Idaho National Laboratory

Technical Memorandum

To:

Title: Enabling Sustainable Landscape Design for Continual Improvement of Operating Bioenergy Supply Systems

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Platform: Feedstock/Analysis

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Purpose/ Summary The purpose of this technical memo is to communicate an established cost baseline for logistics operations employed in the project titled "Enabling Sustainable Landscape Design for Continual Improvement of Operating Bioenergy Supply Systems." The cost baseline is established for the case of corn stover and for switchgrass, and is based on operations of current management practices.

The cost baseline will likely be used as a reference point for management practices employed in the project going forward. Once cost of utilized management practices are estimated, the baselines modeled herein will enable cost comparisons such that tracking of project success and economic feasibility for implementation can be gauged.

Landscape designs must be evaluated at the system level to understand their impacts on the overall supply chain because changes cascade through the system from the initial harvest and can positively or negatively propagate throughout the system. This report provides a feedstock-logistics cost baseline analysis to evaluate landscape design. The base case analysis assumed two separate supply systems and monoculture cropping for corn stover and switchgrass. Base case analysis performed site-specific techno-economic analysis (SSTEA) to understand impact of actual field shape, field efficiency, harvesting efficiency and biomass quality on feedstock logistics cost. SSTEA estimates the feedstock logistics cost per ton of raw biomass delivered to the reactor throat of a biorefinery in dollars per dry matter ton ($/DMT). ANTARES Group Incorporated and the FDC Enterprises provided harvesting field data from projects that involved biomass harvesting. Switchgrass-harvesting data were collected from a DOE-sponsored "Growing Bioeconomy Markets: Farm-to-Fuel in Southside Virginia" project. Corn-stover data were collected from the DOE co-sponsored Biomass Alliance for Logistics Efficiency and Specifications (BALES) project. Eight fields are selected for switchgrass SSTEA. Nine fields are selected for corn stover SSTEA.

Switchgrass base analysis for different fields shows that logistics cost are highly variable across the fields. The modeled logistics cost—the sum of harvest and collection cost, field-side storage cost, transportation and handling cost from field to biorefinery, preprocessing cost, and reactor in-feed and storage cost, but excluding grower payment—varies from $43.45–93.00/dry ton. The variability in logistics costs are due to cumulative impact of variability in harvesting methods, field efficiency, field shape, yield, biomass quality, and bulk density of material. The delivered feedstock cost (grower payment + logistics cost) of switchgrass varies from $66.26–155.25/dry ton. Among different logistics operations, harvest and collection costs are highly variable among different fields.

The modeled logistics cost (sum of harvest and collection cost, field side storage cost, transportation and handling cost from field to biorefinery, preprocessing cost, and reactor in-feed and storage cost) for corn stover varies from $39.55–59.71/dry ton. The variability in logistics cost are due to cumulative impact of variability in baling rate, bale density, yield, biomass quality, and bulk density of material. Assuming an estimated grower payment cost of $35.61/dry ton, the delivered feedstock cost (grower payment + logistics cost) of switchgrass varies from $75.16–95.32/dry ton. Among different logistics operations, harvest and collection costs are highly variable among different fields.

Base case analysis for both switchgrass and corn stover shows that switchgrass logistics costs are highly variable. This is primarily due to the variability of harvesting operations and efficiency and biomass yield. In the base analysis, it was assumed that both switchgrass and corn stover are separate logistics system and monoculture cropping. However, incorporating both switchgrass and corn stover into a landscape design will create several logistical challenges due to additional activities not seen in a design based on a monoculture cropping system. Incorporating multiple crops into a landscape will likely create complex-shaped subfields, which will impact harvesting and collecting operations. Concurrent activities for both crops in a given field during planting and harvest may require additional equipment for simultaneous planting of row crops and harvest of energy crops, as well as additional labor. Although concurrent activities can be mitigated by temporal separation of planting and harvest times, additional equipment hours may be needed, which would reduce service life and increase maintenance costs for existing equipment. In the future, we will update the analyses based on additional logistical barriers in the landscape design incorporating multiple crops.

1. INTRODUCTION

Landscape designs must be evaluated at the system level to understand their impacts on the overall supply chain because changes cascade through the system from the initial harvest and can positively or negatively propagate throughout the system. For example removal of moisture early in the supply chain could reduce the downstream drying requirement, lowering cost and greenhouse gas emissions (Muth, D.J. et al., 2013). An in-depth understanding of biomass logistics as impacted by evolving landscape designs with multi-feedstock is important. It is critical to perform feedstock logistics analysis capturing the intricacies of multiple land management practices, feedstock production and collection practices, extended harvest windows, and potential complications of handling multiple feedstocks within a logistics operation.

Technology and management that support integrated landscape design (ILD) for the production of bioenergy crops are important for at least three reasons. First, new market opportunities for farmers in energy commodity crops suggest an economic potential that may improve farm-level economics. Emerging research findings imply that implementing ILD can offset financial risk that farmers face and can, in some cases, improve farmer profitability (Bonner et al., 2016, Nair et al., 2017). Second, implementing ILD has the potential to improve current farming practices in such a way that the effects of environmental degradation can be reversed. For example, English et al. (2013) found that, in some cases, removal of corn stover is beneficial to soil health while, in other cases, some amount of stover must remain to preserve soil quality. Third, research findings suggest that ILD must play an important role in the sustainable scale up of mobilizing bioenergy resources sufficient to support a thriving bioeconomy (Muth et al., 2013, Bonner et al., 2014, Nair et al., 2017).

In tandem to ILD, technology development and management evolution is the concomitant development of cost-estimating methodologies for measuring accompanying economic consequences. Understanding cost impacts of ILD development is key to projecting economic feasibility of ILD as a method for advancing bioenergy through energy-crop production. This document is the first in a three-part series that will be unfolded through the end of the project timeline for “Enabling Sustainable Landscape Design for Continual Improvement of Operating Bioenergy Supply Systems,” (hereafter, “the project”). This document establishes a cost baseline, i.e., a reference point of comparison, for technologies and management options evaluated by field researchers in the project. The document reflects cost components originating at the field through to the point of the reactor throat at a local biorefinery.

Earlier research findings suggest that ILD is most applicable to marginal lands, that is, areas of a farmer's field where factors such as poor soil quality, slope, or other features constrain profitable production of traditional row crops (Muth et al., 2012, Bonner et al., 2016, Nair et al., 2017). Bearing this in mind, the reference cases are established based on the impact of field obstructions (e.g., stream or gravel beds) and boundary irregularities (non-uniform shapes). Obstructions and irregularities translate to reduced field efficiency of equipment used for field operations. So the reference cases establish a range of field efficiencies such that obstructions or irregularities of fields enrolled in the project will likely fit into one of the modeled field-efficiency cases. Further, the reference cases are divided into two scenarios: one for corn stover and one for switchgrass. The modeled reference cases provide a reference of comparison for fields enrolled in the project once harvest data become available in future project years. Cost analysis on project harvests will then be series two and three of the three-part cost series noted previously.

One can think of using the reference cases in this document in the following way: Given an enrolled project field, the farmer who owns that field would likely observe some irregularity in the field that suggests that the field is a good candidate for ILD. Attributes of the field can be ascertained to estimate approximate field efficiency; then, field performance under ILD can be compared to one of the reference cases listed in this document that most closely resembles the field efficiency of the candidate field and the corn stover crop the field had in it prior to implementing ILD. In order to further understand how to apply the analysis of the document, the organization proceeds as follows. Section 2 describes the assessment of supply and logistics. In it, the text describes a data limitation and how that was overcome by using data from a similar research activity in Virginia. Section 3 discusses the design of the feedstock logistics system, which is assumed in order to conduct the cost analysis. Section 4 presents cost analysis for the reference cases by feedstock scenario, and Section 5 summarizes and concludes.

2. ASSESSMENT OF FEEDSTOCK LOGISTICS

Base case analysis evaluated ILD at the system level to understand their impacts on the overall supply chain, because changes cascade through the system from the initial harvest and can positively or negatively propagate throughout the system. The geographic region wherein to target the logistics analysis is the region of the project site, but data needed for baseline characterization are not yet available. Enrolled fields into the project have not been enrolled with sufficient time such that harvest and other operations have been completed. The complete set of input data from the grower's field to the biorefinery are required in order to estimate the feedstock logistics cost. Fields now enrolled will generate biomass that will be harvested in future project years and will thus generate harvest and other data that will contribute the future series of this cost analysis. This data gap required a "work-around" in order to compute baseline conditions from which reference cost comparisons can be ascertained. The work-around requires that the fields for which data are available be similarly close approximations of the fields likely to be enrolled in the project study site. That is, proxy fields should have in-field obstructions and irregular boundaries so that data from the proxies can be utilized in estimating field efficiencies for such field irregularities. Antares Group led such a project in Virginia where fields of switchgrass were good proxy candidates for Iowa project fields.

2.1 Selected Fields for Base Case Analysis

Cost inputs in the simulated multi-pass harvest and collection system used in this analysis are based on empirically collected switchgrass and corn stover harvesting data using conventional equipment. ANTARES Group Incorporated and the FDC Enterprises provided the harvesting field data from projects that involved biomass harvesting.

2.1.1 Switchgrass

FDC Enterprises collected switchgrass harvest data for a DOE-sponsored “Growing Bioeconomy Markets: Farm-to-Fuel in Southside Virginia” project. Virginia Tech Conservation Management Institute initiated the project in 2006 to use switchgrass to enhance quail habitat in the field, but also to use the material as a fuel once harvested (DOE, 2017) The grass was supplied to Piedmont Geriatric Hospital and directly combusted in the hospital’s boiler. For that project, FDC Enterprises planted the Cave-in-Rock switchgrass cultivar in 2008, 2009, and 2011 (Circle, F., 2018). Cave-in-Rock is an upland native switchgrass species which provides a high yield, which is why it is used for biomass production or as wildlife habitat (Seeds, E., 2018). Biomass was first harvested in 2010 on the first–planted fields, and the direct combustion at the hospital started in 2011.

Switchgrass harvesting field data were collected between October 1st and November 18th, 2017. The biomass was mowed and conditioned, raked, and baled. Each operation produced field operation maps in Geographic Information Systems (GIS) from the data collected by Global Navigation Satellite System (GNCC) data loggers in the machinery. Those tracking systems registered the time of on-field operations at one-second time increments, but did not register the time and location during no operations (for, example, when turning or backing up). The operators filled out additional forms on their mobile devices to mark when an operation started and finished and the distances covered for each field and operation. ANTARES combined the spatiotemporal data and data from the smart sheets with additional measurements, like weight of the bales or moisture content of the biomass. The data were quality-checked and used to calculate average productivity, fuel consumption, and yield. Eight fields (Figure 1) were selected to perform logistics cost analysis.

