FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

Case Study Brief

Task:	8.1 Feedstock Supply TEA
Title	TEA of corn stover storage options considering variable degradation within bale stacks
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Executive Summary:

The objective of this TEA was to estimate costs of delivered corn stover and level of degradation caused by changes in long-term storage design and to align storage cost estimates with characterization studies previously conducted by Task 2. A dynamic simulation model was developed in ExtendSim based on experiments conducted by Task 2 on corn stover bales and field observations in a storage study by Iowa State. The results of this model give ranges of improvements needed in biorefinery operations needed to justify increased investment in storage. It can also provide data to characterize the degradation level of biorefinery incoming feedstock streams for preprocessing and conversion TEAs to identify potential operational disruptions caused by the biomass condition.

Material Attributes	Processing Parameters	Outputs
Moisture content, bale size, bale density	Storage – level of protection	Fraction of delivered supply with (1) mild-to-moderate degradation and (2) moderate-to-severe degradation

Introduction

It has long been known that investment in better protection to keep corn stover drier during storage will reduce degradation - dry matter loss and changes in composition. Degradation impacts biorefinery costs in two critical ways – additional feedstock must be procured to make up for dry matter losses during storage and performance in downstream preprocessing and conversion operations in impacted, often negatively. The goal of this analysis is to estimate costs of delivered corn stover and level of degradation caused by changes in long-term storage design. Degradation levels will be selected to align with characterization studies previously conducted by Task 2.

Methods

This study is based on the former DuPont biorefinery in Nevada, IA. This scenario was selected to align with the corn stover bales studied in Task 2. This supply system (Figure 1) has also been well-documented in publications by the Darr Research group at Iowa State and in the BETO-funded fire risk project (Webb et al., 2018). Key parameters for this supply chain design are shown in Table 1. For this study, all storage changes were assumed to occur in long-term storage.

Table 1. Key parameters for this central Iowa corn stover supply chain modeling study

Parameter	Value
Biorefinery demand	1,000 dry tons/day[1]
Corn stover yield	1.6 dry tons/acre[1]
Long-term storage site design	2 pads per storage site 25,000 bales/pad
Harvest cost (windrowing, baling, field edge stacking, loading/unloading)	$49.54/dry ton[2]

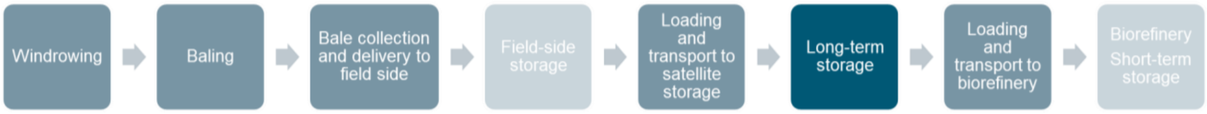

Figure 1. Central Iowa corn stover supply chain, the basis for this modeling study.

Table 2. Storage facility costs based on Turhollow et al. (2009) adjusted for 2019 costs.

Long-term storage design	**$2019/dry ton**
Uncovered on gravel pad	$5.11/dry ton
Tarped on gravel pad	$7.40/dry ton
Covered, open-sided steel-frame structure	$16.44/dry ton

Assigning degradation levels

Prior characterization studies in Task 2 revealed significant differences in quality attributes including changes in cell wall structure and surface attributes (Bose et al., 2020; Groenewold et al., 2020; Li et al., 2020). In this study, we correlated these changes with moisture content and visual changes observed within a stack of corn stover bales over a one-year storage cycle in an Iowa State study (Darr et al., 2018). Based on these studies, and in consultation with Task 2 researchers, we considered two broad categories of degradation: mild-moderate and moderate-severe in this analysis.

A dynamic simulation model was developed in ExtendSim to predict the cost of delivered corn stover and the mass fractions of the two degradation categories: mild-moderate and moderate-severe. Degradation level was determined by the moisture content during most of the storage period. Regions of the bale stacks where moisture stayed above 20% for long periods of time were assumed to be in the moderate-severe category. The rest of the stover was assumed to experience only mild-moderate degradation.

