in real-time
  - DML estimated by $CH_2O + O_2 \rightarrow CO_2 + H_2O$



Self-Heating Profile

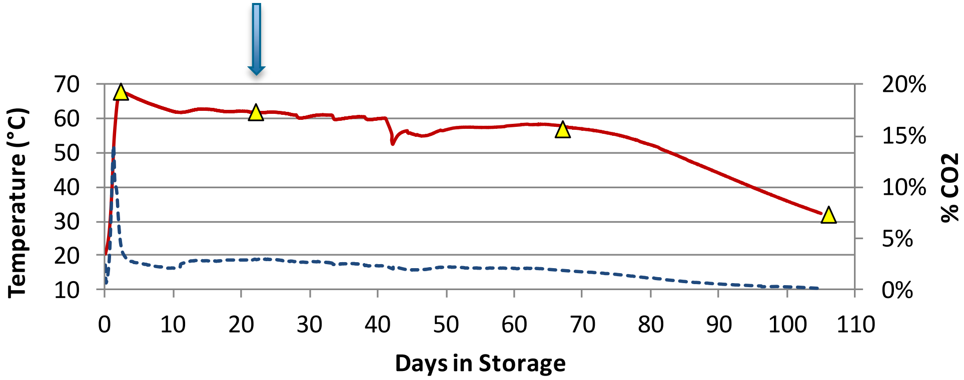
- Initial heating to 65ºC in 2 days
- Spike in microbial respiration to ~15% CO_2
- Soluble sugars utilized

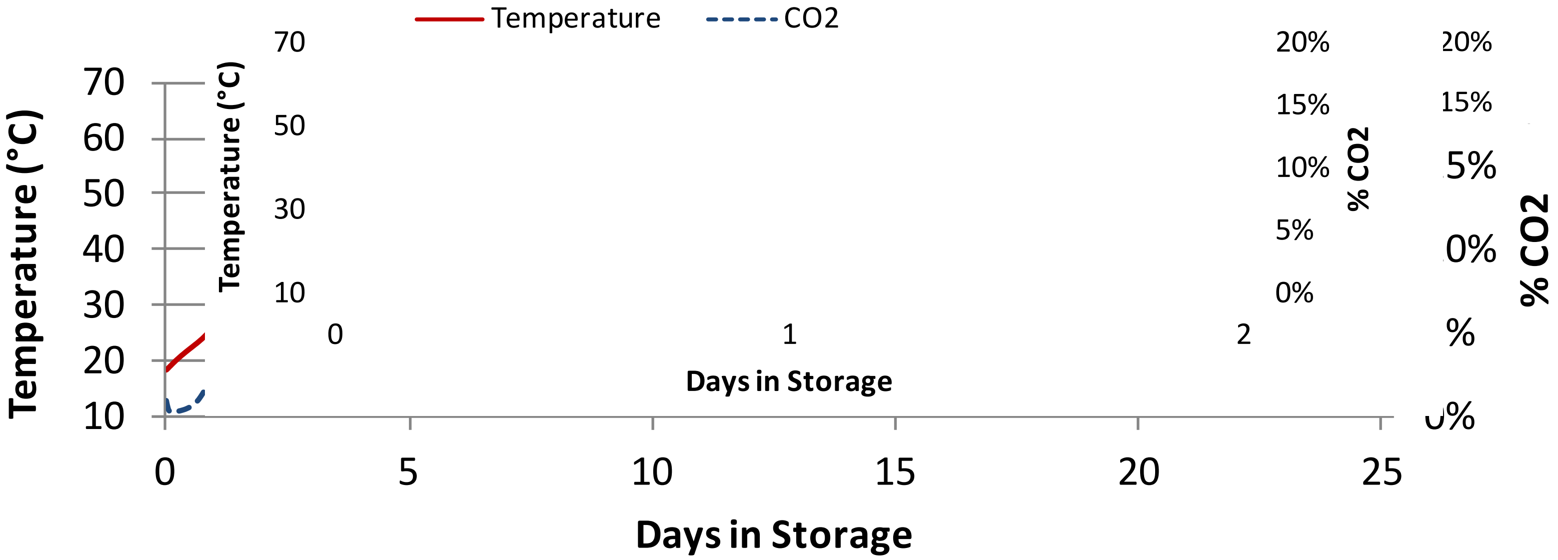




Self-Heating Profile

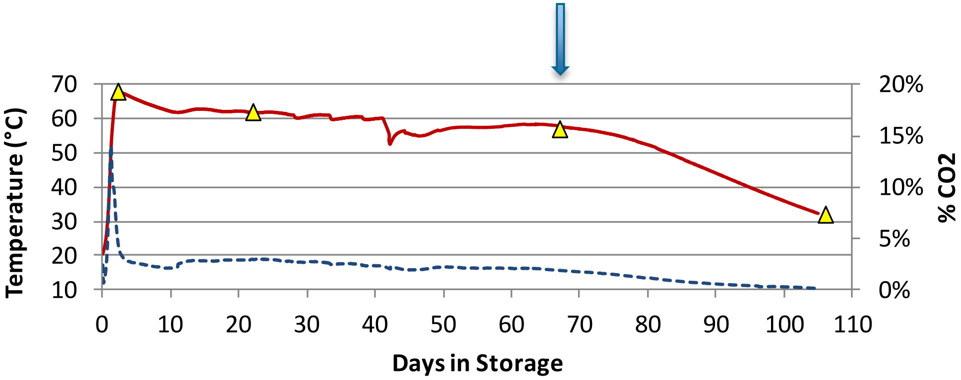
- Temperature drops and stabilizes at 60ºC
- CO_2 maintained at ~3%
- Structural sugar degradation begins