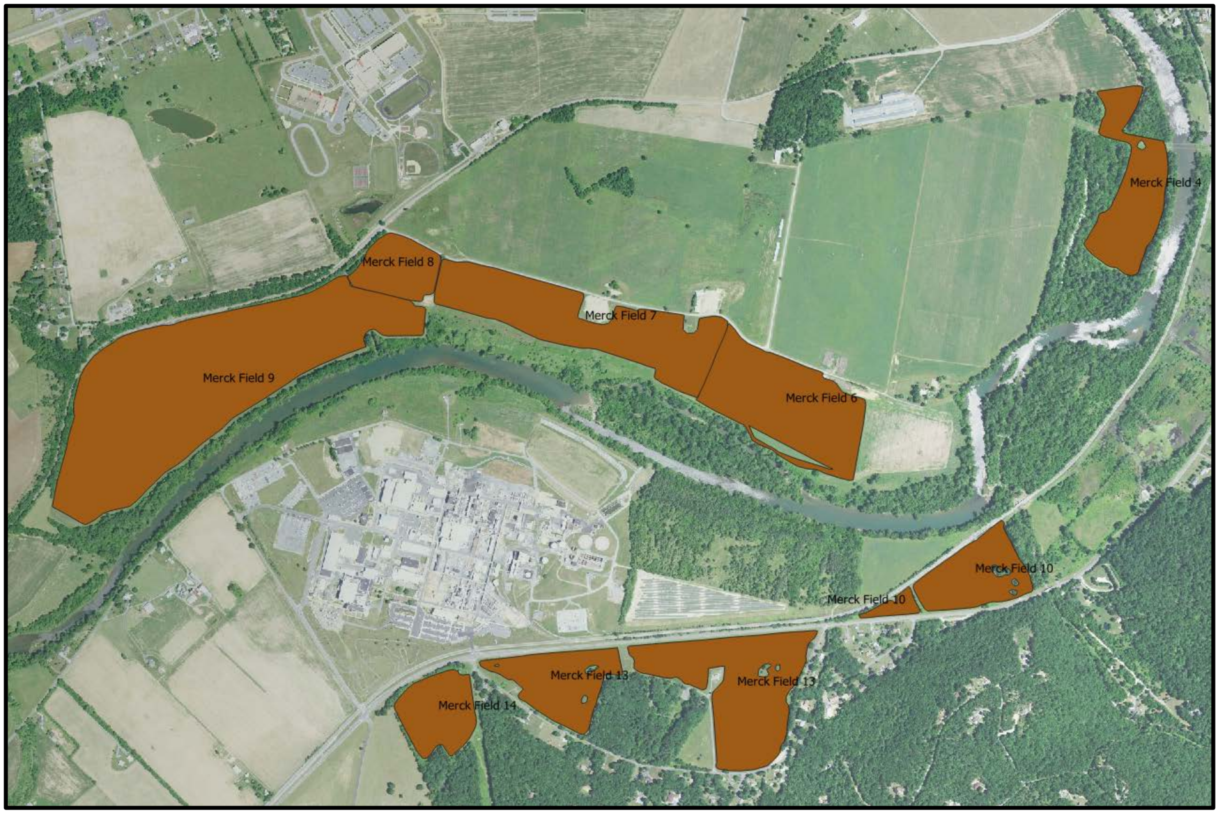

Figure 1: Selected eight fields for logistics cost analysis. Fields are: Merck 4, Merck 6-10, Merck 13-14.

2.1.2 Corn Stover

Nine fields were selected for corn-stover base case analysis. Fields are primarily located in Iowa or near the Iowa state boundary (Figure 2). Figure 3 shows the shape of the selected fields. The selected fields are from another DOE-funded project. Corn stover was harvested as part of the DOE co-sponsored Biomass Alliance for Logistics Efficiency and Specifications (BALES) project, for which FDC Enterprises harvested the biomass. The project started in 2013 to find harvesting and processing strategies that reduce biomass harvesting cost (Comer 2017). Biomass was supplied to the Poet-DSM Liberty cellulosic ethanol facility. Corn stover was collected in 2014, and harvest was conducted between October 17 and December 17, 2014. The same data-processing was performed for corn stover harvest as for switchgrass. The only difference was that mowing and raking were not required on the considered fields; thus, only baling data was collected.

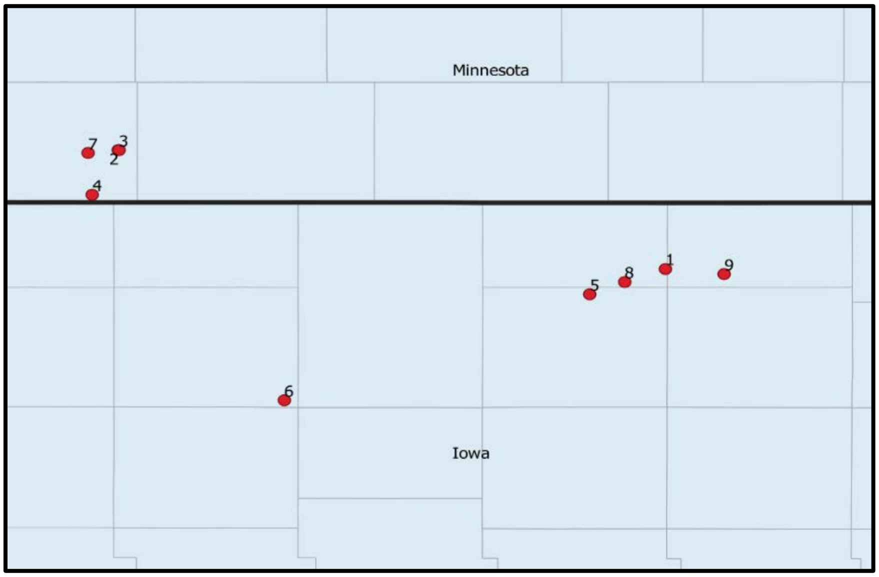

Figure 2: Selected locations of nine fields for corn-stover base case analysis.

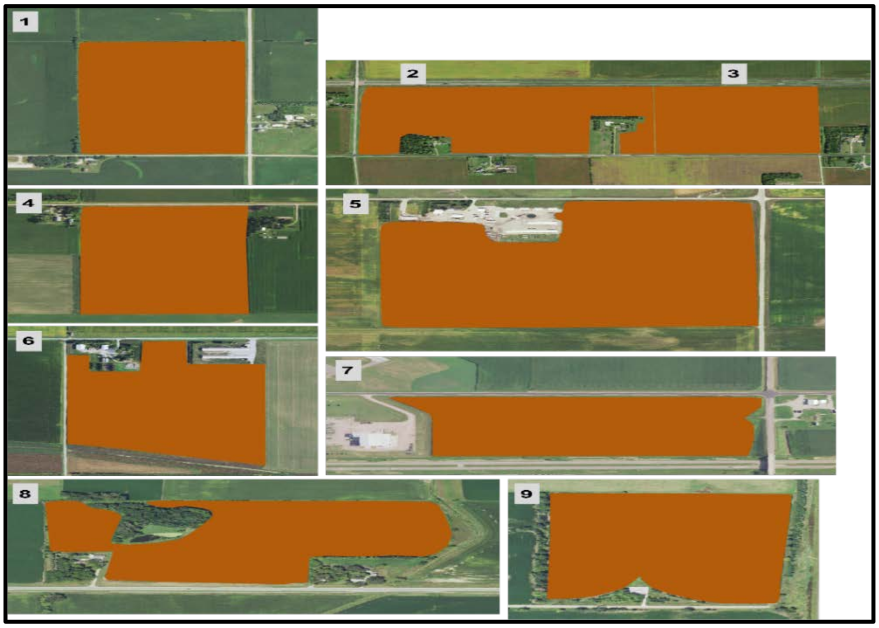

Figure 3: Shape of the selected fields for corn stover base case analysis.

3. FEEDSTOCK LOGISTICS DESIGN FOR SSTEA

Feedstock supply systems are highly complex systems of operations required to move and transform biomass from a raw harvested material at the point of production into a formatted, on-spec feedstock at the throat of the conversion reactor. Feedstock logistics can be broken down into individual operations of harvest and collection, storage, transportation, preprocessing, and queuing and handling. Site-specific techno-economic analysis (SSTEA) estimates the feedstock logistics cost per ton of raw biomass delivered to the reactor throat of a biorefinery in dollars per dry matter ton ($/DMT).

Feedstock logistic costs can be highly variable due to a high variability in the logistic operations. Logistical operations are different for different types of biomass. Typical factors that cause the logistics variability are types of biomass, different harvesting methods, storage locations, desired bale format (round/square bale), feedstock quality variations, different harvesting methods, different types of preprocessing, etc. SSTEA developed a logistics design for base case analysis. The primary biomass that are considered in the integrated landscaped design are switchgrass and corn stover. Therefore, SSTEA focused on logistics of switchgrass and corn stover. The modeled feedstock logistics for SSTEA is shown in Figure 4. Switchgrass is collected by a multi-pass harvesting method, whereas corn stover harvest is assumed to be available via two-pass harvesting methods. The two-pass collection method eliminates the windrowing step and thereby reduces the potential for soil contamination (Shinners et al., 2012, Birrell et al., 2014). The baled biomass delivered from roadside storage is preprocessed by using two-stage grinding. Feedstock logistics are designed for a plant with the capacity of 800,000 dry ton/year. All unit operations, from field to reactor throat, including harvesting and collection, storage, transportation, preprocessing, and handling and queuing are discussed in this section.

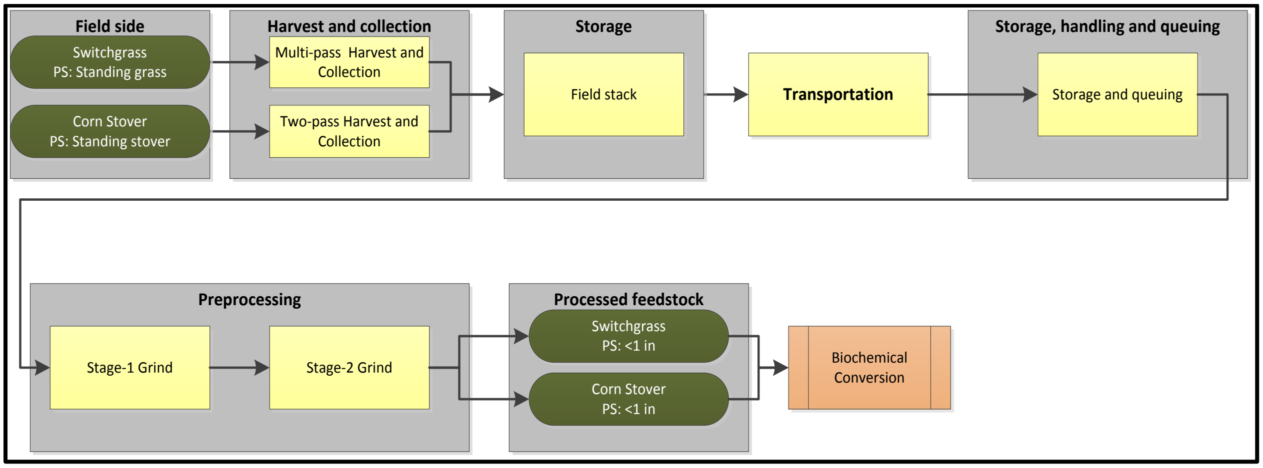

Figure 4: The modeled feedstock supply system for SSTEA. PS=Particle size.

3.1 Harvest and Collection

Harvest and collection processes involve gathering and removing biomass from the field. ANTARES Group, Incorporated, and the FDC Enterprises provided the harvesting field data from projects that involve biomass harvesting. Conventional harvesting and collection equipment were utilized for switchgrass and corn-stover harvesting and are listed in Appendix A (Table A.2-A.4).

3.1.1 Switchgrass

FDC Enterprises collected switchgrass harvest data for a DOE-sponsored "Growing Bioeconomy Markets: Farm-to-Fuel in Southside Virginia" project (DOE, 2017). Different harvesting methods were applied depending on fields. Figure 5 shows the various harvesting scenarios across different fields. Scenario-1 represents the harvesting method when no macerator was used for in-field conditioning. Macerator is combined with mowing in Scenario 2. In this scenario macerator was run behind the mower.

The macerator helps crack the stems so that they dry faster and more thoroughly. In Scenario 3, the maceration operation is performed separately to dry down the biomass. Raking, baling, and road siding operations are common to all three scenarios. A square baler is used in all scenarios. Details of equipment used in harvesting and collection are listed in Appendix A (Table A.2-A.4).

