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Geographic information system tools for the analysis of commercial level multi-pass corn stover harvesting systems

by

Kevin Scott Peyton

A thesis submitted to the graduate faculty

In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Agricultural Engineering

Program of Study Committee:
Matthew Darr, Major Professor
Brian Steward
William Edwards

Iowa State University

Ames, Iowa

2012

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ABSTRACT

Renewable fuel production is essential to improve the energy independence of the United States. Cellulosic ethanol is renewable fuel that is gaining traction in the commercial fuels industry. This fuel can be made from agricultural residues and dedicated energy crops widely available in the Midwestern United States. The biofuels industry is already moving to meet these federal biofuels mandates and to establish sustainable biomass feedstock supply chains. Two companies have scheduled to build dedicated cellulosic ethanol refineries in Iowa. This initial phase of a biofuels supply chain is currently in its infancy and will require significant efficiency improvements and enhancement to current methods to ensure profitability. The resulting harvest costs, transportation costs and material quality all have significant impact on the cellulosic ethanol industry.

The objective of the first chapter of this thesis was to determine the best method for semi-automated and large scale analysis of machinery management parameters. Electronic data logging of GPS position and CAN messages provides the timing and operational status needed for calculation of machinery management terms. Additional information like fuel rate, engine speed, hydraulic flow, or specific implement parameters can also be captured. This data enables detailed performance evaluation. GIS software was used to query the dataset. Appropriate spatial selections and parameter filters were defined for each performance parameter. This ensured measurement of productivity terms in conformance to ASABE Machinery Management Standards.

The objective of the second chapter was to quantify and provide detailed information on the performance of corn stover collection equipment during industrial scale harvest operations. Current equipment developed for the hay and forage industry can be used to

harvest corn stover. Understanding the performance characteristics of this repurposed forage equipment is critically important for the continued development of the cellulosic ethanol industry. Two windrowers, two square balers, and a bale collection system were evaluated as part of a 2010 partial corn stover residue harvest. An examination of machine operation allows researchers to calculate management parameters like field capacity, field efficiency, and fuel consumption.

The combined methods and results developed and reported in these articles can be used to aid with equipment selection, develop economic models, and help managers estimate operating costs associated with process scale up. With accurate performance data on specific equipment, modelers can evaluate the impact of different harvesting scenarios. This can help certify that the prescribed and implement methods are practical, achievable, and sustainable.

CHAPTER 1. GENERAL INTRODUCTION AND REVIEW OF LITERATURE

Renewable fuels have become an important part of the United States economy. In 2010, ethanol alone accounted for nine percent of non-diesel transportation fuel used in the United States (EIA, 2012). The significance of renewable transportation fuel has been recognized by congress as an important step in energy independence. The Energy Independence and Security Act of 2007 outlines a plan to increase renewable fuel production through the year 2022. An important part of this plan is the increased production of cellulosic ethanol.

Cellulosic ethanol is a renewable fuel created from the cellulose and hemi-cellulose available in fibrous plant materials. The United States Department of Energy and Department of Agriculture indicate that corn stover, a residue left after grain harvest, is an underutilized source of cellulose widely available in the Midwestern United States (USDA, 2005).

Iowa is the national leader in ethanol production with 25 percent of the nation's ethanol being produced in Iowa biorefineries (Nebraska Energy Office, 2012). Iowa is also well poised to enter the cellulosic ethanol market. Two companies have developed plans to construct cellulosic ethanol plants and have begun work to develop feedstock supply chains. Both plants will require large amounts of corn stover, 300,000 – 400,000 tons per year per plant, to operate at capacity. This huge need for feedstock requires the partial collection of corn stover from over 150,000 acres around each refinery during nearly the same seasonal time interval as grain harvest. Harvesting at this high level of production requires a significant amount of organization, management, equipment and labor. Understanding the performance and cost of biomass harvesting equipment is of high importance to the industry. Obtaining relevant and accurate measures of operation will help managers design harvesting systems, control costs, and ultimately allow the corn stover supply chain to develop and succeed.