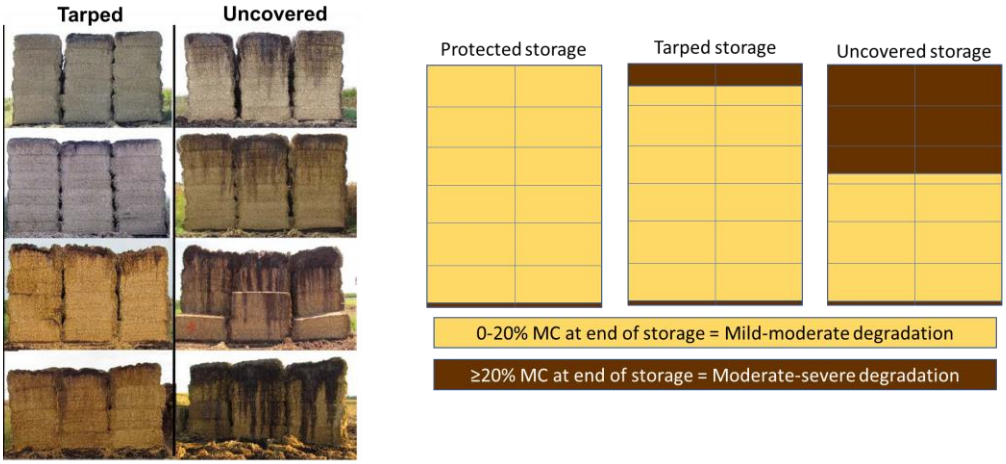

Figure 2. Based on Task 2 characterization studies and bale stack studies by Iowa State (left photos, above), two categories of degradation within corn stover bales were considered in the simulation model: mild-moderate and moderate-severe. The amount of moderate-severe degradation within the stack increases with decreasing level of protection.

Simulation model

During bale storage, some moisture wicks upward from the ground. Although wicking is not a linear process, due to lack of data on how moisture migrates upward through stacks we used a simple linear model to predict moisture content on the bottom of the stack. The height of wicked moisture was assumed to increase linearly from 0 cm at the beginning of storage to the max wicking height observed by Darr et al. (2018) as shown in Figure 2.

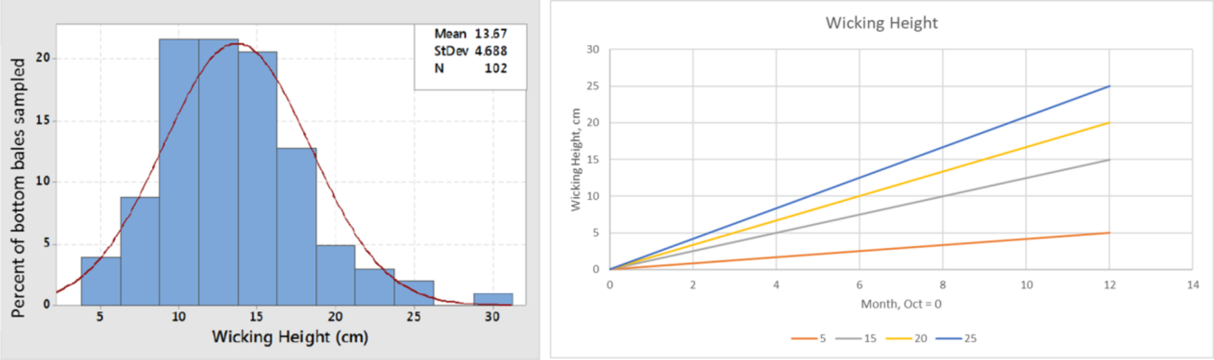

Figure 3. A simple linear model (right) for wicking height at the bottom of the corn stover stack was developed based on observations by Darr et al. (2018) in a year-long storage study.

The depth of severe degradation at the top of the stack was estimated using an exponential saturation function, Equation 1. The function shape and estimates of parameters k_1 and k_2 were determined based on observations in Darr et al. (2018). The k_1 values represent the level of protection offered by the storage treatment and k_2 values represent the rate of moisture migration which depends on ambient weather conditions.

$$y = k_1(1 - e^{k_2 x}) \qquad \text{Eqn. 1}$$

Where y = depth of severe degradation, from top of stack (ft)
k_1 = max curve height
k_2 = steepness of curve
x = month from start of storage period.

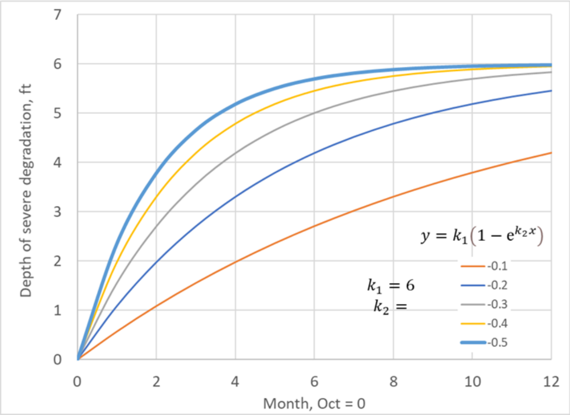

Figure 4. Based on observations by Darr et al. (2018) a saturation exponential function was developed in this study to predict the depth of severe degradation from top of a stover bale stack at month x from the start of storage.