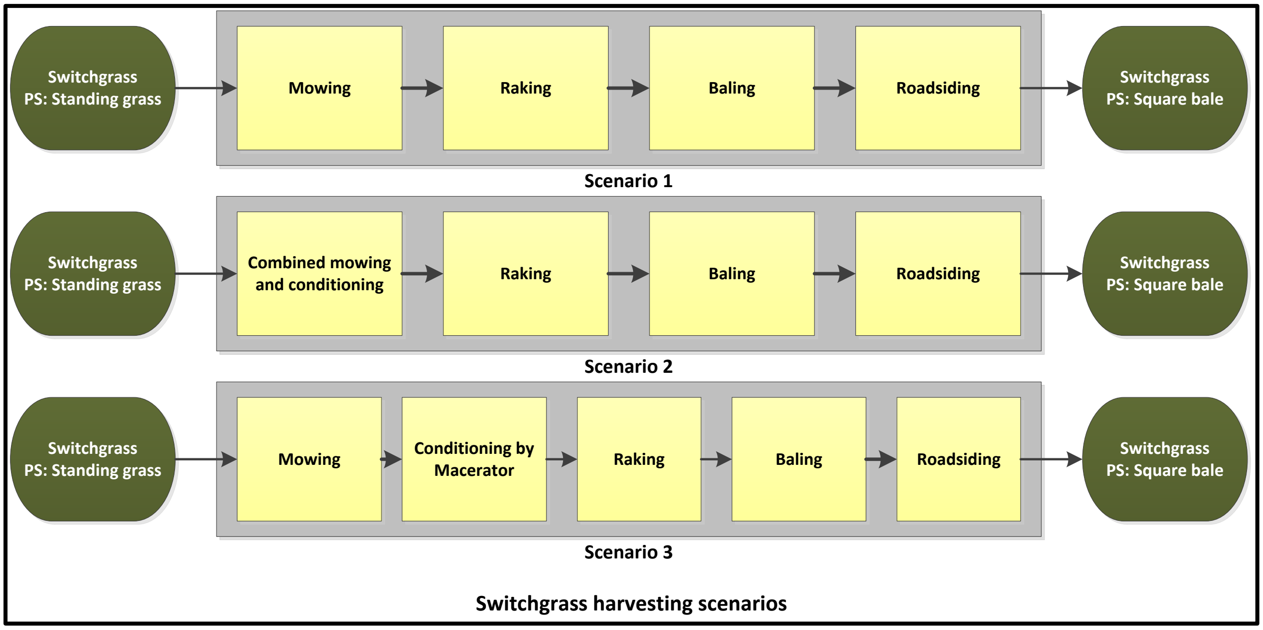

Figure 5: Various switchgrass harvesting scenarios across different fields. PS=Particle size.

Table 1 and Table 2 show the field data under various harvesting scenarios used to perform SSTEA. Four of the eight maceration operations were performed in a separate pass, during which a macerator was separately used to dry the biomass. Maceration was combined with mowing in the harvesting operations of Merck 9, Merck 13, and Merck 14. No macerator was used in Merck 10. Field efficiency was calculated based on time-series analyses using the empirical data and compared results to field-boundary data (details are described in Appendix B). Empirical data (Table 2) show that switchgrass yield varies from 0.69 to 4.27 dry ton/acre. The number of bales processed per hour from field to field varies from 8.7 to 38.13. Primary feedstock-quality data that were collected from the field study are biomass moisture and bale density. Data show that moisture and bale density varies from 12.5 to 19% and 10.7–14.67 lb/ft^3 (dry basis) across the fields.

Table 1: Empirical harvesting data from different fields.

Field name	Mowing field efficiency	Macerator engagement	Macerator field efficiency	Raking field efficiency	Baling rate (bale/hr)
Merck 4	0.79	Separate pass	0.84	0.84	10.35
Merck 6	0.87	Separate pass	0.89	0.89	28.45
Merck 7	0.81	Separate pass	0.87	0.87	30.82
Merck 8	0.75	Separate pass	0.79	0.79	38.13
Merck 9	0.87	Run behind the mower	Same as mowing	0.87	25.42
Merck 10	0.77	Not used	Not applicable	0.78	32.22
Merck 13	0.78	Run behind the mower	Same as mowing	0.78	35.29
Merck 14	0.79	Run behind the mower	Same as mowing	0.80	8.70

Table 2: Empirical yield, bale-moisture and bale-density data from different fields.

Field name	**Total area associated with field (acre)**	**Yield (dry ton/acre)**	**Avg. bale MC (%)**	**Avg. dry bale density (lb/ft^^{3})**
Merck 4	19.2	0.89	17.50	10.70
Merck 6	34.7	4.27	12.50	11.23
Merck 7	37.5	2.99	16.00	11.03
Merck 8	9	3.52	17.00	10.81
Merck 9	93.2	2.43	16.20	11.23
Merck 10	16.2	2.78	15.00	11.87
Merck 13	49.5	0.69	19.00	11.81
Merck 14	12.5	2.56	14.50	14.67

3.1.2 Corn Stover

As discussed above, corn stover was harvested as part of the DOE co-sponsored BALES project. FDC Enterprises harvested the biomass. The project started in 2013 to find harvesting and processing strategies that reduce biomass harvesting cost (Comer, 2017). A two-pass collection method is deployed for base case SSTEA analysis. In this method (Figure 6), the combine drops the material other than grain (MOG) into a loose windrow, which is followed by a separate baler. The two-pass method is utilized by POET-DSM's Advanced Biofuels' Project Liberty.

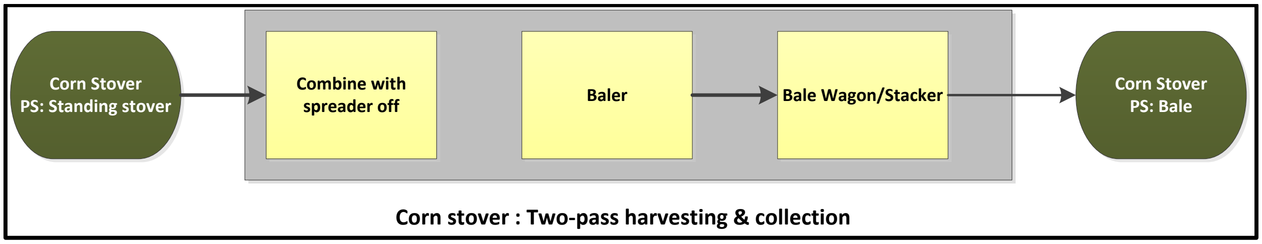

Figure 6: Corn-stover harvesting and collection method for the SSTEA.

Table 3 shows empirical harvesting, yield, and biomass-quality data associated with nine different fields. Empirical data show that corn-stover yield varies from 0.31 to 1.71 dry ton/acre. The number of bales per hour from field to field varies from 9.68 to 30.97. Primary feedstock-quality data that were collected from this field study were biomass moisture and bale density. Data show that moisture and bale density varies from 13 to 23% and 10.7–13.08 lb/ft^3 (dry basis) across the fields.

Table 3: Empirical baling rate, yield, bale-moisture, and bale-density data from different fields.

Field ID	Total area associated with field (acres)	Baling rate (bale/hr)	Yield (dry ton/acre)	Avg. bale MC	Avg. dry bale density (lb/ft^3)
FDC Enterprises,467916	304.35	16.27	0.75	16.67	12.30
FDC Enterprises,467827	219.64	30.91	1.47	13.00	12.01
FDC Enterprises,467919	235.39	25.79	1.71	16.14	13.08
FDC Enterprises,466650	316.66	30.97	0.76	14.00	12.34
FDC Enterprises,466160	127.46	14.27	0.70	15.00	12.14
FDC Enterprises,465757	57.66	16.78	0.99	15.00	11.91
FDC Enterprises,467162	117.01	12.86	0.80	19.67	10.70
FDC Enterprises,467907	165.24	13.37	0.31	23.00	11.85
FDC Enterprises,467263	49.79	9.68	1.13	19.67	12.86

3.2 Storage

Storage involves stockpiling material to provide an adequate lead time for downstream processes and accumulating material quantities for economical transportation. Storage may include diverse infrastructure, including cement, gravel, or asphalt pads, silos, storage bins, tarps, or plastic wrap. Biomass storage systems consider the moisture and dry-matter loss of stored material. Storage design assumptions in the field and at the biorefinery for this analysis are listed in the Appendix A (Table A.5 and A.7). Dry-matter losses incurred during storage were estimated based on 3-month storage tests at INL storage simulators, with initial moisture contents ranging from 20 to 52%.

3.3 Transportation and Handling

Transportation and handling include all processes involved in movement of material from multiple local locations to a centralized location (such as a preprocessing facility or biomass depot co-located with biorefinery) and include processes such as loading, trucking, and unloading. An advanced load-securing system is assumed to be used to replace the intense and slow physical labor used to secure a load of bales with a faster, more efficient loading method. Average transportation distance for this SSTEA is assumed to be 50 miles. Details of transportation and handling design assumptions for this analysis are listed in Appendix A (Table A.6).

3.4 Preprocessing

Feedstock preprocessing cost is affected by feedstock characteristics such as moisture, desired particle size, and format. The purpose of preprocessing is to alter the moisture content and format of the incoming biomass to meet requirements of the conversion process. Preprocessing can also be utilized to adjust biomass quality attributes that impact the operational reliability of biorefinery feeding equipment (such as grinder throughput, flow in bins and hoppers, reliability of feeding to conversion reactors, etc.), to mitigate particle size, moisture and compositional variability in the incoming biomass (these lead to conversion-process upsets), and to mitigate variations in biorefinery product yields (relative composition of convertible versus inert biomass entering the conversion process).

Biomass preprocessing in this SSTEA includes two-stage size reduction. The first stage of the size-reduction process takes the as-received biomass and converts it through grinding into a product that can be further preprocessed. The role of the second-stage grinder is to reduce the particle size further in order to meet particle-size requirements. For this SSTEA, one inch is the target particle-size specification. Results from the process testing from BALES Project (Comer 2017) at INL PDU were used for the prepressing throughput and energy consumption for two-stage grinding. The prepressing throughput and energy consumption were measured based on a 3-inch screen at Stage-1 grinding, a one-inch screen at second stage grinding, and an average 2% moisture loss between first and second stage grinding.

Table 4 shows the preprocessing data for switchgrass base case analysis for different fields. Input moisture from different fields was taken into account while energy consumption and throughput were measured. Test data at INL's PDU show that preprocessing throughput and energy consumption for Stage-1 grinding vary from 4.54–5.24 dry ton/hr and 6.4–19.91 kwhr/dry ton, respectively. Similarly, preprocessing throughput and energy consumption at Stage-2 grinding vary from 3.89–5.02 dry ton/hr and 6.14–7.09 kwh/dry ton, respectively.

Table 4: Preprocessing data for switchgrass base case analysis.

Field name	Moisture after storage	Stage-1 grinding (3-in. screen size)		Moisture after first stage grinding	Stage-2 grinding (1-in.screen size)	
		Measured throughput (dry ton/hr)	Measured energy consumption (kwhr/ton)		Measured throughput (dry ton/hr)	Measured energy consumption (kwhr/ton)
Merck 4	15.00	4.54	19.91	13.00	3.89	7.09
Merck 6	10.00	5.24	6.44	8.00	5.03	6.14
Merck 7	13.50	4.97	6.58	11.50	4.67	6.73
Merck 8	14.50	4.54	19.91	12.50	4.67	6.73
Merck 9	13.70	4.97	6.58	11.70	4.67	6.73
Merck 10	12.50	4.97	6.58	10.50	4.86	6.38
Merck 13	16.50	4.54	19.91	14.50	3.89	7.09
Merck 14	12.00	4.97	6.58	10.00	4.86	6.38

Table 5 shows the preprocessing data used for corn-stover base case analysis for different fields. Input moisture from different fields were taken into account, and energy consumption and throughput were measured. Test data at INL's PDU shows that preprocessing throughput and energy consumption for Stage-1 grinding vary from 3.45–4.28 dry ton/hr and 13.15–15.83 kwhr/dry ton, respectively. Similarly preprocessing throughput and energy consumption at Stage-2 grinding vary from 3.57–4.91 dry ton/hr and 13.39–18.4 kwh/dry ton respectively.

Table 5: Preprocessing data for corn stover base case analysis.

