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Understanding management practices for biomass harvest equipment for commercial scale operation

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Abstract

As second generation biofuels approach commercial scale production, a large fleet of harvesting equipment is required to meet feedstock demand. In the Midwest United States, agricultural residue, such as corn stover, has been identified as a readily available feedstock. Multi-pass corn stover harvest requires the in-field operations of shredding, baling, and stacking. Proper management practices are required to keep machines running at maximum efficiency in order to reduce cost and harvest enough material to meet processing demand. This need for management becomes increasing important as production levels reach commercial scale levels. This study looked at management practices of several individual harvest crews across an entire harvest season. Data was collected from multiple machines, including balers, shredders, and stackers during the 2013 and 2014 fall harvests. The controller area network (CAN) bus system was utilized to record machine data that was linked to specific GPS coordinates within a given field. The information was then analyzed to identify controllable metrics, such as machine productivity, daily bale production, and bale density. Recognizing these controllable metrics will improve overall logistics as production reaches full scale and reduce overall costs. A techno-economic analysis was executed to quantify cost as performance and quality changed.

Keywords

Cellulosic Ethanol, Corn Stover, Supply Chain Management, CAN Data, Productivity

Disciplines

Agriculture | Bioresource and Agricultural Engineering

Comments

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Understanding management practices for biomass harvest equipment for commercial scale operation

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Abstract. *As second generation biofuels approach commercial scale production, a large fleet of harvesting equipment is required to meet feedstock demand. In the Midwest United States, agricultural residue, such as corn stover, has been identified as a readily available feedstock. Multi-pass corn stover harvest requires the in-field operations of shredding, baling, and stacking. Proper management practices are required to keep machines running at maximum efficiency in order to reduce cost and harvest enough material to meet processing demand. This need for management becomes increasing important as production levels reach commercial scale levels. This study looked at management practices of several individual harvest crews across an entire harvest season. Data was collected from multiple machines, including balers, shredders, and stackers during the 2013 and 2014 fall harvests. The controller area network (CAN) bus system was utilized to record machine data that was linked to specific GPS coordinates within a given field. The information was then analyzed to identify controllable metrics, such as machine productivity, daily bale production, and bale density. Recognizing these controllable metrics will improve overall logistics as production reaches full scale and reduce overall costs. A techno-economic analysis was executed to quantify cost as performance and quality changed.*

Keywords. *Cellulosic Ethanol, Corn Stover, Supply Chain Management, CAN Data, Productivity*

Introduction

Recent research has been focused on developing fuels produced from renewable resources that can meet current energy demand without increasing cost. Several feedstocks have been identified as potential targets to produce these fuels, ranging from corn stover to woody biomass. The advantage of using biomass feedstocks is that a conversion process can be tailored to fit the feedstocks of a particular geographical region.

However, more work is needed in the area of feedstock harvesting, storage, and transportation. Collection logistics of biomass is challenging due to the typically low bulk density and variations in material physical properties. Research has been conducted on various stages of the supply chain to optimize the harvest of materials, but as biorefineries reach commercial scale production, more work is required to further reduce cost. The challenge is due to interactions at both the macro and micro level of the supply chain. Each stage of the supply chain must be optimized to reduce cost: harvest, storage, collection, and processing. However, each stage is closely intertwined together and must not negatively impact the subsequent supply chain stages.

Corn stover has been identified as a potential feedstock for cellulosic ethanol production, especially within the Midwestern United States. There is a large supply of corn grain produced annually and the existing grain ethanol biorefineries make for an ideal location. Corn stover is the remaining material left in the field after grain has been harvested, allowing the already existing crop production to remain in place. Currently there are two cellulosic ethanol biorefineries utilizing corn stover that will soon be operational in Iowa. POET Biorefining (25 million gallon per year) and DuPont Cellulosic Ethanol (30 million gallon per year) have plants nearing commercial scale production.

Much of the current machinery used in corn stover harvest is based upon hay or forage harvesting equipment. These machines can be modified for corn stover harvest in order to increase machine productivity and bale quality (Shinners et al., 2011). Large square balers are typically used for harvesting corn stover and produce bales that are 3 ft tall, 4 ft wide, and 8 ft long. Variations exist on what these dimensions can be but for this research a 3 ft x 4 ft x 8 ft bale will be used. These large square bales can be produced in a multi-pass system or in a single-pass system where a baler is pulled directly behind a combine (Shinners et al., 2007; Webster et al., 2010). This research will focus on a multi-pass system which uses a shredder, baler, and bale collection system.