In order to understand the operating costs and supply chain dynamics associated with a corn stover supply chain, a 2,300 acre corn stover harvest was conducted in central Iowa in 2010 to determine the logistics requirements of industrial multi-pass baling. Multi-pass bale harvesting is one of the most common and scalable harvesting options for stover collection. Multi-pass operations utilize windrowing equipment to gather the stover and a baler to densify the material. A variety of harvesting methods were used to condition and bale the corn stover. Each tractor in this multi-pass bale harvest was instrumented to obtain the desired productivity data. GIS tools and methods were developed to synthesize collected data into terms and values necessary for operation management.

Objectives

The objectives for this research were as follows:

- Determine methods to extract performance metrics through GIS analysis
- Assess how performance metrics obtained in a production setting can be used to derive standard management terms
- Quantify the performance of corn stover harvesting equipment
- Develop a required equipment set for a corn stover supply chain

Thesis Organization

This thesis contains a general introduction, two research articles, and a general conclusion, as well as cited references and acknowledgments. The general introduction includes the objectives of the thesis, a description of the thesis organization, an explanation of the authors' role in each article and a brief literature review.

The first article entitled "Using GIS Tools for Analysis of Machinery Logistic Parameters" will be submitted to *Computers and Electronics in Agriculture*. This article describes how performance metrics can be extracted from spatial datasets. The second article, "Logistical and Productivity Analysis of Multi-Pass Corn Stover Harvesting Systems", will be submitted to the *Applied Engineering in Agriculture* journal. This article describes the performance of corn stover collection equipment during a production scale harvest in the fall of 2010. References for each section are included at the end of each chapter.

Authors' Role

The primary author, with the guidance, support, and assistance of co-authors composed all of the research articles presented in this thesis. Unless otherwise indicated, all procedures were performed by the primary author.

Dr. Matthew Darr conceived the original idea for performance measurement through spatial analysis. Dr. Matthew Darr also provided continual guidance throughout the result analysis and also provided writing and editing assistance.

Literature Review

Performance Metrics

Analysis and comparison of equipment systems requires a thorough understanding and standardization of performance metrics. Full definition of performance metrics will enable cross system comparison and ensure accuracy of results. To serve this purpose, the American Society of Agricultural and Biological Engineers have developed several standards documents that aim to clearly define and explain machinery management terms like field capacity, field speed, field efficiency, and operating width. ASABE standard S495.1 provides a glossary of performance terms that can be used to analyze agricultural systems. These terms are explained in further detail in an accompanying engineering practice document, ASABE standard EP496.3. Adherence to these standards is helpful as analysis results are used for purposes such as: machinery management, system design, economic modeling, biomass supply chain development, and countless others.

The performance terms described can be utilized to develop ideal harvesting systems that optimize equipment sets for maximum functionality. Buckmaster (2006) developed a model that was used to size a forage harvesting system. This model incorporates equipment performance metrics to optimize a harvest to storage system. Another model was developed by Sogaard et.al (2004) to optimize farm mechanization. The accuracy of this model is related to the accuracy of the provided input values. These inputs include experimentally obtained performance metrics described in the related ASABE standards.

Machinery performance data is also useful beyond system modeling activities. The same operational information used for system development can provide value and impact to individual operators. Taylor et. al (2002) developed methods to aid in farm management. Taylor explained how machinery performance indicators can be used to aid in machinery selection and implementation of support equipment.

Iowa State University Extension has developed an extensive tool that is designed to aid farm operators in effective management of all farm operations. A portion of this *Ag Decision Maker* is designed to help manage equipment needs and estimate costs. Machinery performance calculations and previously published experimental results are synthesized into modules that help estimate the time and economic requirements of farm operation.

The need for corn stover collection in Iowa is rapidly approaching and researchers are working to determine the impact and cost of the activities associated with partial stover collection. This corn stover supply chain is affected by a variety of factors and economic models are challenged to evaluate how these factors should be combined and scaled to produce the most realistic results. Supply chain models like the corn stover model developed by Sokhansanj et. al (2002) or the switchgrass model developed by Cundiff et. al (1996) utilize custom harvest rate surveys to compile cost data. Custom harvest rate surveys are compiled based upon averages of costs charged for services rather than the calculated cost to run the equipment.