			Stage-1 grinding (3 in. screen size)			Stage-2 grinding (1-in. screen size)	
Field name	**Field Id**	**Moisture after storage (%)**	**Measured throughput (dry ton/hr)**	**Measured energy consumption (kwhr/ton)**	**Moisture after first stage grinding (%)**	**Measured throughput (dry ton/hr)**	**Measured energy consumption (kwhr/ton)**
FDC Enterprises,467916	1	14.17	3.82	13.29	12.17	4.06	18.09
FDC Enterprises,467827	2	10.50	4.28	15.83	8.50	4.91	13.39
FDC Enterprises,467919	3	13.64	3.82	13.29	11.64	4.06	18.09
FDC Enterprises,466650	4	11.50	4.04	14.33	9.50	4.40	13.85
FDC Enterprises,466160	5	12.50	3.95	15.05	10.50	4.16	18.40
FDC Enterprises,465757	6	12.50	3.95	15.05	10.50	4.16	18.40
FDC Enterprises,467162	7	17.17	3.69	13.15	15.17	3.64	17.40
FDC Enterprises,467907	8	20.50	3.45	15.49	18.50	3.57	15.43
FDC Enterprises,467263	9	17.17	3.69	13.15	15.17	3.64	17.40

Other equipment used for preprocessing are destringer, various conveyors, metering bin, and dust-collection equipment. Figure 7 shows the block flow diagram of various preprocessing equipment. Details of equipment used for preprocessing is found in Appendix A (Tables A.8–A.16).

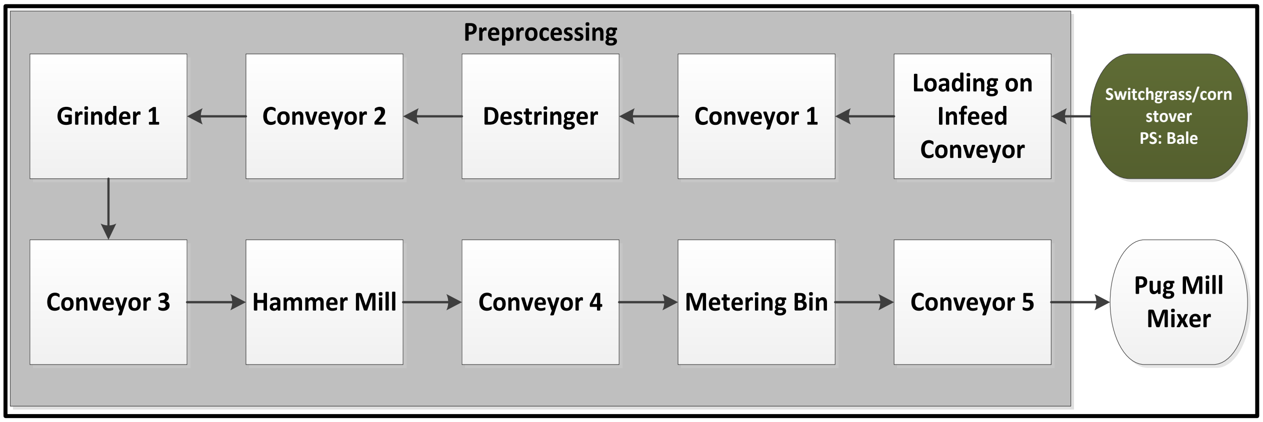

Figure 7: Block flow diagram of the preprocessing equipment.

3.5 Modeling Feedstock Logistics

The Biomass Logistics Model (BLM) (Cafferty, K.G. et al., 2013) was used to model feedstock logistics cost. The BLM incorporates information from a collection of databases that provide (1) engineering performance data for hundreds of equipment systems, (2) spatially explicit labor-cost data sets, and (3) local tax and regulation data. The BLM's analytic engine is built in the systems dynamics software package Powersim. The BLM is designed to work with thermochemical- and biochemical-based biofuel-conversion platforms and to accommodate a range of lignocellulosic biomass types (e.g., herbaceous residues, short-rotation woody and herbaceous energy crops, woody residues, and algae). The BLM simulates the flow of biomass through the entire supply chain while tracking changes in feedstock characteristics (i.e., moisture content, dry matter, ash content, and dry bulk density) and calculating cost and energy consumption (Cafferty, K.G. et al., 2013).

4. FEEDSTOCK LOGISTICS COST BASELINE ANALYSIS

4.1 Switchgrass

The modeled logistics cost of switchgrass for different fields are shown in Table 6. The modeled cost includes individual operations such as harvest and collection, storage, transportation, preprocessing, and queuing and handling of different fields. Results show that harvest and collection cost varies from $17.33 to 60.33/dry ton. Variation in harvesting methods, yields and field efficiency are the primary causes of variation in harvest and collection cost. Field "Merck 10" had the lowest harvest and collection cost. This field did not use the macerator during harvesting for field conditioning and has relatively high yield (2.78 dry ton/acre). Field "Merck 4" has the highest harvest and collection cost. This is because maceration operation was performed separately to dry the biomass in the field, and this field has relatively low yield (0.89 dry ton/acre).

Field side storage cost varied from $3.28 to 5.69/dry ton. Variation in storage cost is primarily attributed to variation in the cost of dry-matter loss and storage space. Dry-matter-loss cost at storage is affected by the cost of downstream operations prior to storage. Hence, biomass from a field having lower harvest and collection cost will incur low dry-matter-loss cost at storage. High-density bales require fewer bales to meet annual biomass demand. As a result, high-density bales reduce storage costs by reducing storage space and materials. Transportation and handling costs from field to biorefinery varies from $7.12 to 9.74/dry ton, assuming the transportation distance between field-side storage and biorefinery is 50 miles. Field "Merck 10" had the lowest transportation and handling cost from field-side storage to biorefinery. Field "Merck 4" has the highest transportation and handling cost from field-side storage to biorefinery. Given fixed transportation distance, transportation cost variability are attributed to variability in biomass moisture content and bale density from different fields.

Switchgrass preprocessing cost at biorefinery varies from $11.24–14.66/dry ton. Variability of biomass moisture content, bulk density causes this variability in preprocessing cost. High-moisture biomass results in high energy consumption and reduced throughput during both Stage-1 and 2 grinding. As the biomass from Field "Merck 6" has lowest moisture, Field "Merck 6" has the lowest preprocessing cost. Reactor in-feed and storage at biorefinery varies from $1.9–2.58/dry ton. This variability in cost are attributed to the variability in moisture and bulk density of biomass material.

Table 6. *Modeled feedstock-supply costs for switchgrass under different scenarios, and the 2017 delivered feedstock cost target. All costs are presented on a per dry ton basis and are in 2014 dollars.*

Field name	Merck 4	Merck 6	Merck 7	Merck 8	Merck 9	Merck 10	Merck 13	Merck 14
Harvest and collection cost($/dry ton)	$60.33	$19.35	$21.75	$19.60	$22.03	$17.33	$40.69	$32.34
Field side storage ($/dry ton)	$5.69	$3.34	$3.47	$3.37	$3.62	$3.28	$4.59	$3.92
Transportation and handling cost from field to birefinery ($/dry ton)	$9.74	$9.30	$9.49	$9.66	$9.30	$8.81	$8.86	$7.12
Preprocessing cost at biorefinery($/dry ton)	$14.66	$11.24	$11.88	$13.47	$11.91	$11.66	$14.37	$11.74
Reactor in-feed and storage ($/dry ton)	$2.58	$2.50	$2.50	$2.55	$2.50	$2.37	$2.38	$1.90
Logistics cost ($/dry ton)	$93.00	$45.73	$49.09	$48.65	$49.36	$43.45	$70.89	$57.02

The modeled logistics cost excluding grower payment (sum of harvest and collection cost, field-side storage cost , transportation and handling cost from field to biorefinery, preprocessing cost, and reactor in-feed and storage cost) varies from $43.45–93.00/dry ton. The variability in logistics cost are due to cumulative impact of variability in harvesting methods, field efficiency, field shape, yield, biomass quality and bulk density of material. Field "Merck 10" and "Merck 4" have the lowest and highest logistics cost, respectively.

In order to estimate the variability of delivered feedstock cost, a break-even grower payment is estimated based on yield for different fields. This grower payment is assumed to primarily consist of fertilizer cost, cost of herbicide and pesticide required to control weed and pest attack, seed cost, and machinery cost to cover all the cost of performing the farming operations. A detailed description of this estimation is provided in Appendix D. The estimated grower payment cost varied from $20.53–77.55/dry ton. This variability in grower payment was primarily due to yield variations from field to field. Figure 8 shows delivered feedstock cost from different fields. The delivered feedstock cost (grower payment + logistics cost) of switchgrass varied from $66.26–155.25/dry ton. Field "Merck 6" had lowest delivered feedstock cost due to fact that this field had lower grower payment with a high-yield (4.27 dry ton/acre), high-efficiency field producing low-moisture (12.5%) biomass. Field "Merck 4" had the highest delivered feedstock cost due to the fact that this field had higher grower payment with a low yield (0.89 dry ton/acre), producing high-moisture (17.5%) biomass. Results also show that grower payment and harvest and collection costs are highly variable among different fields. Details of cost are further presented in Appendix C (Table C-1).

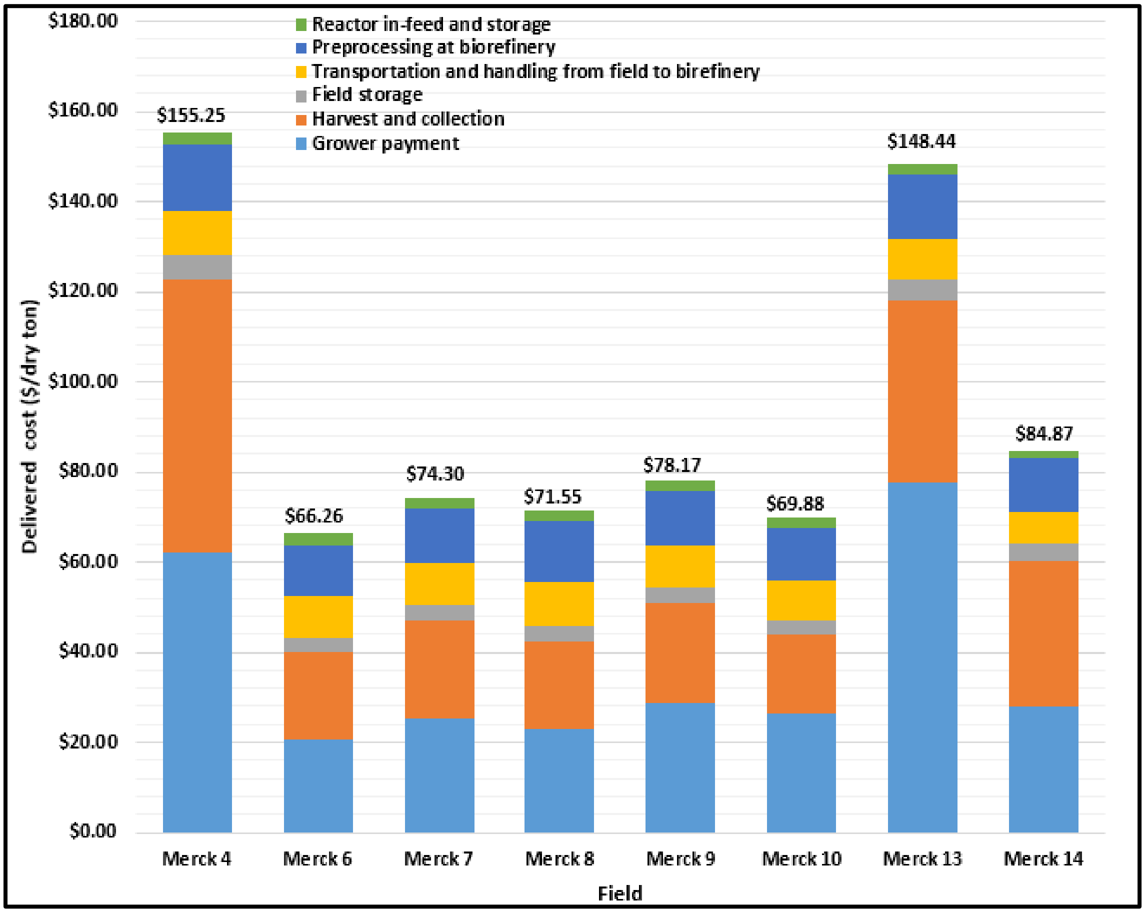

Figure 8: Delivered feedstock cost of switchgrass from different fields.