Objectives

The focus of this study is to investigate management practices associated with corn stover harvest for a commercial scale cellulosic ethanol biorefinery. Key Performance Indicators (KPI's) have been developed in order to identify which factors have the largest impact on harvest performance and efficiency. By using these KPI's, increases in corn stover harvesting can be achieved in bale density, daily bale production levels, and overall machine efficiency. A techno-economic analysis has been conducted to show how improving these metrics can reduce harvest costs for a commercial scale harvest system.

Previous studies have investigated corn stover logistics on field level scale but there is a need for work on commercial scale operations. Targets have been established for commercial scale operation which help to optimize biorefinery plant size and harvest region size in order to reduce cost. However, as harvest operations are increased to commercial scale levels, the interactions between supply chain stages become more complicated and can potential increase harvest costs. Finding the existing supply chain inefficiencies is the first step before improvements can be made. These adjustments to individual supply chain stages must be made with the final objectives of maintaining feedstock quality, increasing machinery productivity, and reducing overall cost.

Material and Methods

Data Collection

The data used in this study was collected during the fall harvest of 2013 and 2014 with approximately 200,000 bales were harvested each year. The data collection was part of a joint research project between Iowa State University and DuPont Cellulosic Ethanol. Once fully operational, the biorefinery is expected to require approximately 700,000 bales, annually. Machinery data was collected on 160 machines including shredders, balers, and stackers using telemetry data loggers developed by Iowa State University and Rowe Electronics (Norwalk, IA). The loggers collected data off the machine Controller Area Network (CAN Bus). Data collected included, but was not limited to, engine speed, fuel consumption, and PTO speed. The SAE J1939 protocol regulates CAN bus networks to allow for communication compatibility across all major agricultural manufactures.

The telemetry data loggers were designed to access the tractor CAN Bus and record transmitted messages. A sampling rate of once every 15 seconds was established to record information. All data points were collected with a timestamp and corresponding GPS coordinate. This allowed data to be sorted either by date or location. Reports were generated to show productivity on a daily level or on a field by field level.

Field Equipment

For a multi-pass harvest system there are typically three in-field operations: shredding and/or windrowing, baling, and bale collection. Once grain harvest is complete, a shredder will shred the remaining corn stover and place the material into a windrow for the baler to collect (Figure 1). The shredders used for this harvest study were 20 ft wide with a side discharge. This allowed for two passes to be placed in a single windrow, thus creating a 40 ft swath of material for the baler to collect. The shredder determines how much material will be taken from the field, depending on speed and shredder height.

Figure 1: Windrowing of corn stover

After the windrow has been created, the baler will pass over the windrow and create bales (Figure 2). Bales will typically weigh between 1200-1600 lb depending on material moisture content, operator baler settings, and field conditions. Large square bales offer the advantage of creating a high density, high quality format that can easily be handled. The quality of the material must be maintained as it is transported, stacked, and stored prior to plant processing.

Figure 2: Baling of corn stover

The baler drops the bales in the field creating a need for a collection system. A tractor-pulled bale stacker or self-propelled bale truck can be used to collect bales and transport them to field edge (Figure 3). Typically, the bale collection system can transport 12 bales at a time. Once bales are collected, they are stacked at a field edge location for either long term storage or until they can be transported.

Figure 3: Stacking of bales with pull-behind (left) and self-propelled (right) stackers

After being collected, bales are transported by semi-truck to either a satellite storage facility or directly to the biorefinery (Figure 4). Depending on State Department of Transportation (DOT) regulations and truck configurations, 36 or 39 bales can be transported in a single load. Creating and maintaining high quality bales is essential to the supply chain because several pieces of equipment will handle the bale before it reaches the biorefinery. In a system that uses field edge stacking and satellite storage facilities, a bale may be handled five times prior to reaching the biorefinery. Each time a bale is handled, the risk increases of damaging the integrity of the bale. For this reason it is essential that high quality bales are created by the baler and maintained by each piece of equipment in the supply chain. Damaged bales require special handling or may be unusable if the damage is too severe. This slows the supply chain process down and increases overall cost of the system.