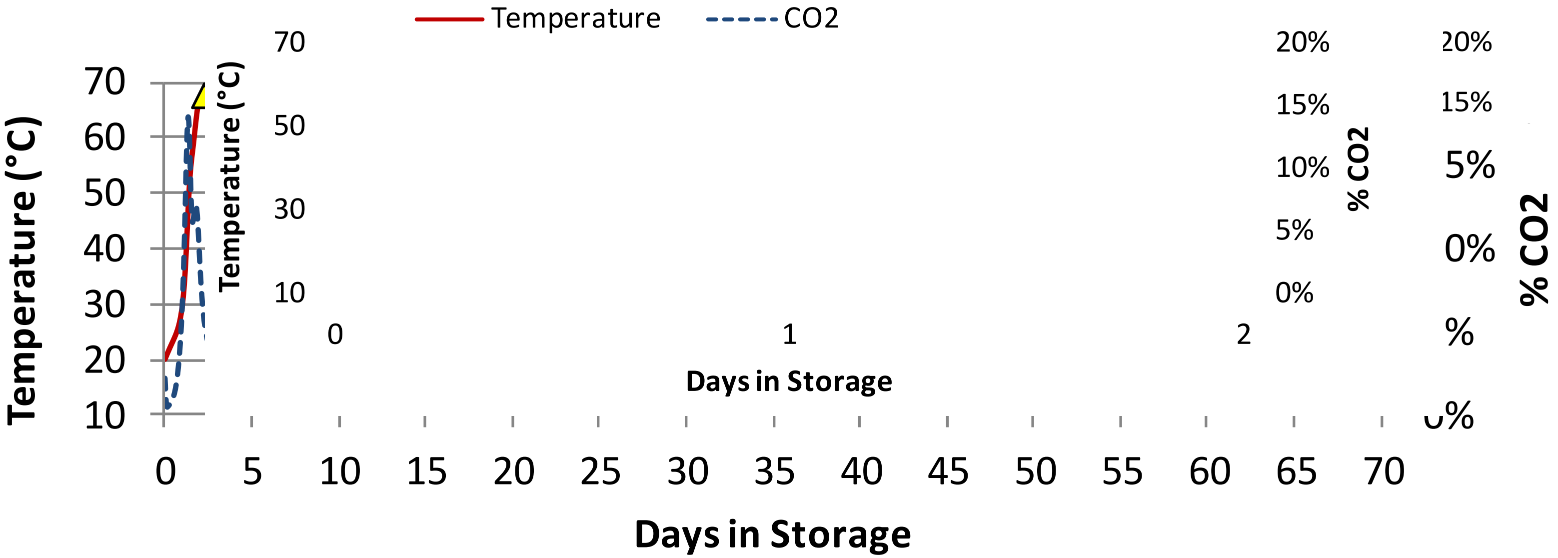




Self-Heating Profile

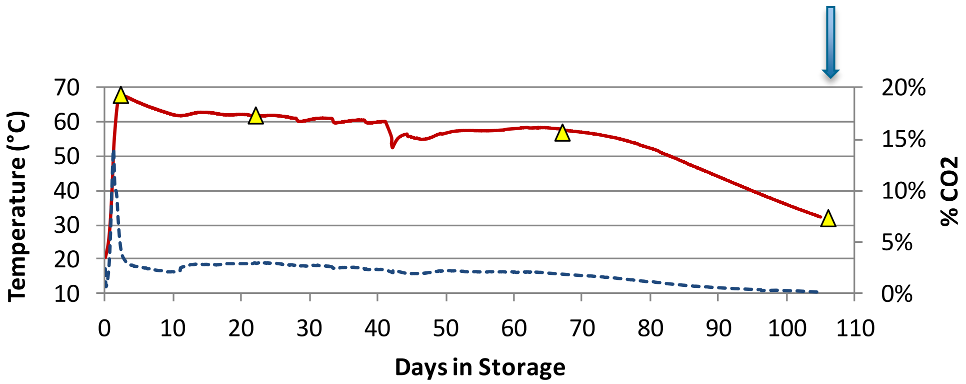
- Slow drop in temperature from 60ºC to 55ºC over 60 days
- CO$_2$ maintained at 2-3%
- Structural sugar degradation likely sustaining microbial growth