4.2 Corn Stover

The modeled logistics cost, including individual operations of harvest and collection, storage, transportation, preprocessing, and queuing and handling of different fields are shown in Table 7. Results show that harvest and collection cost varies from $12.13 to 28.08/dry ton. Variation in baling rate is the primary cause of this variation in harvest and collection cost. Field 4 (baling rate 30.97 bales/hr) has the lowest harvest and collection cost. Field 9 (baling rate 9.68 bales/hr) has the highest harvest and collection cost. Field side storage cost varied from $2.94 to 4.52/dry ton. Variation in storage cost is primarily attributed to variation in the cost of dry-matter loss and storage space.

Transportation and handling cost from field to biorefinery varies from $7.97 to 9.74/dry ton, assuming the transportation distance between field-side storage and biorefinery is 50 miles. Both Field 2 and Field 3 have the lowest transportation and handling cost from field-side storage to biorefinery. Field 7 has the highest transportation and handling cost from field side storage to biorefinery. Given fixed transportation distance, transportation cost variability is attributed to variability in biomass moisture content and bale density from different fields.

Preprocessing cost at the biorefinery varied from $13.74–16.82/dry ton. This variability in preprocessing cost was primarily due to the variability of biomass moisture content from different fields. High-moisture biomass results in high energy consumption and reduced throughput during both Stage-1 and 2 grinding. Field 2 has the lowest preprocessing cost as the biomass entering in the preprocessing has lowest moisture. As the biomass from Field 8 has the highest moisture, Field 8 has the highest preprocessing cost. Reactor in-feed and storage at biorefinery varies from $2.15–2.59/dry ton. This variability in cost is attributed to the variability in moisture and bulk density of biomass material.

Table 7. *Modeled feedstock logistics costs for corn stover under different scenarios. All costs are presented on a per dry ton basis and are in 2014 dollars.*

Field name	Field 1	Field 2	Field 3	Field 4	Field 5	Field 6	Field 7	Field 8	Field 9
Harvest and collection cost ($/dry ton)	$19.21	$12.45	$12.92	$12.13	$21.58	$19.37	$26.61	$23.28	$28.08
Field side storage ($/dry ton)	$3.60	$3.05	$2.94	$2.98	$3.85	$3.68	$4.52	$4.08	$4.30
Transportation and handling cost from field to birefinery ($/dry ton)	$8.51	$7.97	$7.97	$8.49	$8.61	$8.79	$9.74	$8.84	$8.13
Preprocessing cost at biorefinery($/dry ton)	$15.42	$13.74	$15.25	$14.37	$15.36	$15.28	$16.26	$16.82	$16.12
Reactor in-feed and storage ($/dry ton)	$2.29	$2.34	$2.15	$2.28	$2.32	$2.36	$2.59	$2.38	$2.18
Logistics cost ($/dry ton)	$49.03	$39.55	$41.23	$40.25	$51.72	$49.48	$59.71	$55.40	$58.82

The modeled logistics cost (sum of harvest and collection cost, field side storage cost , transportation and handling cost from field to biorefinery, preprocessing cost, and reactor in-feed and storage cost) varied from $39.55–59.71/dry ton. The variability in logistics costs were due to cumulative impact of variability in baling rate, bale density, yield, biomass quality, and bulk density of material. In order to estimate the variability of delivered feedstock cost, a $35.61/ton grower payment was added to the logistics cost. This grower payment is estimated from the three-year national average of actual corn-stover prices (Hartley and Thompson, 2018). Figure 9 shows total delivered-feedstock cost from different fields. Field 2 had the lowest delivered-feedstock cost because this field's yield was high (1.47 dry ton/acre) and moisture was low (13%). Field 7 had the highest delivered feedstock cost. This field had low yield (0.31 dry ton/acre) and a low baling rate, and it produced high moisture (19.67%) biomass. Harvest and collection costs were highly variable among different fields. Details of cost are further presented in Appendix C (Table C-2).

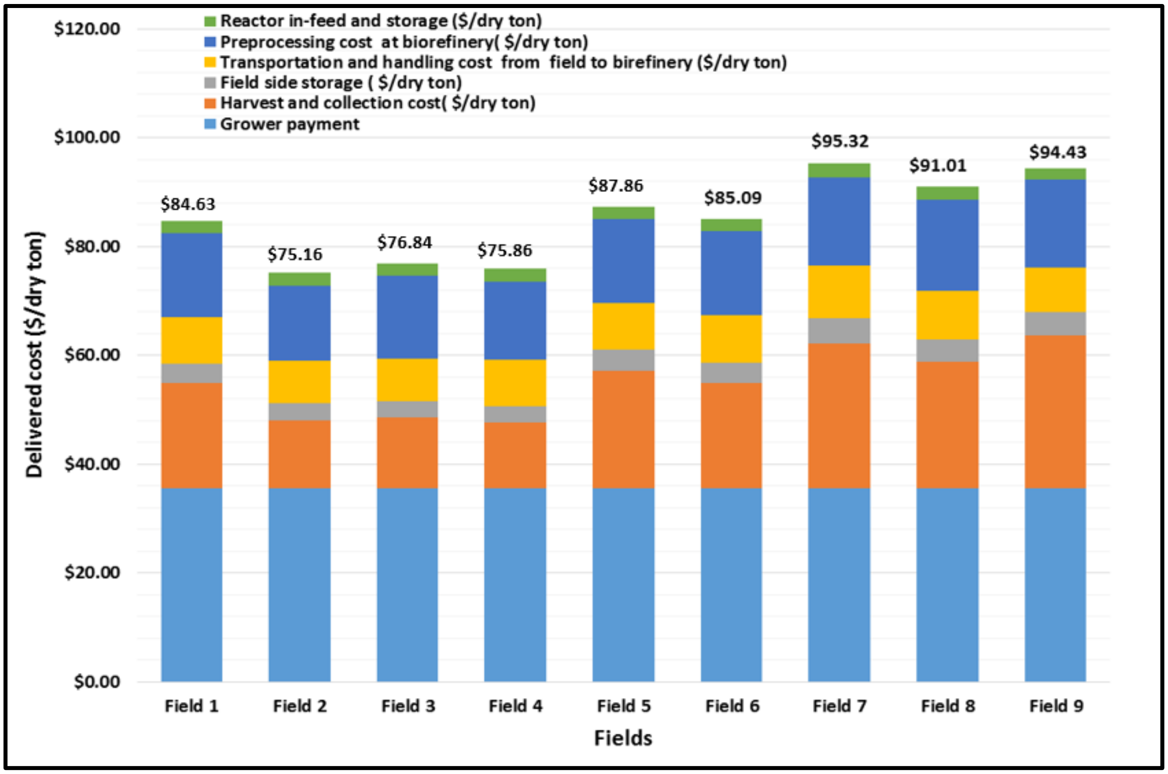

Figure 9 : Delivered feedstock cost from different fields assuming a grower payment of $35.61/dry ton.

5. SUMMARY

This report provides a feedstock-logistics cost baseline analysis. The base case analysis assumed two separate supply systems for corn stover and switchgrass. Base case analysis performed SSTEA to understand impact of actual field shape, field efficiency, harvesting efficiency and biomass quality on feedstock logistics cost. SSTEA estimates the feedstock logistics cost per ton of raw biomass delivered to the reactor throat of a biorefinery in dollars per dry matter ton ($/DMT). ANTARES Group, Incorporated, and FDC Enterprises provided the harvesting field data from projects that involved biomass harvesting. Switchgrass harvesting data were collected from a DOE-sponsored "Growing Bioeconomy Markets: Farm-to-Fuel in Southside Virginia" project. Corn-stover data were collected from the DOE co-sponsored BALES project. Eight fields were selected for switchgrass SSTEA. Nine fields were selected for corn-stover SSTEA.

Switchgrass base analysis for different fields shows that logistics cost were highly variable across the fields. The modeled logistics cost, excluding grower payment (i.e., the sum of harvest and collection cost, field-side storage cost, transportation and handling cost from field to biorefinery, preprocessing cost, and reactor in-feed and storage cost) varied from $43.45–93.00/dry ton. The variability in logistics costs were due to the cumulative impact of variability in harvesting methods, field efficiency, field shape, yield, biomass quality, and bulk density of material. The estimated delivered-feedstock cost (grower payment + logistics cost) of switchgrass varied from $68.79–214.3/dry ton. Among different logistics operations, harvest and collection cost are highly variable among different fields.

The modeled logistics cost (sum of harvest and collection cost, field side storage cost , transportation and handling cost from field to biorefinery, preprocessing cost, and reactor in-feed and storage cost) for corn stover varied from $39.55–59.71/dry ton. The variability in logistics costs was due to cumulative impact of variability in baling rate, bale density, yield, biomass quality, and bulk density of material. Assuming an estimated grower payment cost of $35.61/dry ton, the delivered feedstock cost (grower payment + logistics cost) of switchgrass varied from $66.26–155.25/dry ton. Among different logistics operations, harvest and collection cost were highly variable among different fields.

Base case analysis for both switchgrass and corn stover shows that switchgrass logistics costs are highly variable. This is primarily due to variability among harvesting operations, efficiency, and biomass yield. In the base analysis, it was assumed that both switchgrass and corn stover are separate logistics and monoculture cropping systems. However, incorporating both switchgrass and corn stover into a landscape design will create several logistical challenges arising from additional activities that become necessary for a design not based on a monoculture cropping system. Incorporating multiple crops into a landscape will likely create complex-shaped subfields, which will impact harvesting and collecting operations. Concurrent activities occurring simultaneously for both crops in a given field during planting and harvest may require additional equipment for simultaneous planting of row crops and harvest of energy crops, and well as additional labor. Although concurrent activities can be mitigated by temporal separation of planting and harvest times, additional equipment hours may be needed, which would reduce service life and increase maintenance costs for existing equipment. In the future we will update the analyses based on additional logistical barrier in the landscape design.

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APPENDIX A

Process Design and Cost Estimation Assumption Details

A.1. SYSTEM PARAMETERS

Table A.1. General parameters.

Cost index year	**2014**	**All price are listed in 2014 $ if not indicated otherwise**
Bale size (ft × ft × ft)	3 x 4 x 8	Field data
Biorefinery demand (dry ton/yr)	800,000	Assumption
Interest Rate	8%	Assumption
Electricity Price	$0.0675/kWh	Estimated based on 2017 price
Natural Gas Price	$3.38/MMBtu	Estimated based on 2017 price
Electricity price	$2.02/gal	Estimated based on 2017 price
Farm labor rate ($/hr)	$15.44	Assumption based on labor statistics of IOWA
Truck labor rate ($/hr)	$25.33	Assumption based on labor statistics of IOWA
Bulk handling rate($/hr)	$24.69	Assumption based on labor statistics of IOWA
Plant operator rate	$24.98	Assumption based on labor statistics of IOWA
Grinding operator ($/hr)	$18.17	Assumption based on labor statistics of IOWA

A.2. HARVEST AND COLLECTION

Table A.2. Harvesting equipment assumption.

Machine	**List Price**	**Year**	**Operational Width (ft)**	**Power (hp)**	**Avg Field Speed (mph)**	**Power required (hp)**	**Notes/Source**
Mower	$36,000	2018	10		6	220	Survey : FDC, equipment manufacturers; Estimated based on Pottinger Novacat 351
Tractor for mower	$270,000	2018		220			Survey : FDC, equipment manufacturers
Rake	$34,000.00	2018	28		10	120	Estimated based on Vermeer R2800 Twin Rake (Bar Rake)
Tractor for Raking	$270,000.00	2018		220			Survey : FDC, equipment manufacturers
Macerator	$30,000		4		9	100	Survey : FDC ; estimated based on Agland Macerator 6610
Tractor for Macerator	$270,000	2018		220			Survey : FDC, equipment manufacturers
Baler	$155,000	2018	6		3	130	Survey : FDC, equipment manufacturers ; Estimated based on Challenger Baler 2270
Tractor, for baler	$270,000	2018		220			Survey : FDC, equipment manufacturers

Table A.3.Collection assumptions.

Machine	**List Price**	**Year**	**Capacity per Load (bales)**	**Load, haul, unload time (bales/hr)**	**Notes/Source**
Stinger	$261,500	2018	12	100	Survey : FDC, equipment manufacturers

Table A.4.Harvest time assumptions.