Figure 4: Telehandler loading semi-truck with bales

Harvest KPI Metrics

The corn stover harvest industry is relatively new in comparison to traditional grain harvest or forage harvest operations. For this reason there exists a need to develop performance metrics to evaluate the supply chain. The supply chain evaluation can be broken down into two distinct categories: bale quality metrics and machinery performance metrics. Together these two categories provide insight into how efficiently the system is performing, both on the micro and macro level. The machinery performance metrics look at the individual stages and provide the low level details. The bale quality metrics are more of an overall supply evaluation as several operations impact the final bale condition.

The machinery performance KPI's are used to evaluate performance both across the harvest season and also to compare one harvest year to another. One of the most useful metrics used to evaluate machine performance is machine productivity. This is a measurement of how much time the machinery is in a productive state divided by total machine on time. This is evaluated differently for each type of machine. Based upon previous studies, a performance evaluation has been developed based upon ground speed and PTO speed (Covington, Askey, Powell). For shredders and balers if the ground speed is between 2 mph and 10 mph and the PTO speed is greater than 700 RPM, then the machine is considered to be in a productive state. If the machine is turned on but is not moving and the PTO is not running then it is considered to be idle. When the machine is traveling at a speed greater than 10 mph then it is considered to be in transport mode. Every data packet sent from the telemetry data logger sends a status of either "Productive," "Idle," or "Transport." From these status updates the overall productivity of the machine can be determined in total time (hours) or as a percentage. Typically, on time will be reported as a total time and machine status will be reported as a percentage.

Evaluating the machine status is important because it provides a detailed view of how well a machine is being utilized. A machine may have a low productivity percentage for a number of reasons: poor field conditions, excessive machinery breakdown, or management practices. If a field has several balers in it operating at the same time, the productivity of each machine may be reduced due to the in-field interaction of multiple machines. Using these KPI's addresses management practices that may seem counterintuitive. The belief may be that sending multiple machines to a field will allow for faster field completion time and will improve productivity. However, too many machines in a field actually hurts individual machine performance and results in a reduction of potential performance. Keeping machines productive is critical to maximizing value in the supply chain. Harvest equipment machinery is a valuable asset and when the machines are in an idle status they are increasing operating costs without adding value.

Results

Baler Performance KPI's

During the 2013 and 2014 harvest seasons, productivity reports were made available to management within the supply chain. Having transparency for the harvest data identified where inefficiencies existed and showed where improvements could be made. The desire was to get to a deeper level of understanding on what changes could be made to management practices. Many of the decisions for harvest practices were based upon limited data availability or on past experience. This isn't to completely discredit management experience but sometimes the data will show a different outcome than was expected.

Figure 5 shows the comparison between 2013 and 2014 data for baler productive hours. In 2013 a baler was in productive status for nearly 3.5 hours per day while 2014 had an increase to 4.6 hours per day. This does not take into account the total time the machine was operating but only shows the actual time where bales were being produced. It is important to know what the actual operating time during the day is to know what the expected bale production is. One of the observations of this study was how much a baler can actually run in a productive state for a given day.