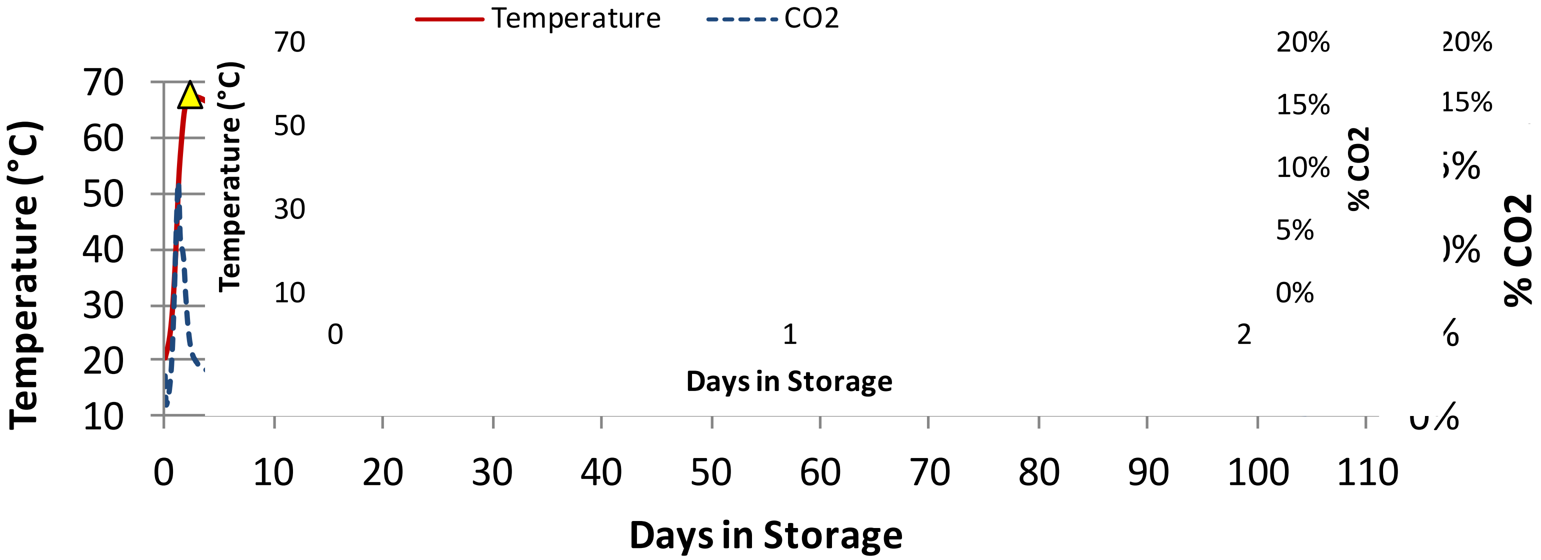




Self-Heating Profile

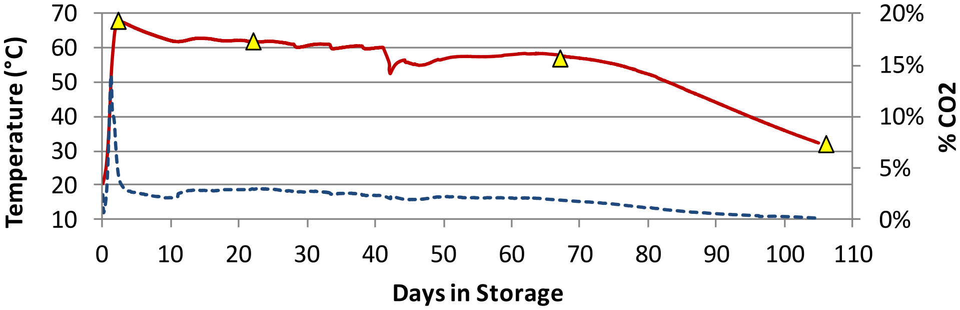
- Gradual drop from 55ºC to 30ºC
- Decrease in microbial respiration towards ambient concentrations
- Growth limiting factor likely cause of reduced microbial activity



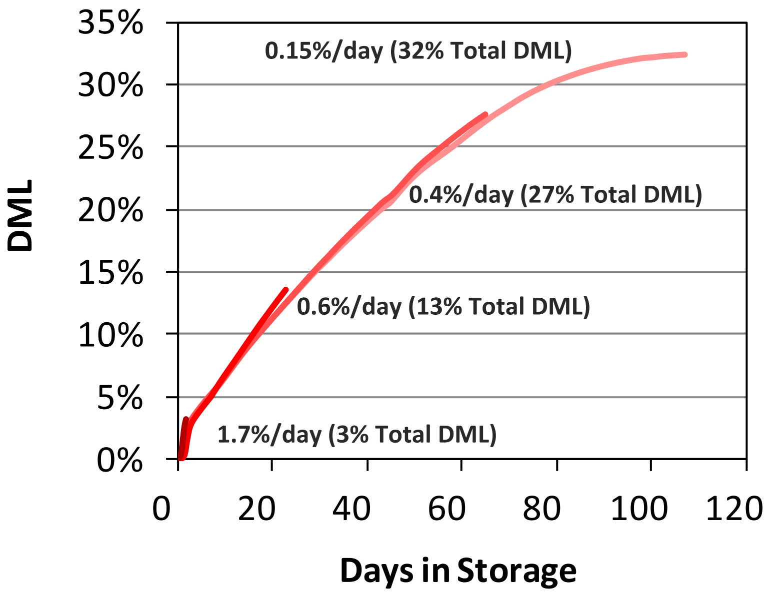


Dry Matter Loss

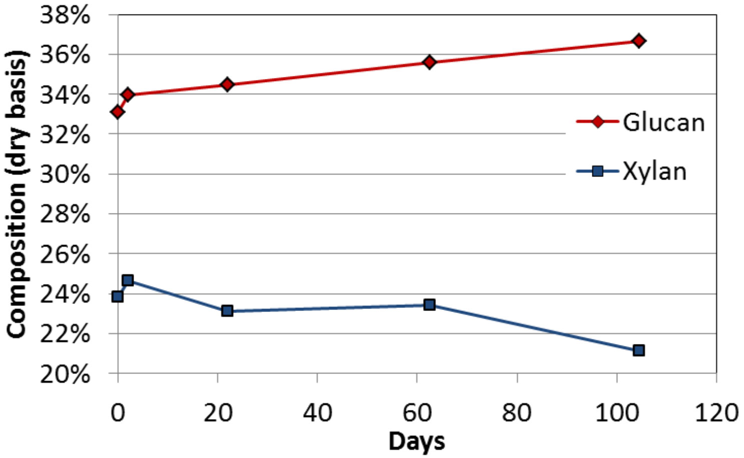
Days	DML Rate	Total DML
0-2	1.7%/day	3%
2-22	0.6%/day	13%
22-63	0.4%/day	27%
63-105	0.15%/day	32%