Data Collection

Evaluation of machinery performance parameters is typically accomplished through some method of experimental data collection. The method in which this data is obtained has grown and improved along with the technology available to researchers. Renoll (1969) developed a method in which to use operation timing to calculate performance parameters.

The machinery operation was subdivided into core events (i.e. field travel, turning) and the time required for each event was recorded (Renoll, 1969).

This time-motion style analysis was very useful and is still very effective for the calculation of basic performance metrics. Time-motion studies require judicious researcher oversight. Harrigan (2003) utilized ride-in researchers to record time data for each activity in a corn silage harvesting operation. The timing data is combined with static information about the experimental region.

Global Positioning Systems (GPS) have rapidly become an important tool for agricultural operations. This tool has impacted the methods of agricultural data collection. Many farm operators utilize GPS based guidance systems for field operations. The yield monitors and mapping displays that are a part of guidance systems can be used to calculate performance metrics (Grisso, 2002). Timing information that was used with previous evaluation methods can be extracted from these guidance systems. Taylor et. al (2002) used data collected from a combine yield monitor to collect time-motion data and also measure additional performance parameters. Taylor was able to extract average harvest speeds and area information from his dataset through the use of GIS software tools.

Other researchers have utilized spatial data collection methods to their advantage. Amiama et. al (2008) utilized a custom telemetry system to collect performance parameters from a self-propelled forage harvester. The system utilized data collection through a direct connection to several sensors pre-existing on the machine. Additional aftermarket sensors were added to gain further analysis capability (Amiama, 2008). Like Taylor, Amiama used software tools to extract the data inputs necessary to derive standardized performance parameters.

Modern tractors are controlled by several microcontrollers that communicate on a controller area network (CAN). These controllers work together to synchronize activity on the tractor. The communication messages that are transmitted on the CAN bus can be a valuable source of information. These messages contain continuously updating information on engine performance, transmission activity, implement status, hydraulic system activity, navigation, PTO status, fuel rate and many others. Webster (2011) used spatially collected CAN data to assess a range of performance metrics. The additional availability of fuel consumption information allowed Webster to perform a full cost analysis and breakdown using the CAN parameters.

Previous methods to obtain operational fuel consumption involved additional fuel flow meters or fuel tank top off methods. Dumas et. al (1983) developed a method to determine the average fuel consumption of an experimental area. The tractor fuel tank was filled at the experiment start and refilled after the experiment was complete to obtain the volume of fuel consumed.

Kichler et. al (2007) created a system to measure the flow rate of fuel pumped to the combustion chambers. This measured flow rate and spatial information was recorded on a data acquisition system. GIS software was used for parameter extraction.

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CHAPTER 2: USING GIS TOOLS FOR ANALYSIS OF MACHINERY LOGISTIC PARAMETERS

A paper to be submitted to *Computers and Electronics in Agriculture* Journal

Kevin Peyton, Matthew Darr

Abstract

The performance evaluation of agricultural machinery aims to provide information about equipment capacity, efficiency, and variable costs when conducting standard field operations. An accurate assessment of agricultural machinery performance is a key factor in the development of system level supply chain models for agricultural and biofuels products. The method for collection of machinery operational data has transformed throughout the last century. Dated methods using stopwatches, clocks, and timers have been replaced by spatial data analysis. Electronic data logging of GPS position and CAN messages provides the timing and operational status needed for calculation of machinery management terms. Additional information like fuel rate, engine speed, hydraulic flow, or specific implement parameters can also be captured. This data enables detailed performance evaluation of machinery systems.

GIS software provides a platform to perform the spatial querying and data filtering necessary for accurate analysis. Appropriate spatial selections and parameter filters were defined for each performance parameter. This ensured measurement of productivity terms in conformance to ASABE Machinery Management Standards. The establishment of spatial

analysis techniques facilitates future process automation and real time calculation of performance terms.