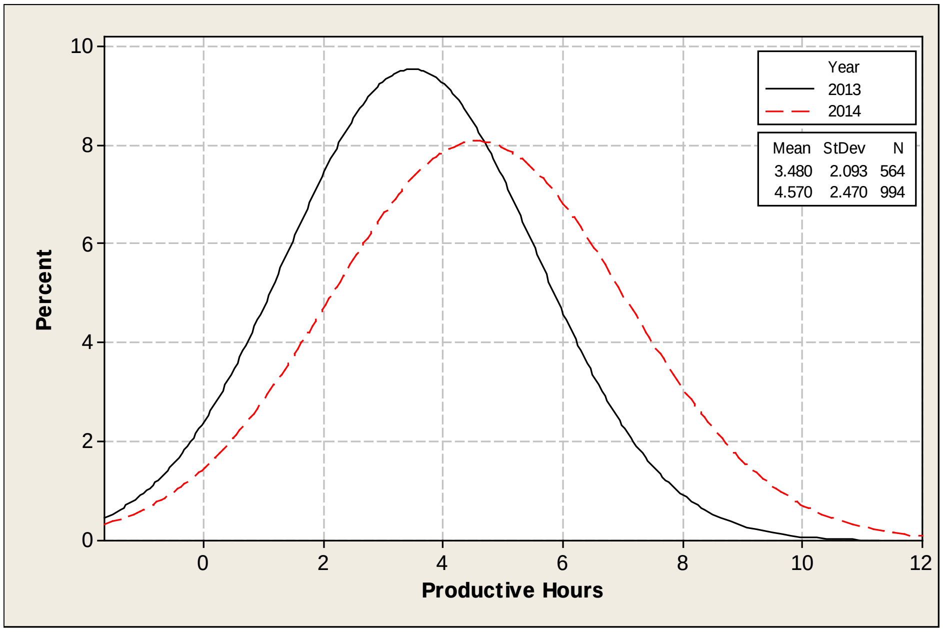

Figure 5: Baler daily productive time by year

The daily productive time is only part of the time the baler is operating. There are still instances where the baler will be running but not producing bales; this is denoted as idle time. Because of this idle time it is important to understand what percentage of the total operating time the baler is being productive. The baler productivity metric shows what percentage of total operating time the baler is producing bales. Figure 6 shows the baler productivity being 58% for 2013 and 71% for 2014.

The daily productivity values had one of the largest increases of all KPI metrics from 2013 to 2014. There were several reasons for this increase. A managerial decision was made in 2014 to incentivize harvest crews to minimize idle time in order to improve machine productivity and reduce overall supply chain costs. Because of this, machine operators paid more attention to machine idle times and shut the tractor off rather than idling the machine. The machine performance KPI data was also made more transparent to all crews in 2014 and allowed for improved management. Having data available created feedback on machine performance and allowed for quicker adjustment to machine operating settings.

When evaluating baler performance the metric of daily bale production is used. Productivity is an important metric but it does not provide a complete description. The productivity metric does not show what the total operating time is. It is possible to have two balers with high productivity but can have very different operating times. The productivity and operating time metrics are important but the main factor is the number of bales produced during a given day. Ideally a baler will be operating at a high productivity and producing a high number of bales each day.

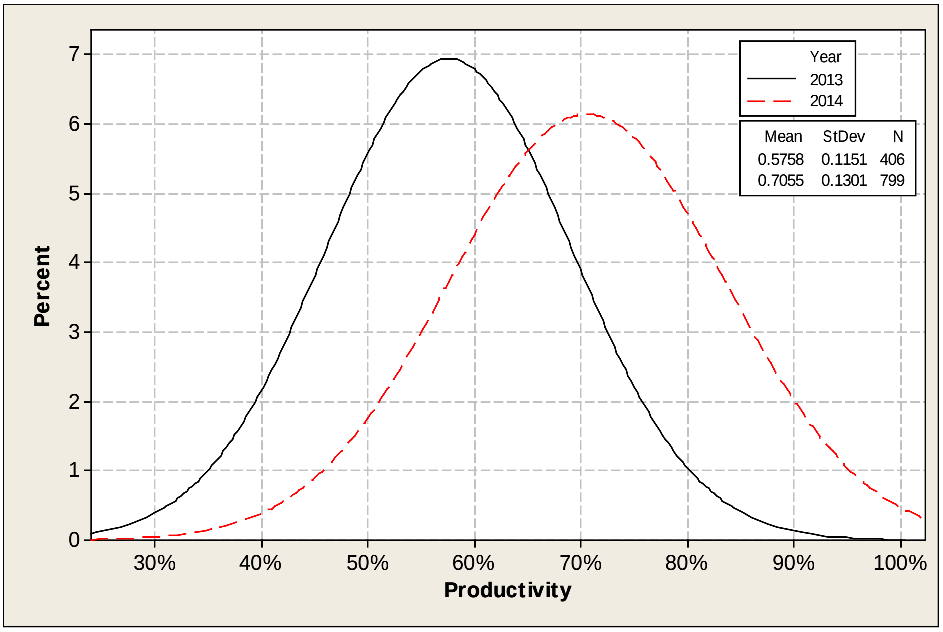

Figure 6: Daily baler productivity % by year

The other part of the bale productivity evaluation is the actual number of bales being produced. Typically this is evaluated as bales per productive hour or bales per day. Both metrics are valuable for monitoring machine performance. The bale per productive hour metric shows how efficiently bales are being produced when the machine is in productive state. This simply calculated as the number of bales produced divided by total productive time. This does not take into account any idle or transport time where the machine is not capable of producing bales.