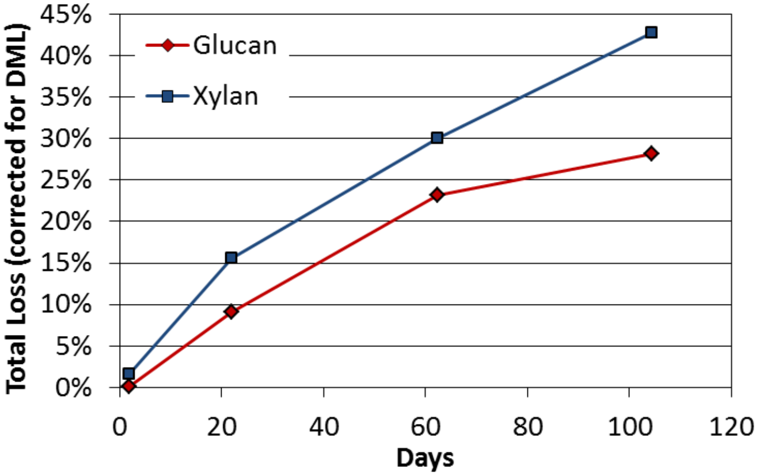


- Three phases of DML
  - Initial spike
  - Sustained loss during high temperatures
  - Gradual decrease upon cooling
- Initial loss of 3-5% DML inevitable
- Shelf-life window is influenced by rate of DML
- Long, sustained rate of DML is target for future improvements