Introduction

The performance evaluation of agricultural machinery aims to provide information about equipment capacity, efficiency, and variable costs when conducting standard field operations. An accurate assessment of agricultural machinery performance is a key factor in the development of system level supply chain models for agricultural and biofuels products. Currently standards exist which provide core definitions of machinery productivity terms and document general performance parameters for many standard agricultural practices. ASABE Standard S495.1, *Uniform Terminology for Agricultural Machinery Management*, was developed to provide standardized definitions of machinery assessment metrics. ASABE Standard EP496.3, *Agricultural Machinery Management*, was produced to demonstrate how measured data can be used to calculate the terms developed in S495.1. These machinery management standards have been used for a range of decision making tools including farm operations (Buckmaster, 2006), (Sogaard et. al, 2004), farm production economics (Iowa State University Extension, 2012), and biomass feedstock supply chains (Cundiff et. al, 1996).

While current standards do provide a starting point for machinery management, the performance data and crop applications that are included in the standard are dated and limited in scope (Grisso et. al, 2002). These limitations yield application constraints on the use of standards data outside of these standard parameter areas. For biomass feedstock development in particular, very little field data on machinery performance exists. Key generalized machinery performance metrics for field capacity, field efficiency, and productivity can be applied across many sectors of biomass supply chains. Additionally, simple variable cost functions such as fuel usage and breakdown intervals are very useful for complete documentation of system operation and optimization.

Effective area field capacity is a measure of the amount of area per unit time a machine can process (ASABE, 2005). Effective area capacity is a function of machine in-field speed during steady state conditions, the working width of the implement and field efficiency. In-field steady state speed is measured during an active pass of a specific machine in the central portion of the field. The field efficiency parameter applies capacity losses associated with headland operations and turning as well as inefficiencies from swath overlap. A simplified measure of effective field capacity is the total amount of area covered divided by the total time it took to complete that area including the time the machine was operating on the headlands. The theoretical area field capacity is measured in a similar manner, although without including the field efficiency term. The theoretical area field capacity is helpful in directly comparing the peak potential capacity of machines under steady state conditions and without biases caused by field efficiencies that may be more spatially dependent than machinery specific.

Effective material capacity is similar to area capacity, although it is measured in mass throughput rather than area coverage (ASABE, 2006). This term is a better measure of capacity for harvesting or material collection operations where the yield of the crop will have a significant impact on rate at which area is covered. Effective material capacity is expressed as a function of the field speed, implement width, crop production yield, and field efficiency.

Like the area capacity, a theoretical material capacity also exists which represents the steady state crop harvesting capacity.

Field efficiency is defined a ratio between the effective field capacity and the theoretical field capacity (ASABE, 2005). This value could also be determined from a time basis; the ratio between the theoretical time necessary and the time spent in the field (Sirvasta et. al, 1993). The general methodology for determining field efficiency is to directly measure the effective field capacity and to calculate a theoretical field capacity based on a segment of steady state performance. Once both field capacity parameters are directly measured the resulting field efficiency is calculated. Although calculated specifically to a single machinery function, the true field efficiency and capacity level will be dependent on local operating conditions such as soil suitability, field slope and shape, and specific machinery settings among others. These spatial factors are one reason why the estimates for capacity and efficiency in standards are highly variable.

True operational speed and the resulting material capacity at that speed is an important component in accurate determination of field capacity and other management calculations. This operational speed, or field speed, is the average travel rate for a machine operating continuously under normal conditions. This average should not include disturbances or interruptions in travel (ASABE, 2005).