Figure 7 shows the relationship for bale production and productive hours for 2013 and 2014. Each data point represents a single baler for a single day. The relationship is very linear with an R-squared value of 0.83 and 0.89 for 2013 and 2014, respectively. This is due to the fact that there is an upper limit to how many bales can be produced in a given timeframe. The baler has a mechanical limitation that will physically limit how much material can be baled. An increase in ground speed or available material will not be able to further increase this value. For 2013 and 2014 harvests, the average baler production was 51 and 55 bales per hour, respectively.

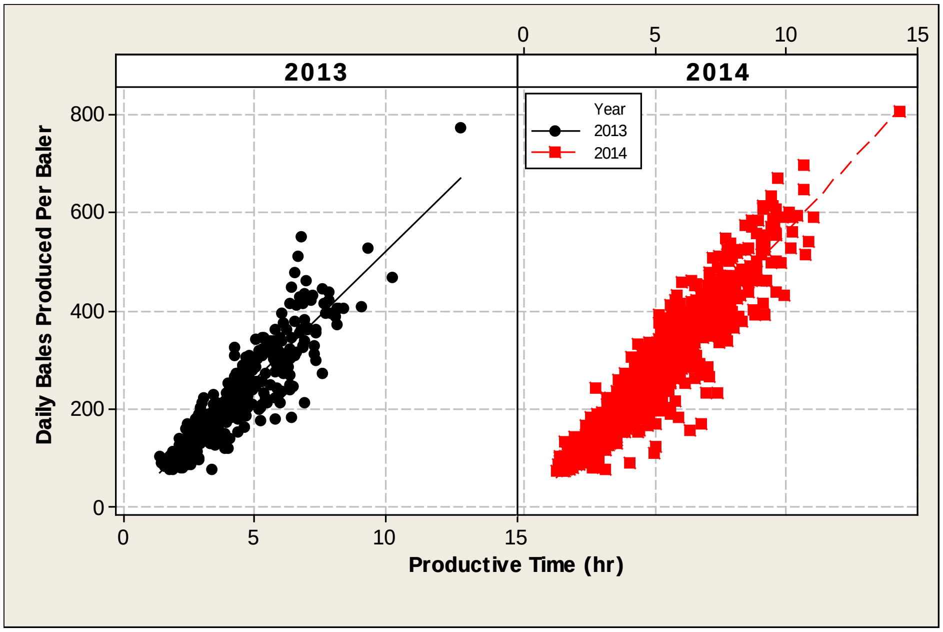

Figure 7: Daily bales produced vs productive time for 2013 and 2014

The bale per productive hour value had a low level of variation due to the fact that when the balers were running near capacity when operational. Because of this linear relationship and low variability, knowing the baler productive hours for a specific day provided insight into what the expected bale production would be. Based upon the known productivity of the balers and the field conditions, a target goal of 300 bales per day per baler was established. This would result from a baler operating for six productive hours and producing 50 bales per productive hour. Based upon the plot shown in Figure 8, approximately 20% of balers were producing 300 bales each day in 2013 while 40% reached the target in 2014.