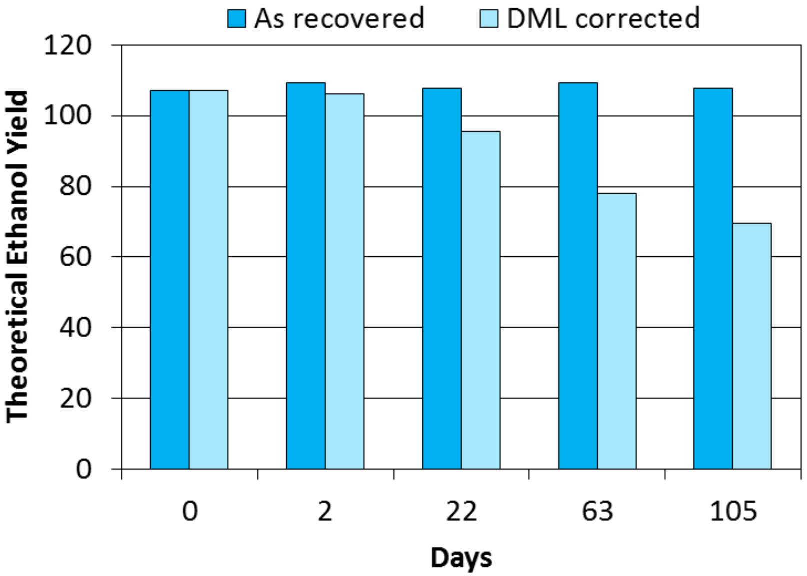


Compositional Changes

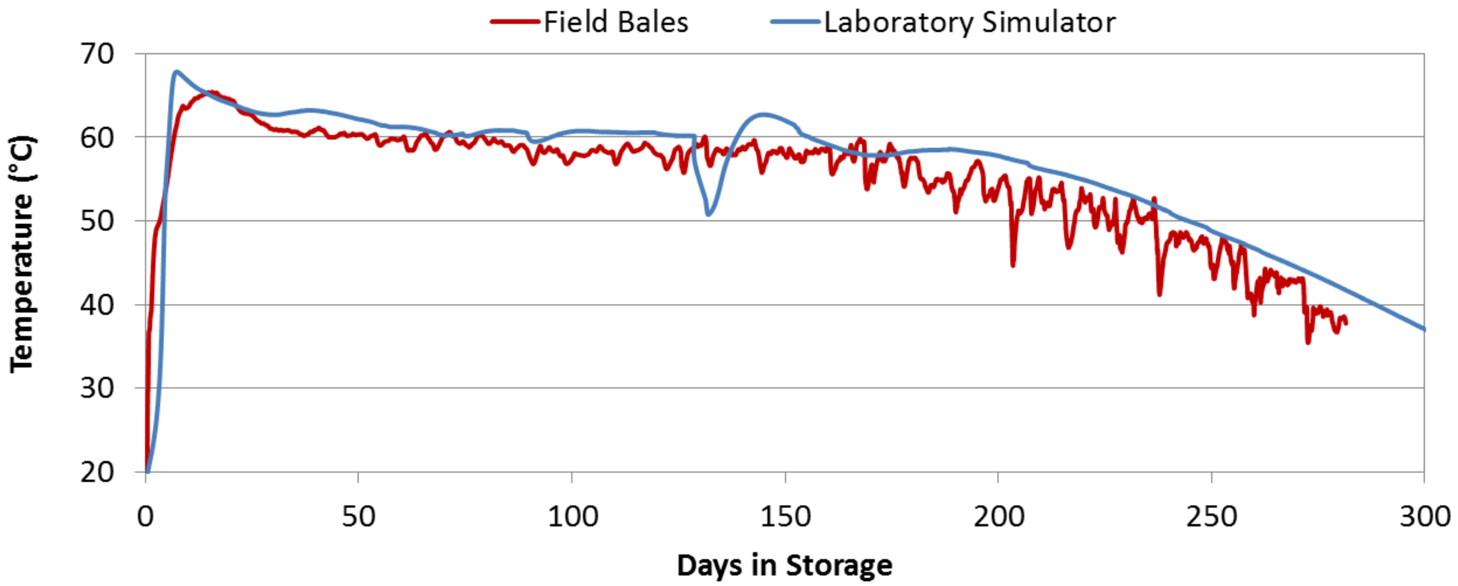




- Recovered biomass is slightly reduced in hemicellulose and enriched in cellulose
- When corrected for DML, high degradation occurred, preferential to hemicellulose
- This behavior is reflected in TEY



Comparison of Time Scales



- Storage simulator time scales by a factor of ~3
- Varies from 2 to 4 depending upon the specific bale location in the stack
- **Not microbial kinetics, but volumetric extent of bale undergoing active biodegradation**

Current Best Management Practices

The ideal storage system allows internal moisture to escape while preventing uptake of external moisture

Storage Method	Internal Moisture	External Moisture	Recommendations
Open	Maximum potential for loss	Maximum potential of gain	Arid regions where precipitation is minimal
Tarped	Potential for loss from open faces, accumulation under tarp	Minimal with proper ground prep	Adequate for most regions and conditions
Wrapped	Internal redistribution, minimal loss	none	High moisture bale storage in wet regions

Preprocessing SOT Improvements: Grinder Capacity/Efficiency

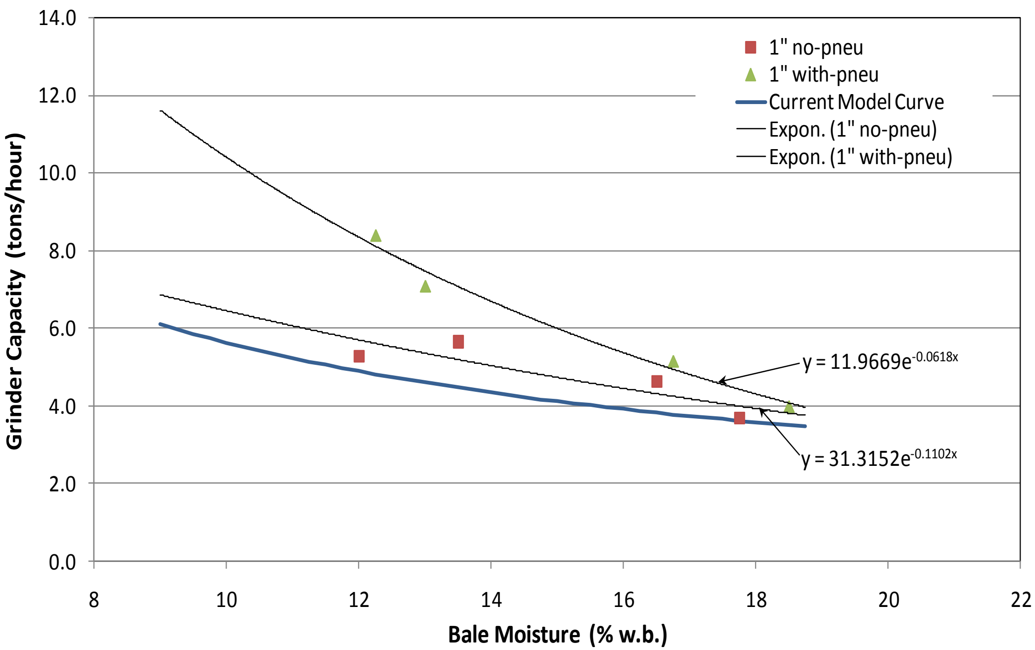
- 2006: industrial tub grinder, 26.7 kWh/ton, $11/ton
- 2012: horizontal hammer mill, 23.4 kWh/ton, $9/ton
- Successes:
  - 18% cost reduction, 12.5% increase in efficiency, >60% capital reduction
    - Improved grinder configuration / operation
      - Improved hammer design
      - Increased hammer tip speed
      - Modified shear plate tolerance
    - Pneumatic conveyance
  - Improved understanding of particle size distribution
    - Order of magnitude difference between screen size and mean particle size
    - Pneumatic conveyance narrows particle size distribution

Improving Biomass Size Reduction Efficiency

Pneumatic transfer system (blue, left) supplied air flow through the grinder, increasing capacity by a factor of two.