One of the significant cost impacts of feedstock degradation during storage is the need to acquire additional biomass to meet biorefinery demands. In this simulation model, with increasing degradation, the supply chain radius increased to accordingly.

Results and Discussion

Figure 5 shows model behavior for two scenarios of the same storage design. In the top graph, wetter weather conditions, $k_1 = 6$ and $k_2 = -0.6$. In the bottom graph, drier weather conditions, $k_1 = 6$ and $k_2 = -0.1$. Over the duration of the storage period, the amount of severely degraded material increases until it reaches steady state conditions. The rate of increase is determined by the k_2 parameter, representing ambient weather conditions.

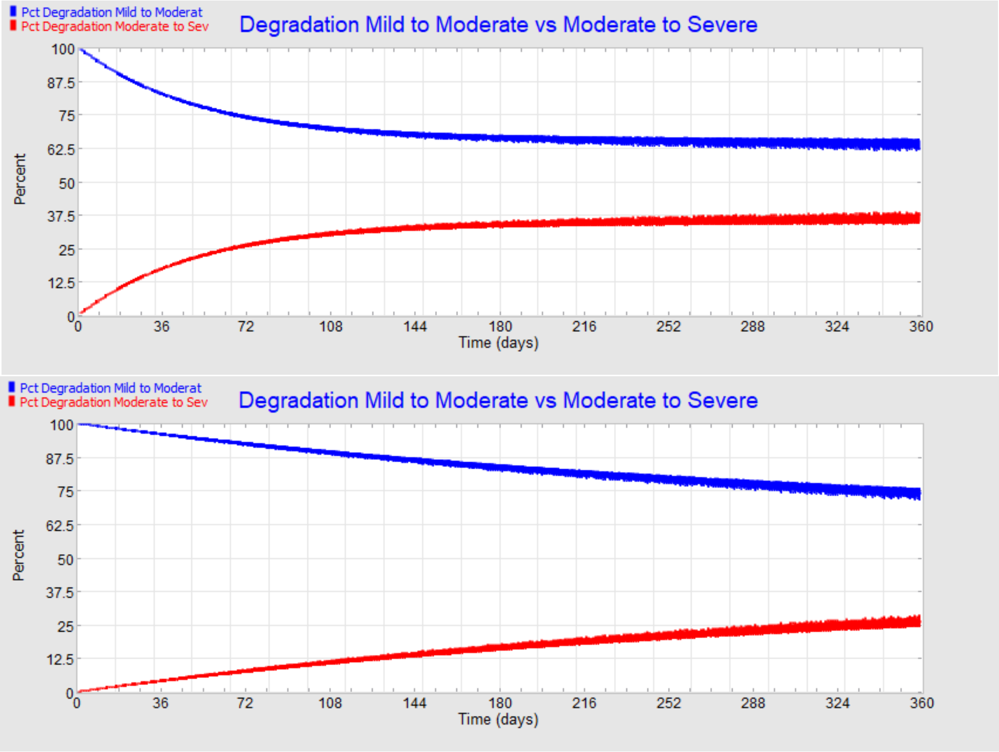

Figure 5. Model behavior for two scenarios: wet weather conditions (top) and dry weather conditions (bottom).

Figure 6 shows contour plots of model results for combinations of storage design and weather conditions. Selecting the appropriate level of protection for the ambient conditions minimizes storage losses and costs.

Table 3 shows the estimated costs of stover at biorefinery gate, accounting for variable degradation within bale stacks for uncovered, tarped, and covered storage designs. If a biorefinery has costs reductions in preprocessing or conversion of approximately $1-2/dry ton for tarped stover or $10 for covered storage, the higher investment in storage protection is justified.

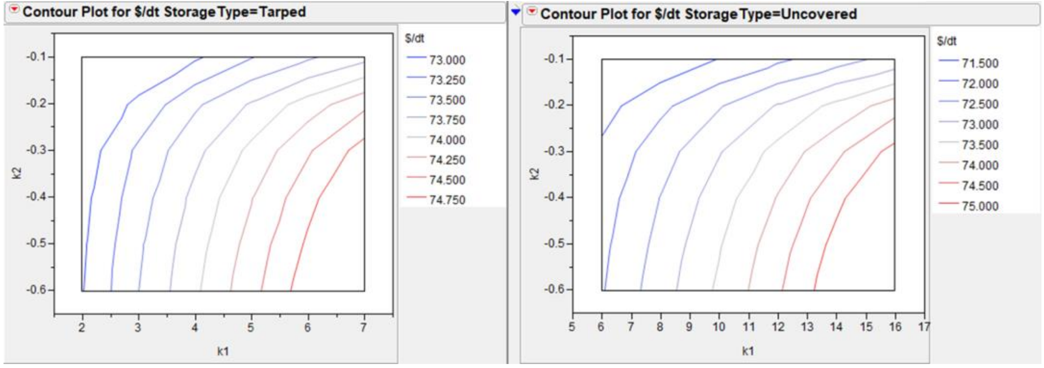

Figure 6. Model results for tarped vs uncovered storage. Maximum depth of moderate-to-severe degradation is represented by the k_1 value and weather conditions are represented by the k_2 (decreasing values representing drier conditions).