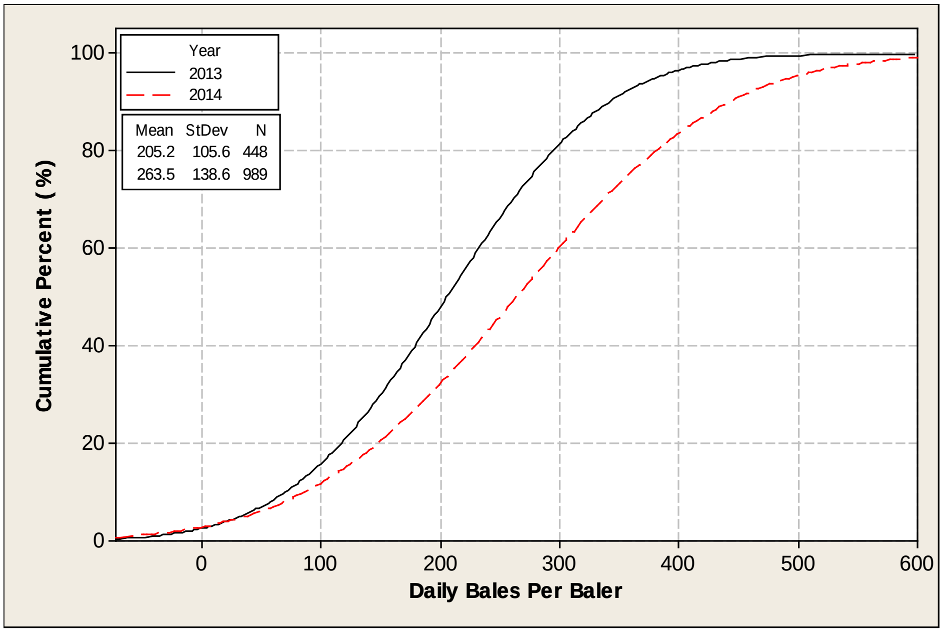

Figure 8: Cumulative percentage of daily bales produced per baler

Bale Quality KPI's

While performance KPI metrics evaluated how well the machinery was operating, bale quality KPI metrics evaluated the bales once they were produced. As previously stated, bale quality is important because it impacts several aspects of the supply chain. Low quality bales will increase handling and storage costs and increase the difficulty of transportation to the biorefinery.

The primary bale quality KPI metric is bale density. The bale density is important because it has a significant impact on overall supply chain cost. Based upon the work of Shah, bale density is the single most influential factor in determining overall supply chain cost for delivered corn stover to a biorefinery (Shah, 2013). Increasing bale density reduces the number bales required to be produced. This will decrease the operating cost for shredders, balers, and stackers and will reduce the number of loads to be transported to the biorefinery. Every time a bale is moved or transported, additional cost is accrued. A reduction in total bales will result in an overall supply chain cost reduction.

Bale density is calculated from the bale weight divided by bale volume. An adjustment factor is added to account for moisture content which impacts the density of bales. Because of the moisture content factor, all bale density calculations are adjusted for 0% moisture content to remove bias. With all bales being calculated as 3 ft tall, 4 ft wide, and 8 ft long, each bale has a volume of 96 ft^3. Additionally, bale density was calculated on a field average rather than a daily average used for machine performance. Bale core samples were taken from bales once a field was harvested and a field level density value was calculated from the reported moisture content.

Figure 9 shows the bale density for 2013 and 2014. Two distinct trends are shown in the year by year comparison. First, the average density made an increase of 0.5 lbs/ft^3 from 2013 to 2014. This was a significant improvement that showed how bale quality was able to increase as data became more available to harvest crews. Also, the majority of the harvest crews that were used during the 2013 harvest returned the following year. This continuity between years allowed for the knowledge gained during the 2013 harvest year to be used during the 2014 season. Typically, there is a ramp up period early on in the season where machinery settings are being fine-tuned based upon the field conditions. In 2013 it was observed that densities were lower during the early season harvest as crews adjusted. However, in 2014, it was shown that crews could use the knowledge of the previous season and begin harvesting at higher densities earlier on in the harvest season.

The second trend observed was the decrease in standard deviation, or variability, in the bale density from 2013 to 2014. Not only was the average density value increased, but the range was decreased, resulting in a more uniform density across the entire 2014 harvest. This is important because variability increases cost for the supply chain. As previously stated, there is an upper limit to the actual densities that balers can achieve. In order to increase the overall bale density mean, the lower density needs to be increased. This was achieved by reducing the variation in bale density. While field conditions and stover availability vary from field to field, a bale density of at least 11 lb/ft^3 is the target for bale production.