Harvest time	Corn stover/switchgrass	Notes/source
Operational hours	6 weeks/year, 6 days/week, 14 hour/days	Assumptions

A.3. STORAGE

Table A.5. Field side storage assumptions.

Item	Assumption	Notes/Source
Storage method	Stack configuration, 4 x 4 tarped	Assumption
Price of tarp ($/Sq.ft)	$0.31	Survey
Land rent cost ($/acre)	$105.00	Survey
Insurance cost ($/ton)	$0.05	Survey
Time in Storage	Up to 12 months	Assumption
Dry-matter Loss(corn stover)	8%	Laboratory-scale storage experiments conducted at INL
Dry-matter Loss(switchgrass)	7%	Assumption

A.4. TRANSPORTATION AND HANDLING

Table A.6. Assumptions for transportation/handling of bales from field-side storage to biorefinery gate.

Item	Assumption	Notes/Source
Loader/unloader		
List Price	$83,989	Survey and estimated based on equipment model Caterpillar TH220B Telehandler
Fuel Economy (gal/hour)	4.38	Calculated
Capacity (bales/load)	38	
Fuel Type	Diesel	
Semi-Truck		
Speed (miles/hr)	50	
Type	Day cab	
List Price	127,827	Survey and estimated based on Peterbilt 367 Conventional-Day Cab.
Trailer		
Type	53-ft flatbed with ALSS	
Volume	3,600 ft3	
List price	$77,369	Survey and estimated based on 53' Flat Bed Trailer. ALSS price is included with the list price
Load Time (min)	6	Stinger Advanced Load Securing System (ALSS) presentation
Unload Time (min)	34	Estimated
Strap Time (min	2	Estimated
Average Transport Distance to Satellite Storage	50	Assumption

A.5. PREPROCESSING, BIOREFINERY HANDLING AND BIOREFINERY STORAGE

Table A.7 Biorefinery storage assumptions.

Item/Machine	Assumptions	Notes/Source
Storage method	Crushed Gravel Pad	Assumption
Listed price ($/sqft)	$1.78	Survey
Loader listed price	$83,989	Survey and estimated based on equipment model Caterpillar TH220B Telehandler
Loader capacity (bales/hr.)	80	
Horsepower	100	

Table A.8 Assumptions for handling from refinery storage to infeed.

Machine	Loader	Note/ source
Purchase Price	$132,360.00	Estimated based on model Case 721E
Capacity (tons/hr)	80	
Horsepower	183	

Table A.9. Assumptions for bale conveyance to destringer.

Machine	Bale Infeed	Note/ source
Purchase Price	$46,044.00	Estimated based on Schuon Single Bale Infeed
Capacity (tons/hr)	100	

Table A.10. Assumptions for destringer.

Machine	Destringer	Note/ source
Purchase Price	$24,168.00	Estimated based on W&B Twine Remover (CV)
Capacity (tons/hr)	20	

Table A.11. Assumptions for conveyance to first grinder.

Machine	Drag Chain Conveyor	Note/ source
Purchase Price	$10,898.00	Estimated based on 20,000 BPH, 20' En Masse Conveyor
Capacity (ft3/hr)	24,889	

Table A.12. Assumptions for grinder 1.

Machine	Stage 1 Grinder	Notes/source
Purchase Price	$180,000.00	Estimated based on Vermeer BG480E
Capacity (tons/hr)	6.91	
Screen Size	3 inch	
Energy Type	Electricity	
Moisture Reduction	2%	Estimated based on PDU experiment

Table A.13. Assumptions for conveyance to second grinder.

Machine	Drag Chain Conveyor	Notes/source
Purchase Price	$10,898.00	Estimated based on 20,000 BPH, 20' En Masse Conveyor
Capacity (ft3/hr)	24,889	

Table A.14. Assumptions for grinder 2.

Machine	**Stage 2 Grinder**	**Notes/source**
Purchase Price	$104,242.00	Estimated based on Hammer Mill FG-290-100
Capacity (tons/hr)	10	
Screen Size	1 inch	
Energy Type	Electricity	

Table A.15. Assumptions for conveyance to the metering bin.

Machine	**Drag Chain Conveyor**	**Notes/source**
Purchase Price	$100,757.00	Estimated based on 35,000 BPH, 150' En Masse Conveyor
Capacity (ft3/hr)	43,556	

Table A.16. Assumptions for the metering bin.

Machine	**Metering Bin**	**Notes/source**
Purchase Price	$70,000	Estimated based on warren and Baerg metering bin
Capacity (tons/hr)	100	

APPENDIX B

Modeling Operational Field Efficiency

Because empirical data are typically not available at large scales or prior to bioenergy crop establishment, it is necessary to build robust methodologies to model operational field efficiencies using widely available field-boundary geometry data. Field boundaries can be digitized using publically available National Agriculture Imagery Program (NAIP) data or acquired via the latest release of Common Land Unit boundary data, both administered by the United States Department of Agriculture (USDA) Farm Service Agency (FSA).\

Field efficiency (FE) is defined as follows:

$$FE = \frac{T_{df}}{T_{df} + T_d}$$

where T_{df} (delay-free time) is the time to complete the operation with no delays or disengagement, and T_d (time disengaged) is the time spent where the equipment is disengaged for durations of 60 seconds or less. T_d is impacted by field geometry which impacts turn efficiency, the number of turns required during the operation at headlands and when navigating around obstructions, and distance travelled in the headlands (Oksanen, T., 2013).

Ideally, agricultural fields would be rectilinear and free of in-field obstructions resulting in minimal time spent in fields disengaged while transitioning in turns or around obstructions. However, field geometry is often complex, resulting in varying field geometry configurations impacting field geometry and field efficiency. Integrated landscape management (ILM) practices can introduce additional changes to field geometry by delineating subfield areas more suitable for energy crop production versus traditional row crops. The geometrical properties of these subfield areas will, in turn, impact harvest and collection costs impacting farm-gate feedstock costs.

FDC Enterprises will perform harvest and collection operations for Iowa project sites in the coming years. However, biomass logistics modelling via BLM will take place prior to field operations, necessitating field-efficiency modelling to upgrade BLM assumptions impacted by site-specific field-boundary configurations. FDC Enterprises performs switchgrass harvest and collection operations in Virginia and made field tracks data available to derive a field efficiency model. The data were collected with Raven controllers logging equipment locations and timestamps at a one-second frequency during equipment engagement times for mowing and raking operations in 2017. Fields ranged in size from 1.5 to 162.5 acres.

INL researchers conducted time-series analysis to calculate field efficiency using the empirical data and compared results to field-boundary data. Analysis of the field tracks data indicates operators open fields by making approximately six headland passes around the inside perimeter of the field. They then transition to back-and-fourth passes to cover the interior of the field. Additional headland passes are sometimes made to navigate around in-field obstructions. In most cases, data logging was interrupted during disengagement times occurring at headlands and in proximity to obstacles where the equipment was disengaged to navigate to the next coverage path initialization point. These intermittent breaks were used to compile the total amount of time when the equipment was disengaged for durations of 60 seconds or less (T_d) (Figure 1).

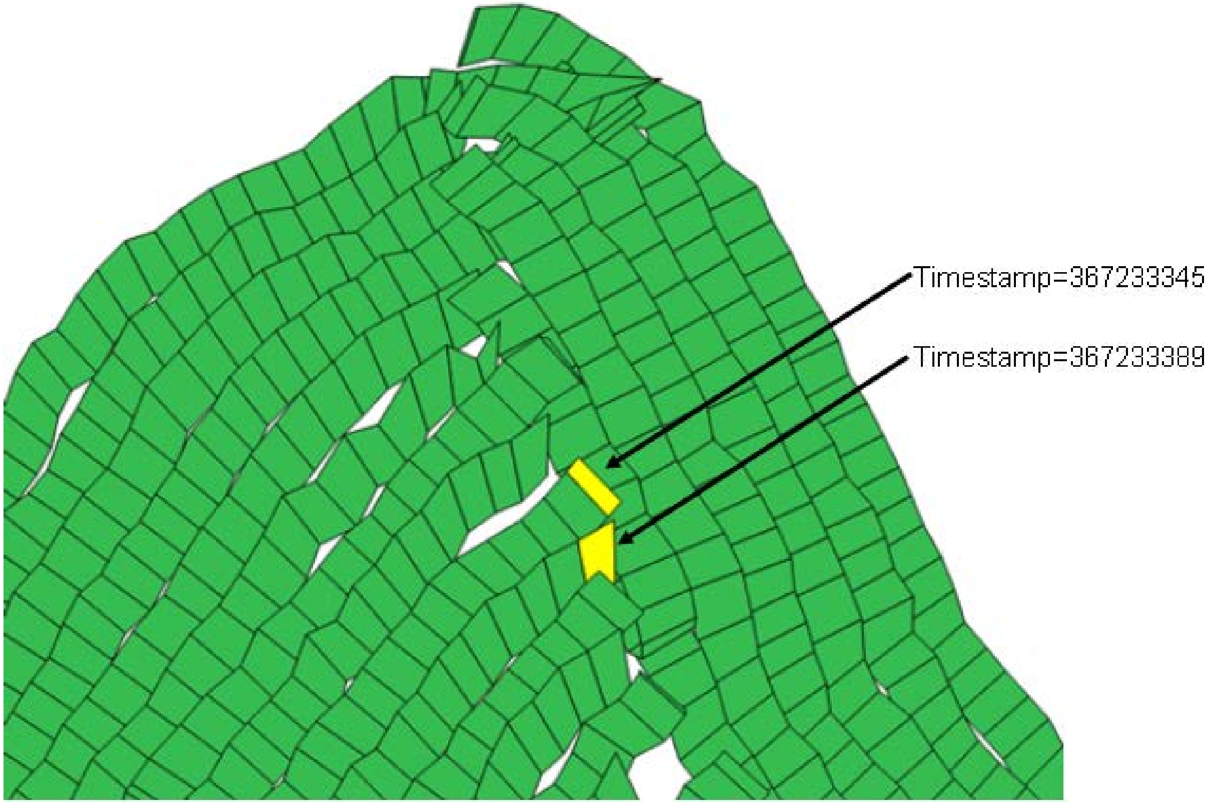

Figure 10. The green polygons represent switchgrass mowing coverage at one-second intervals and the yellow polygons show the last logged coverage at the end of a pass and the first logged coverage at the initializing of the next pass. In this case, the timestamp data indicates 44 seconds transpired as the equipment transitioned from one pass to the next.

Field boundaries were digitized using NAIP imagery and overlaying field tracks data. Oksanen evaluated multiple indices describing field boundary geometry complexity including a curb index (CI), a parametrized index quantifying the ratio of the headland area to the total field area (Oksanen, T., 2013). Because the index takes into account headland areas and matched the operational patterns of the field tracks data, INL researchers chose to evaluate potential statistical relationships of empirical field tracks data to the field CI (Figure 11). Field track data were evaluated on a field-by-field basis and patterns not fitting the CI description were eliminated from the analysis.