Pith and other tissues rapidly deconstruct upon impact

Rind and vascular tissues hold together under impact forces and require shear / torsion forces to effectively size reduce

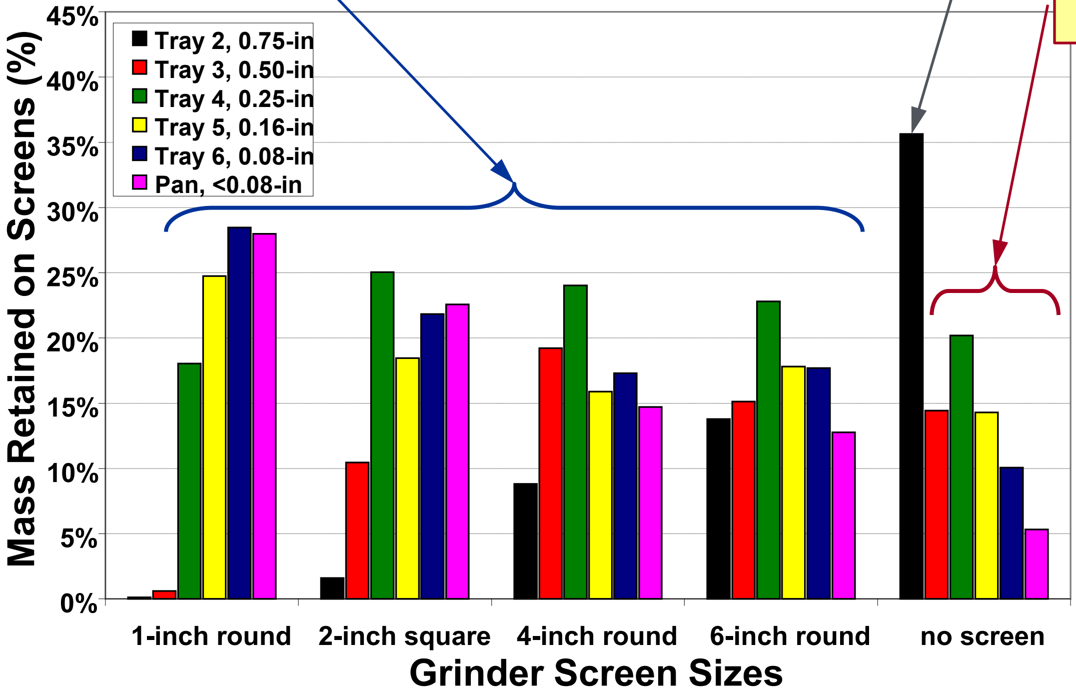


Fractionation/Separation

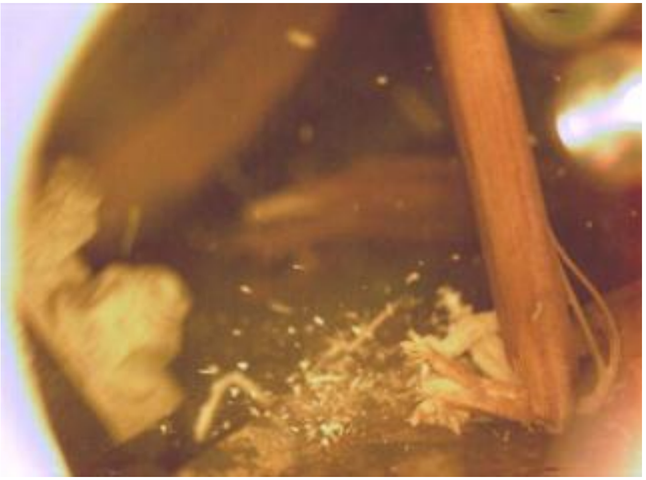
Impact alone does not deconstruct rind and vascular tissues

- Screen results in shear forces to effectively reduce grind size
- Screen size affects distribution

- Impact with no screen deconstructs pith and other tissues
- Higher lignin content