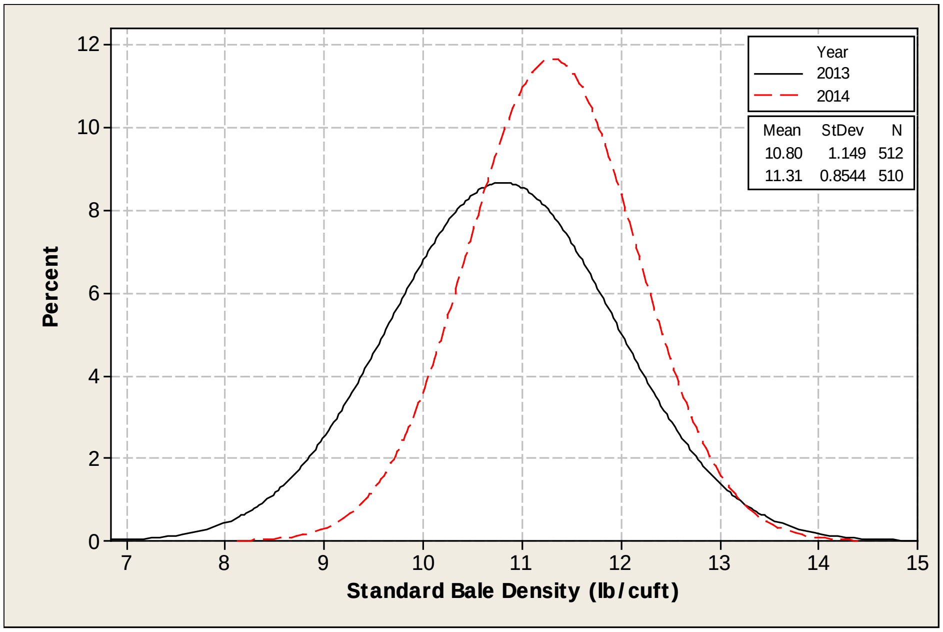

Figure 9: Standard bale density for 2013 and 2014

The previously described KPI metrics were chosen in part to their impact upon overall cost of harvested corn stover. Bale density and machinery productivity have been identified as having significant impact upon cost (Shah, 2013). Additionally, these are metrics that are both observable and to a certain extent, controllable. There are factors that may be able to reduce cost, but they are not realistically adjustable. For example, increasing the harvest rate of material removed from a field will reduce cost because it reduces the number acres required to reach target harvest quantities. However, the harvest rate is dictated by the available stover and varies greatly from year to year and from field to field. Harvest rate must also be controlled in such a way to remain sustainable.

Techno-economic Analysis

Understanding the harvest performance and KPI's gives valuable insight into what expected ranges of operation are achievable for a commercial scale corn stover harvest. These values can be used to compare yearly harvest costs. Identifying which factors have the most potential for improvement will allow for reduction in overall cost. In some cases, changes in one area of the supply chain will lead to changes in another. A techno-economic analysis allows for these tradeoffs to be evaluated for impact on total supply chain costs.

A techno-economic analysis has been developed at Iowa State University to analyze yearly harvest costs. This model uses the previously discussed KPI metrics as well as other recorded data from the telemetry data loggers. The yearly increase in machinery productivity and bale quality can be quantified by overall changes in cost to the supply chain. For this analysis, an in-field only analysis was performed on the operations of shredding, baling, and stacking at field edge.

Based upon the analysis the in-field harvest operation cost for 2013 and 2014 was $42.03 and $33.14 per dry ton, respectively. The year-to-year improvement in harvest productivity resulted in cost reduction of nearly $9.00 per dry ton, or about 20%. From table 1**,** the greatest reduction in operational cost was observed by the baler. A reduction of $6.83 per dry ton was observed from 2013 to 2014. The baler productivity increased significantly from 58% to 71%. The increase in productivity increases the total material that can be baled by the baler and reduces the total number of machines required for harvest.

The increase in productivity only impacts the baling operation. However, the increase in bale density impacts both the baling and stacking productivity, thus reducing cost in both operations. From 2013 to 2014, the bale density increased from 10.8 lb ft^{-3} to 11.3 lb ft^{-3}. This increase in density reduced the total number of machines for harvest and the total machine hours required. Also, this increase in density impacted the stacking operation. The stacker typically collects a dozen bales per load and the increase in bale density reduces the total number of loads required to move material from the field to field edge stack. While this analysis does not include over the road transportation, the increase in bale density would reduce those costs as well.

Table 1: Techno-economic analysis for 2013 and 2014 harvest

Operation	**2013**	**2014**
Shredding	$7.49	$7.13
Baling	$24.20	$17.37
Stacking	$10.34	$8.64
Total	**$42.03**	**$33.14**

Conclusion

As cellulosic ethanol biorefineries reach commercial scale operation, it will be important to monitor performance and continually evaluate efficiency. Use of telemetry data collection allows for data to be quickly processed and analyzed. Field conditions can vary greatly and having access to data will allow for improvements in harvesting performance. Collecting the appropriate data is also important for developing KPI metrics that drive change in the harvesting operation.

Improvements in machinery productivity can be attributed to having data available that allows for feedback on performance. The baler productivity improved from 58% to 71% between 2013 and 2014. The bale density also increased from 10.8 lb ft^{-3} to 11.3 lb ft^{-3} between 2013 and 2014. Improvements in machinery performance and bale quality KPI's will further reduce overall supply chain system and help to identify other areas where potential for cost reduction exists.

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