Table 3. Estimated costs of stover at biorefinery gate, accounting for variable degradation within bale stacks

Storage Design	Wetter conditions	Drier conditions
Uncovered on gravel pad	$72-74/dry ton	$70-73/dry ton
Tarped on gravel pad	$73-74/dry ton	$72-73/dry ton
Covered, open-sided structure	$82/dry ton	

Conclusion and Next Steps

The next steps in this research are to prepare model outputs to be inputs for preprocessing and conversion TEAs that will explore how mildly- and severely- degraded stover behaves in the biorefinery. In previous storage TEA models, it was assumed that all biomass received by the biorefinery are of the same condition. This oversimplification means that preprocessing and conversion TEAs can not account for the dynamic changes in biomass condition which lead to operational disruptions. The approach developed here makes it possible to predict the impact of biomass changes during storage on dynamic performance of biorefinery operations.

We also hope that this study can be used to develop storage study designs for future field projects to better parameterize the model developed here. We hope to publish results and share with collaborators to encourage additional instrumentation and advanced sampling in biomass storage studies.

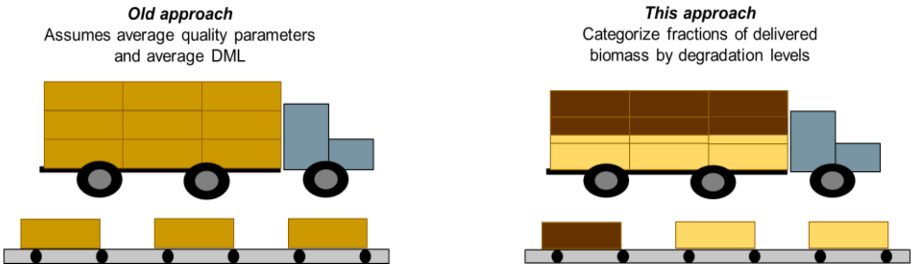

Figure 7. Prior TEA models that use average estimates of losses and composition miss the operational impacts of biomass variability. The approach developed in this study makes it possible to predict the impact of biomass changes during storage on dynamic performance of biorefinery operations.

References

Bose, E., Leal, J. H., Hoover, A. N., Zeng, Y., Li, C., Ray, A. E., Semelsberger, T. A., & Donohoe, B. S. (2020). Impacts of Biological Heating and Degradation during Bale Storage on the Surface Properties of Corn Stover. *ACS Sustainable Chemistry & Engineering*, *8*(37), 13973–13983. https://doi.org/10.1021/acssuschemeng.0c03356

Darr, M. J., Webster, K., & Bearden, R. (2018). <i>Storage Dynamics and Lignocellulosic Degradation in Industrial Biomass Storage</i> *2018 Detroit, Michigan July 29 - August 1, 2018*. 2018 Detroit, Michigan July 29 - August 1, 2018. https://doi.org/10.13031/aim.201800219

Groenewold, G. S., Hodges, B., Hoover, A. N., Li, C., Zarzana, C. A., Rigg, K., & Ray, A. E. (2020). Signatures of Biologically Driven Hemicellulose Modification Quantified by Analytical Pyrolysis Coupled with Multidimensional Gas Chromatography Mass Spectrometry. *ACS Sustainable Chemistry & Engineering*, *8*(4), 1989–1997. https://doi.org/10.1021/acssuschemeng.9b06524

Li, C., Kerner, P., Williams, C. L., Hoover, A., & Ray, A. E. (2020). Characterization and Localization of Dynamic Cell Wall Structure and Inorganic Species Variability in Harvested and Stored Corn Stover Fractions as Functions of Biological Degradation. *ACS Sustainable Chemistry & Engineering*, *8*(18), 6924–6934. https://doi.org/10.1021/acssuschemeng.9b06977

Turhollow, J., Webb, E., & Sokhansanj, S. (2009). *Cost Methodology for Biomass Feedstocks: Herbaceous Crops and Agricultural Residues* (ORNL/TM-2008/105). Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States). https://doi.org/10.2172/969956

Webb, E., Chambers, J., & Webster, K. (2018). Addressing Fire Risk in Biomass Storage. *Resource Magazine*, 4.