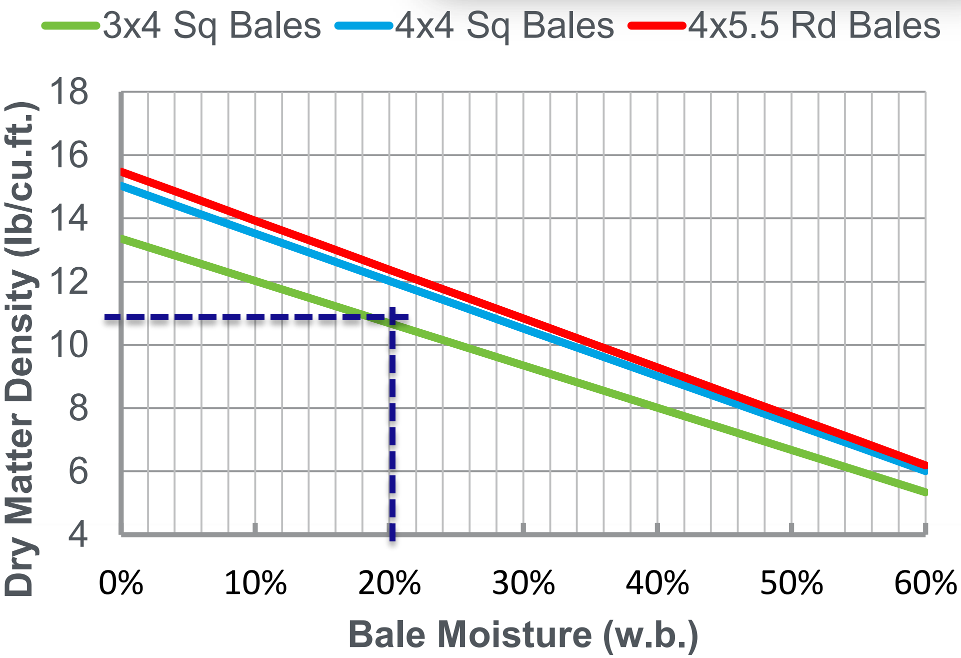


Miscanthus Particle Size Distribution



Transportation and Handling SOT Improvements – Bulk Density

- 2006: 9.2 dry lb/ft^3, \$14/ton
- 2012 Demo: 11.1 dry lb/ft^3, \$7/ton
- Successes:
  - 50% cost reduction
  - 21% increase in bale density
  - Demonstrated high-density baling technology exists to produce stover bales > 12 lb/ft^3 (testing average 12.8 lb/ft^3)
  - Demonstrated ability to increase density (11.2 dry lb/ft^3) through optimization of direct-baling configuration/settings

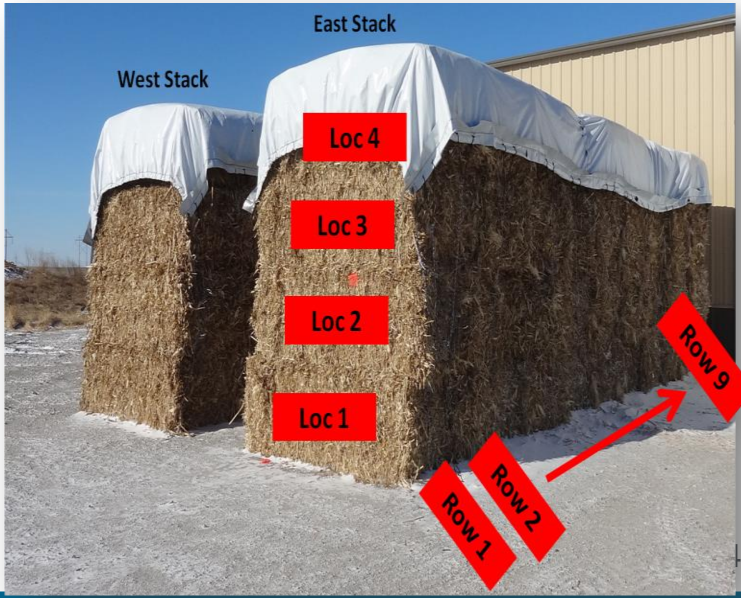


2012 Demo: Harvest & Collection

- Contracted to Iowa State University
- 170 acre field, 175 bu/ac, 4.99 dry ton/ac stover, 1.9 ton/acre removal rate (38% collection efficiency)
- Windrowing: Hiniker 5600 series side discharge windrowing stalk chopper
- Baler: Krone 3 ft x 4 ft x 8 ft large square baler
- Bale Samples at Harvest:
  - Moisture Content: Average 23.6%
  - Ash Content: Average 12.1%
  - Dry Bale Density: Average 11.1 lb/ft^3
- Collection: CASE 240 tractor, ProAg Bale Wagon
- Cost: $14/dry ton

2012 Demo: Storage

- Contracted to Iowa State University
- 2 stacks, each 1-bale wide x 4-bales high x 9-bales long
- Stacks placed on aggregate base
- Stacks tarped immediately after stacking
- Data collection: weight, moisture – initial and following 6 months storage
  - 2 core samples/bale initial, 12/bale final
  - DML ranged from 0% to 14%
  - DML averaged 7.7%
- Cost ($/dry ton):
  - Tarp, labor, and land rent: $2.50
  - Dry matter loss: $1.50
  - Total: $4



2012 Demo: Preprocessing

- Approx. 25 tons (50 bales) removed from storage and shipped from Iowa State
- Unloaded and staged at INL, then continuously processed through feedstock PDU
  - Grinder: Vermeer BG480E, 2-inch screen
  - Target particle size: ¼-inch minus
  - Conveyed from grinder into metering bin (truck)
- Data collection:
  - Bale moisture content
  - Grinder throughput
  - Power consumption
- Cost: $9/dry ton

2012 Demo: Transportation

- Contracted to Iowa State University
- Loader with bale spears
- 53-ft semi tractor/trailer, 39 bales per truck
- Assumed 35.1 mile haul distance
- Data Collection
  - Loader cycle times – used data from Iowa State
- Cost: $7/dry ton

3 - Relevance

- BETO
  - Demonstrated achievement of 2012 cost goal
  - 2012 accomplishments directly apply to 2017 targets
  - R&D directly contributes to the development of biomass-specific (not merely an adoption of hay, forage, and logging) equipment and processes.
- Industry
  - Inform improved practices to reduce cost, improve quality of biomass feedstocks
  - Development of science-based best management practices deploys
- Applications of the expected outputs
  - Inform selection of equipment and process selection
  - Inform design of new equipment
  - Inform quality measurement procedures and practices
  - Inform best management practices for growers, aggregators, and biorefiners

4 - Critical Success Factors

- Critical Success Factors
  - Technology transfer of R&D accomplishments into deployable solutions
    - Best Management Practices
    - Processes/Procedures
- Challenges
  - Industry collaborations
    - Complement and provide access to field testing\demonstration
    - Continue competitive feedstock FOA
  - Quality Measurement Tools
    - Develop lower-cost, higher-throughput laboratory analytical tools to characterize a greater range of feedstocks and feedstock conditions rapidly and economically.
    - Move beyond composition-based material description to performance-based material measurements such as conversion efficiency and product yield.
- Advancing the State of Technology
  - Developing and demonstration of process specific for an emerging biomass industry