Using equipment-width parameters described in the field tracks data for individual fields and six headland passes, assumptions taken from the empirical field tracks data, the offset distance (D) and CI were calculated for each field boundary, as shown below. W_e represents equipment width and H_n denotes the number of headland passes. A_f represents the total field area and A_p represents the field area inside the offset region (Oksanen, T., 2013).

$$D = W_e * H_n$$
$$CI = \frac{A_f - A_p}{A_f}$$

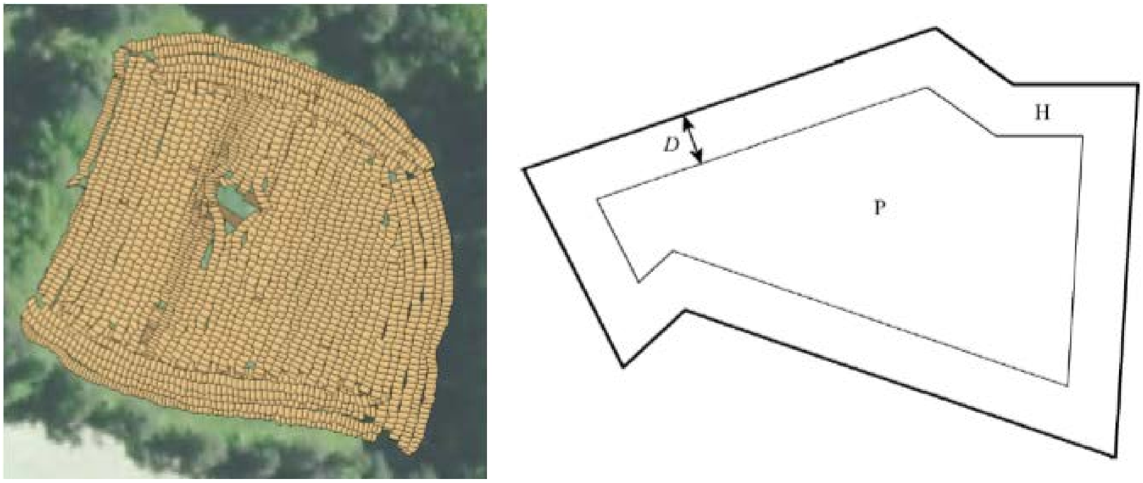

Figure 11. Empirical field tracks data of a switchgrass mowing operation in Virginia in 2017 (left) and a graphical representation of the CI calculation (right) (Oksanen, T., 2013). The empirical operations data closely matched the CI modelling assumption that operators establish a headland area (H) of a specific offset distance (D) around the inside perimeter of the field and then cover the interior area (P) using a back-and-forth strategy.

Using linear regression, a total of 66 fields with switchgrass-mowing data were analyzed for statistical relationships. A total of 45 fields with switchgrass-raking data were analyzed. Linear regression indicates the coefficient of determination to be 0.82 for mowing and 0.63 for raking. The mean square error (MSE) of the predicted FE and the empirical FE for the mowing and raking data was 0.0008 and 0.002 for mowing and raking respectively. Linear regression of baling field tracks data showed no significant relationship to CI and was excluded from this analysis.

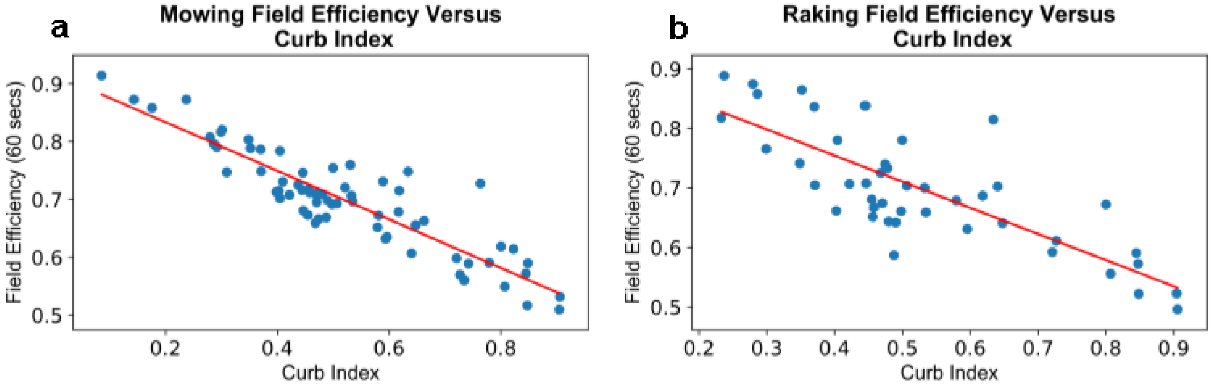

Figure 12. Plots a and b show empirically derived FE plotted against the CI for mowing (a) and raking (b) operations.

Based on the regression analysis, mowing and raking field efficiency (FE_m and FE_r) for switchgrass using equipment width and headland assumptions matching the empirical Virginia operations can be calculated as shown below. Using harvest and collection assumptions derived from Virginia operations, these models will be used to calculate Iowa field efficiency for mowing and raking operations.

$$FE_m = -0.420 * CI + 0.917$$

$$FE_r = -0.439 * CI + 0.930$$

APPENDIX C

Cost Breakdown by Operation

Table C-1. Cost breakdown by operations for different fields of switchgrass.

Field name	**Merck 4**	**Merck 6**	**Merck 7**	**Merck 8**	**Merck 9**	**Merck 10**	**Merck 13**	**Merck 14**
Harvest and collection	$60.33	$19.35	$21.75	$19.60	$22.03	$17.33	$40.69	$32.34
Mowing	$10.89	$2.27	$3.25	$2.76	$3.99	$3.49	$14.10	$3.79
Conditioning with mower	$13.61	$2.67	$3.88	$3.63	$1.55	$0.00	$6.07	$1.59
Raking	$6.95	$1.36	$1.98	$1.85	$2.45	$2.40	$9.61	$2.52
Baling	$24.99	$9.34	$8.87	$7.52	$10.33	$7.93	$7.39	$21.53
Roadsider	$3.89	$3.71	$3.77	$3.84	$3.71	$3.51	$3.52	$2.91
Field storage	$5.69	$3.34	$3.47	$3.37	$3.62	$3.28	$4.59	$3.92
Stack	$5.69	$3.34	$3.47	$3.37	$3.62	$3.28	$4.59	$3.92
Transportation and handling from field to birefinery	$9.74	$9.30	$9.49	$9.66	$9.30	$8.81	$8.86	$7.12
Trucking/unloading	$9.74	$9.30	$9.49	$9.66	$9.30	$8.81	$8.86	$7.12
Preprocessing at biorefinery	$14.66	$11.24	$11.88	$13.47	$11.91	$11.66	$14.37	$11.74
Grinder 1	$8.03	$6.13	$6.45	$8.03	$6.45	$6.45	$8.03	$6.45
Grinder 2	$3.84	$3.02	$3.27	$3.27	$3.27	$3.13	$3.84	$3.13
Conveyors	$0.38	$0.33	$0.35	$0.36	$0.33	$0.29	$0.31	$0.19
Dust collection	$2.14	$1.49	$1.54	$1.54	$1.59	$1.52	$1.92	$1.70
Surge bin	$0.05	$0.05	$0.05	$0.05	$0.05	$0.05	$0.05	$0.05
Misc. equipment[a]	$0.22	$0.22	$0.22	$0.22	$0.22	$0.22	$0.22	$0.22
Reactor in-feed and storage	$2.58	$2.50	$2.50	$2.55	$2.50	$2.37	$2.38	$1.90
Storage at refinery	$1.02	$1.03	$0.99	$1.01	$1.03	$0.97	$0.98	$0.77
Handling and queuing at refinery	$1.56	$1.47	$1.51	$1.54	$1.47	$1.40	$1.40	$1.13
Logistics cost	$93.00	$45.73	$49.09	$48.65	$49.36	$43.45	$70.89	$57.02

a: Miscellaneous equipment consists of moisture meters, bale rejecters, electromagnets, etc.

Table C-2. Cost breakdown by operations for different fields of corn stover.

Field name	**Field 1**	**Field 2**	**Field 3**	**Field 4**	**Field 5**	**Field 6**	**Field 7**	**Field 8**	**Field 9**
Harvest and collection cost ($/dry ton)	**$19.21**	**$12.45**	**$12.92**	**$12.13**	**$21.58**	**$19.37**	**$26.61**	**$23.28**	**$28.08**
Baling	$15.84	$9.01	$9.74	$8.76	$18.15	$15.88	$22.74	$19.78	$24.84
Roadsider	$3.37	$3.44	$3.18	$3.37	$3.43	$3.49	$3.87	$3.50	$3.24
Field storage	**$3.60**	**$3.05**	**$2.94**	**$2.98**	**$3.85**	**$3.68**	**$4.52**	**$4.08**	
Stack	$3.60	$3.05	$2.94	$2.98	$3.85	$3.68	$4.52	$4.08	$4.30
Transportation/handling cost from field to biorefinery	$8.51	$7.97	$7.97	$8.49	$8.61	$8.79	$9.74	$8.84	$8.13
Trucking/unloading	$8.51	$7.97	$7.97	$8.49	$8.61	$8.79	$9.74	$8.84	$8.13
Preprocessing at biorefinery	**$15.42**	**$13.74**	**$15.25**	**$14.37**	**$15.36**	**$15.28**	**$16.26**	**$16.82**	**$16.12**
Grinder 1	$8.74	$8.12	$8.74	$8.41	$8.64	$8.64	$9.00	$9.75	$9.00
Grinder 2	$4.56	$3.65	$4.56	$3.99	$4.51	$4.51	$4.87	$4.78	$4.87
Conveyors	$0.26	$0.26	$0.24	$0.26	$0.26	$0.27	$0.38	$0.33	$0.24
Dust collection	$1.59	$1.44	$1.44	$1.44	$1.68	$1.59	$1.74	$1.69	$1.74
Surge bin	$0.05	$0.05	$0.05	$0.05	$0.05	$0.05	$0.05	$0.05	$0.05
Misc. Equipment[a]	$0.22	$0.22	$0.22	$0.22	$0.22	$0.22	$0.22	$0.22	$0.22
Reactor in-feed and storage	**$2.29**	**$2.34**	**$2.15**	**$2.28**	**$2.32**	**$2.36**	**$2.59**	**$2.38**	**$2.18**
Storage at refinery	$0.94	$0.96	$0.88	$0.93	$0.95	$0.97	$1.03	$0.98	$0.89
Handling and queuing	$1.35	$1.38	$1.27	$1.35	$1.37	$1.39	$1.56	$1.40	$1.29
Logistics cost	**$49.03**	**$39.55**	**$41.23**	**$40.25**	**$51.72**	**$49.48**	**$59.71**	**$55.40**	**$54.52**

a: Miscellaneous equipment consists of moisture meters, bale rejecters, electromagnets, etc.

APPENDIX D

Switchgrass Grower Payment Cost Estimation

Switchgrass Grower Payment Calculation

Consider a dedicated switchgrass, established in 2014 in Iowa. The grower payment is broken into several components: fertilizer, herbicide and pesticide, seed, and machinery costs. We have assumed that the land rent is a sunk cost(DOE, 2016). The discounted grower payment[a] is calculated using equation (1).

$$DGP = (1 + FR) \times (FC + HC + SC + MC) \qquad (1)$$

Where, FR is the financial return or premium or markup on cost that needs to be paid to the growers, FR=0 for breakeven analysis; FC, HC, SC, and MC are fertilizer cost, herbicide and pesticide cost, seed cost, and machinery cost respectively. Average discounted grower payment (ADGP) per dry ton (DT) is calculated by dividing DGP by total yield as shown in equation (2).

$$ADGP = \frac{DGP}{\sum_{j=E}^{E+L} Y_j} \qquad (2)$$

Where, j is the index of year, E is establishment year; L is stand life of the crop; and Y_j is the yield of Switchgrass in particular year measured in DMT.

Switchgrass has a stand life (L) of 10 to 20 years (Garland, C.D., 2008). Various crop budget and studies used a stand life of 10 years (Dolginow, J. and R. Massey, 2013). The yield (Y) for switchgrass vary over its stand life and actual yield from different was utilized to estimate the grower payment. It is assumed that nothing is produced in the establishment year and in the second year a 50% of mature yield can be harvested, reaching mature yield from the third year.

Fertilizer Cost: The fertilizer cost is the cost of fertilizer materials[b] required in the field to grow switchgrass is found in crop budgets. The fertilizer materials requirements vary in difference crop budget and also depending on the time of the stand. During the establishment (year-1), we have assumed to use 80 lb P_2O/acre and 40 lb K_2O_5/acre following U.S. Department of Energy (2016), while Dolginow and Massey (2013) suggested to use 14.6 lb P_2O/acre and 2 lb K_2O_5/acre. We have assumed zero nitrogen fertilizer during establishment as it would facilitate weed growth (Hoque, M. et al., 2015). For the maintenance years (2–10), fertilizer use depends on the removal of biomass from the field. We have assumed 10 lb N/dt(PennStateExtension, 2014, Hoque, M. et al., 2015, DOE, 2016), 4 lb P_2O_5/dt(PennStateExtension, 2014, DOE, 2016), and 15 lb K_2O/dt(PennStateExtension, 2014).