5. Future Work

- Design report update with 2012 accomplishements and “high-tonnage projects” will lock down the conventional design
- Ash
  - Include single-pass harvest systems
  - Develop predictive understanding/models of the relationship between sub-field scale variables and machinery performance related to soil contamination
- Storage
  - Develop predictive understanding of biomass storage
  - Update/refine storage BMPs as informed by R&D
  - Develop deployable applications/solutions
- Preprocessing
  - Develop technology/processes to control particle size distribution
- Transportation & Handling
  - Address handling issues that have historically been failure points for industry scale-up

Summary

- 6-years of R&D culminated in full-scale demonstration of the conventional feedstock design
  - R&D informed many changes to the initial 2007 design
  - This design should enable pioneer refineries
  - This design serves as a solid baseline for developing advanced systems
  - Demonstrated achievement of the he $35 feedstock cost target
- Harvest and Collection
  - Field-scale R&D has concluded that current machinery is capable of sustainable removal rates
  - Soil contamination is among the most significant challenges, but it is easily remedied with supporting data
- Storage
  - Isopleth method of moisture measurement greatly improves DML measurement/estimation
  - Laboratory simulation is informing mechanisms and kinetics of DML never before realized in field-scale studies
  - These mechanisms will inform predictive storage methods (no more black box), ultimately represented by shelf-life

Additional Slides

Responses to Previous Reviewers' Comments

- **Critical Success Factors:**
  - Reviewer Comments: They need to end up with methods/recommendations that will maintain quality and management of the moisture in the biomass. What will be the additional cost to manage the moisture?
  - Response: Research since the last Peer Review has focused on extending the moisture range of conventional, aerobic storage methods. In this approach, dry matter losses, compositional degradation, and moisture are managed by understanding the time-scale (discussed in terms of shelf-life, or "use by date") associated with these storage phenomena. This approach minimally increases storage cost, but adds additional monitoring and inventory control. Our research is translated to best management practices for biomass storage that are based on our current understanding of the relationship between biomass moisture going into storage and the characteristics of different storage systems. These BMPs are updated as research and our understanding progresses
  - Reviewer Comment: Structural sugars is a key measure of biomass quality. Are they working with conversion people as to what they want the product to be when in reaches the biorefinery?
  - Comment: Understanding and limiting compositional changes in storage is a major objective of our research. Rather that seeking input from biorefinery end users to define acceptable limits of degradation that define storability limits, we have been studying the rates and mechanisms/relationships of degradation that will ultimately lead to cost-effective mitigation strategies.

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Responses to Previous Reviewers' Comments

- **Technology Transfer and Collaborations**
  - Reviewer Comment: Who is the target audience for the results of the research? How will the results be transferred?
  - Response: We are ultimately interested in developing storage solutions that minimize losses and degradation at an acceptable cost for biomass feedstocks. In this case, our target audience is growers, biorefiners, and feedstock aggregators that will ultimately implement these solutions. For this purpose, the results of our research are communicated via best management practices that are updated as research and our understanding/recommendations progress. As researchers, we are also interested in transferring knowledge and discovery to the research community. Results are communicated to this audience via conference presentations and publications, both of which we produce as a product of our annual work plans.
- **Overall Impressions**
  - Reviewer Comment: the field data and lab storage simulators info are good. ensiling effort is appropriate but they did not give the recommendations on whether this is a good or bad practice.
  - Response: In our opinion, neither conventional aerobic storage nor anaerobic storage via ensiling are optimum solutions because neither address the problematic moist (20-30 moisture, wet basis) region that is common with biomass crops. Conventional recommendations would be aerobic storage for dry conditions and ensiling for wet conditions. This complicates the storage solution. Our research is focused on extending the moisture range of aerobic storage to provide a simple and economical solution that can be implemented under all conditions.

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Publications, Presentations, and Commercialization

- Kenney KL, Smith WA, Gresham GL, Westover TL. Perspectives on Biomass as a Feedstock for Existing Conversion Technologies. Biofuels 4(1), 111-127, 2013.
- Smith WA, Bonner IJ, Kenney KL, Wendt LM. Practical Considerations of Moisture in Baled Biomass Feedstocks. Biofuels 4(1), 95-110, 2013.
- Tumuluru, JS, Wright CT, Kenney KL, Hess, JR. A review on biomass densification systems to develop uniform feedstock commodities for bioenergy application, BioFPR, 2011.
- Hess, JR, Kenney KL, Wright CT, Perlack R, Turhollow A. Corn Stover Availability for Biomass Conversion: Situation Analysis. Cellulose, 16:599-619, 2009.
- Hess, JR, Wright CT, Kenney KL. Cellulosic Biomass Feedstocks and Logistics for Ethanol Production. Biofuels, Bioproducts and Biorefining, 1:181-190, 2009.
- Foust, T. D., K. N. Ibsen, D. C. Dayton, J. R. Hess, K. E. Kenney. 2008. “The Biorefinery.” Biomass Recalcitrance: Deconstructing the Plant Cell Wall for Bioenergy. Ed. Michael Himmel. Oxford:Blackwell, 2008.

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