Table D-1: The unit costs of fertilizer used in switchgrass production.

Fertilizer	Unit	Dolginow & Massey (2013)	Penn State Extension (2013)	Hoque, Artz, & Hart (2014)
Nitrogen	\$/lb N	0.55	0.56	0.44
Phosphorus	\$/lb P_2O_5	0.49	0.63	0.43
Potassium	\$/lb K_2O	0.47	0.48	0.41
Lime (including application)	\$/ton	18.55	38.00	29.00

Various crop budgets used different fertilizer cost[c]. For example, nitrogen cost is \$0.55/lb (Dolginow, J. and R. Massey, 2013), or \$0.56/lb, or \$0.44/lb (Hoque, M. et al., 2015). Table D-1 provides the unit costs of different fertilizers used in Switchgrass field. We have used fertilizer cost from Penn State Extension (2013) for all types of fertilizers used including lime in order to be conservative in cost estimate. As

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[a] Setting discount rate, r=0 for all the subsequent equations that follows will result in non-discounted grower payment.

[b] For lime, the fertilizer cost includes the application of lime.

[c] The cost of fertilizer differs based on location and time. It also differ based on whether the purchase is wholesale or retail.

fertilizer costs vary depending on time, USDA fertilizer index is used to normalized fertilizer cost (USDA, 2017b).The spatial and purchase volume (wholesale or retail) variability of fertilizer cost is not accounted for in the model. The fertilizer cost is calculated as shown in equation (3).

$$FC = \sum_{i=1}^{N} \sum_{j=E}^{E+L} (1 + r)^{(y-j)} \times F_{ij} \times \frac{Q_j}{Q_u} \times V_{iu} \qquad (3)$$

Where, i is the index of fertilizer type; N is the total number of fertilizer, j is the index of year, E is establishment year; L is stand life of the crop; r is selected discount rate; y is selected cost year; F_{ij} is amount of fertilizer required for a particular year and type; Q_j is USDA fertilizer index for a particular year; Q_u is USDA fertilizer index for fertilizer cost for a year; V_{iu} is the fertilizer cost per unit (lb or ton) for fertilizer cost year and fertilizer type.

Herbicide and Pesticide Cost: Herbicide and pesticide are required to control weed and pest attack in the field. The cost and amount of required herbicide are found in the crop budget.[d] The suggested amount and type of herbicide varies among crop budget. In the establishment year, we assumed 3 passes of herbicides (Atrazine, Acetochlor, and 2-4,D), and in year 2, 5, and 8, one pass of 2-4,D(DOE, 2016). The application rate is assumed following Dolginow and Massey (2013). We have used the prices of herbicide as per Dolginow and Massey (2013). The equation (4) is used to calculate herbicide cost.

$$HC = \sum_{i=1}^{N} \sum_{j=E}^{E+L} (1 + r)^{(y-j)} \times H_{ij} \times X_i \qquad (4)$$

Where, i is the index of herbicide and pesticide type; j is the index of year, E is establishment year; L is stand life of the crop; r is selected discount rate; y is selected cost year; H_{ij} is amount of herbicide required for particular year and particular type; X_i is the herbicide cost per unit (lb).

Seed Cost: The seed cost refer to the cost of material that germinates as energy crop. The plantation cost is considered as machinery cost. The amount of seed required is found in switchgrass crop budgets. The prices of switchgrass depend on cultivars and location of the field. Some of the crop budget shows that there are some replantation at the Year 2. Table D-2 presents the seed unit cost, planting amount, and replanting rate for switchgrass. In our analysis, we have used 6 lb PLS/acre to ensure 30 PLS in one square feet (MSUExtension, 2010). The price of the seed is taken as $20/lb PLS following grower payment study (Soldavini, S. and W.E. Tyner, 2018) because the study was conducted in Iowa in the most recent year. We have used the highest replantation rate (30%) based on the literature. Given the parameters, the seed cost is calculated using the following formuls:

$$SC = \sum_{j=E}^{E+L} (1 + r)^{(y-j)} \times S_j \times Z \qquad (5)$$

Where, j is the index of year; E is establishment year; L is stand life of the crop; r is selected discount rate; y is selected cost year; S_j is amount of seed required for particular year; Z is the seed cost per unit (lb PLS).

Table D-8: Seed unit cost, planting amount and replanting rate for switchgrass.

Study	Amount (lb PLS/acre)	Price ($/lb PLS)	Replanting rate (%)
MSU Extension (2010)	6	11.33	0
Soldavini and Tyner (2018)	5	20.00	25
Penn State Extension (2014)	8	10.00	30
U.S. Department of Energy (2016)	6	4.75 – 14.49	10
Hoque, Artz, and Hart (2015)	5	15.00	10

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[d] No pesticide is used in Switchgrass growing.

Machinery Cost Machinery cost covers all the cost of performing the farming operations. It includes fertilizer application, herbicide and pesticide spraying, lime spreading, site-preparation machinery, and planting machinery. The amount of machinery application (unit: pass) is found in crop budget of switchgrass (PennStateExtension, 2014). The machinery cost data come from the custom rate of the operations, which vary both specially and temporally. Custom rates data from different states come from various sources. We have used Iowa custom rates 2017(ISU, 2017) , that does not have data for 'brush hogging,' which is performed in switchgrass establishment. In this case, our model calculates the custom rate based on the average of some other states (such as Michigan, Missouri, and Pennsylvania). These custom rates are then normalized using USDA custom-rates index. USDA published custom-rates index from 1990 to 2016 (USDA, 2017a). Custom rates index for later years are estimated using extrapolation.[e] Then, the machinery cost is computed using equation (6).

$$MC = \sum_{i=1}^{N} \sum_{j=E}^{E+L} (1+r)^{(y-j)} \times M_{ij} \times \frac{I_{js}}{I_{cs}} \times R_{ics} \tag{6}$$

where, i is the index of machinery operations; j is the index of year, E is establishment year; L is stand life of the crop; r is selected discount rate; y is selected cost year; M_{ij} is amount of machinery operation required for selected operation, an particular year; I_{js} is USDA custom rate index for particular year and selected state; I_{cs} is USDA custom rate index for custom rate and year; R_{ics} is the custom rate for machinery operation, and custom rate year.

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[e] Simple linear regression is performed. It follows the following formula: $y=1.7064x+62.132$ with $R^2=0.9242$.

Table D-3: Assumptions to estimate grower payment.

Item	Units	Assumptions	Assumption basis
Stand Life	years	10	Garland (2008): 10 to 20 years Soldavini and Tyner (2017): 10 years MSU Extension (2010): 10 years Dolginow & Massey (2013): 10 years BT 16: 10 years Hoque, Artz, and Hart (2015): 10 years
Seed	$/lb	20	MSU Extension (2010): $11.33/lb PLS Soldavini and Tyner (2017): $20/lb PLS BT 16: $4.75 - $14.49/lb Hoque, Artz, and Hart (2015): $15/lb PLS
Planting rate	lb/acre	6	Penn State Extension (2014): 6 lb PLS/acre BT 16: 6 lb/acre Soldavini and Tyner (2017): 5 lb PLS/acre Hoque, Artz, and Hart (2015): 5 lb PLS/acre
Replanting rate	%	30	Penn State Extension (2014): 30% BT 16: 10% Soldavini and Tyner (2017): 25% Hoque, Artz, and Hart (2015): 10%
Planting equipment	NA	No-till drill	Soldavini and Tyner (2017): No-till drill BT 16: No-till drill Penn State Extension (2014): Drill Hoque, Artz, and Hart (2015): Drill
Herbicide treatments	number, passes	3,3	Dolginow & Massey (2013): 2,2 (Atrazine and Acetochlor) BT 16: 3,3 (Atrazine, Quinclorac , 2,4-D) Hoque, Artz, and Hart (2015): 2,2
Nitrogen (establishment)	lb N/acre	0	Hoque, Artz, and Hart (2015): 0 lb N/acre Dolginow & Massey (2013): 60 lb N/acre BT 16: 0 lb N/acre Penn State Extension (2014): 0 lb N/acre
Phosphorous (establishment)	lb P2O5/acre	40	Dolginow & Massey (2013): 2 lb P2O5/acre BT 16: 40 lb P2O5/acre Hoque, Artz, and Hart (2015): 0 lb P2O5/acre
Potassium (establishment)	lb K2O/acre	14.6	Dolginow & Massey (2013): 14.6 lb K2O/acre BT 16: 80 lb K2O/acre Hoque, Artz, and Hart (2015): 0 lb K2O/acre
Limestone (establishment)	tons/acre	1	Dolginow & Massey (2013): tons/acre BT 16: 1 tons/acre
Total establishment costs	$/acre	373.44	Soldavini and Tyner (2017): $294.56/acre BT 16: $215 - $410/acre
Reseeding	year	2	Penn State Extension (2014): 2 BT 16: 2 Soldavini and Tyner (2017): 2 Hoque, Artz, and Hart (2015):
Herbicide treatments	Number passes by year	1 in years 2,5,8	Dolginow & Massey (2013): 2,4-D in year 2 BT 16: 2,4-D in year 2,5,8 Hoque, Artz, and Hart (2015): 2,4-D in all years
Nitrogen (maintenance)	lb N/dt	10	Dolginow & Massey (2013): 10 lb N/dt BT 16: 10 lb N/dt Hoque, Artz, and Hart (2015): 10 lb N/dt Penn State Extension (2014): 10 lb N/dt
Phosphorous (Maintenance)	lb P2O5/dt	4	Dolginow & Massey (2013): 0.33 lb P2O5/dt BT 16: 4 lb P2O5/dt Hoque, Artz, and Hart (2015): 0 lb P2O5/dt Penn State Extension (2014): 4 lb P2O5/dt
Potassium (Maintenance)	lb K2O/dt	15	Dolginow & Massey (2013): 2.43 lb K2O/dt BT 16: 14 lb K2O/dt Hoque, Artz, and Hart (2015): 0 lb K2O/dt Penn State Extension (2014): 15 lb K2O/dt

Table D-4: Estimated break even grower payment cost.

	Merck 4	Merck 6	Merck 7	Merck 8	Merck 9	Merck 10	Merck 13	Merck 14
Fertilizer Cost	**$16.17**	**$10.95**	**$11.54**	**$11.25**	**$11.99**	**$11.69**	**$18.08**	**$11.87**
Nitrogen	$3.50	$3.50	$3.50	$3.50	$3.50	$3.50	$3.50	$3.50
Phosphorous	$4.19	$2.12	$2.35	$2.24	$2.53	$2.41	$4.94	$2.48
Potassium	$8.48	$5.33	$5.68	$5.51	$5.96	$5.78	$9.63	$5.88
Lime	$0.0020	$0.0004	$0.0006	$0.0005	$0.0007	$0.0006	$0.0025	$0.0007
Herbicide Cost	**$8.68**	**$1.80**	**$2.58**	**$2.19**	**$3.17**	**$2.78**	**$11.20**	**$3.01**
Atrazine	$0.86	$0.18	$0.25	$0.22	$0.31	$0.27	$1.11	$0.30
Acetochlor	$1.91	$0.40	$0.57	$0.48	$0.70	$0.61	$2.46	$0.66
2,4-D	$5.92	$1.23	$1.76	$1.50	$2.16	$1.90	$7.65	$2.06
Seed Cost	**$16.18**	**$3.36**	**$4.80**	**$4.09**	**$5.91**	**$5.18**	**$20.89**	**$5.61**
Machinery Cost	**$21.21**	**$4.41**	**$6.29**	**$5.36**	**$7.74**	**$6.78**	**$27.37**	**$7.36**
Site Preparation	$9.58	$1.99	$2.84	$2.42	$3.50	$3.06	$12.37	$3.32
Plantation	$2.35	$0.49	$0.70	$0.59	$0.86	$0.75	$3.04	$0.82
Chemical Application	$9.27	$1.93	$2.75	$2.34	$3.39	$2.97	$11.97	$3.22
Total	**$62.25**	**$20.53**	**$25.21**	**$22.90**	**$28.81**	**$26.43**	**$77.55**	**$27.85**