The method for collection of machinery operational data has transformed throughout the last century. Past methods have utilized stopwatches, clocks, and careful oversight by an in-field researcher to collect field operation timing data (Renoll, 1969). This timing data is combined with information on the area of farmland covered and equipment details to calculate performance parameters. Global Positioning Systems (GPS) have changed the way that operational data can be collected. Many farmers utilize GPS based guidance systems for field operations. The yield monitors and mapping displays that are a part of guidance systems can be used to calculate performance metrics (Grisso et. al, 2001). The evaluation of these performance indicators can lead to better machinery management decisions (Taylor et. al, 2002). The position information can be combined with other inputs for more in depth analysis. Physical switches and sensors can be placed on a machine and tied directly into the data logger to indicate exact machine operation at each position in the field (Amiama et.al, 2008). Additional performance metrics can be calculated as supplementary data is available.

Fuel consumption, typically reported in volume per area, can be determined by filling a fuel tank at the beginning and end of an experiment (Dumas et. al, 1983). However, real time sensors can be installed and used to measure the instantaneous flow rate of fuel pumped to the engine (Kichler et. al, 2007). Another method is available to obtain fuel consumption information on modern tractors. Modern tractors are controlled by several microcontrollers that communicate on a controller area network (CAN). These controllers work together to synchronize activity on the tractor. The communication messages that are transmitted on the CAN bus can be a valuable source of information. These messages contain continuously updating information on engine performance, transmission activity, implement status, hydraulic system activity, navigation, PTO status, and many others. For example, one message indicates the current fuel consumption rate (Webster, 2011).

The demonstrated capability for GPS based systems with integrated CAN parameter logging provides a unique platform for improved determination of machinery management parameters such as field capacity and efficiency. Although the data structures and tools are in place, additional work is required to develop specific data manipulation criteria that can serve as standardized methods for rapidly assessing field level performance parameters. These rapid assessment tools will lead to a broader assessment of machinery performance for specific operations like biomass harvesting and will provide the framework to identify spatial influences and supply chain optimizations.

Research Objective

The research objective of this study is to establish a protocol for determination of effective and theoretical field area and material capacity for agricultural machinery based on analysis of machinery performance parameters commercially available through GPS and CAN based data acquisition systems. For the purpose of this research objective, a case study example of corn stover biomass harvesting systems was used.

Materials

Machinery Parameter Data Collection

Embedded CAN and GPS data logging systems were used to collect specific machinery parameters. The embedded and stand-alone nature of the loggers allowed units to be deployed into field level production environments with no additional input from equipment operators. Information transmitted from GPS through an RS-232 serial interface and from the vehicle Implement CAN bus was recorded simultaneously. Connection to the vehicle CAN bus provided continual information about the current status and operation of the tractor and implement. Specific machinery attributes collected included vehicle position as well as operational parameters for speed, engine loading and performance, and implement engagement among others. Table 1 provides detail on the parameters of interest and indicates what source was used to collect each attribute.

Table 1: Description and source of recorded parameters

Data	Source	CAN Parameters			Data Byte Filter Values		
		PGN	Start Bit	Length (Bits)	D0	D1	D2
Latitude	RS-232	-	-	-	-	-	-
Longitude	RS-232	-	-	-	-	-	-
GPS Speed	RS-232	-	-	-	-	-	-
Engine Load	CAN	61443	16	8	-	-	-
Engine Speed	CAN	61444	24	16	-	-	-
Engine Torque	CAN	61444	16	8	-	-	-
Hydraulic SCV Flow	CAN	65040	0	8	-	-	-
PTO Speed	CAN	65091	0	16	-	-	-
Engine Hours	CAN	65253	0	32	-	-	-
Fuel Consumption	CAN	65266	0	16	-	-	-
AGCO Flywheel Speed	ISOBUS VT	59174	24	8	168	251	46
AGCO Flakes Per Current Bale	ISOBUS VT	59174	24	8	168	249	46
AGCO Lifetime Bale Counter	ISOBUS VT	59174	24	8	168	249	3
Krone Flakes Per Bale	ISOBUS VT	59174	24	8	168	99	86
Krone Bale Count	ISOBUS VT	59174	24	8	168	85	86

For material capacity determination the harvest rate of the crop was also required. ISOBUS virtual terminal (VT) update messages were recorded from the CAN bus to provide key information related to location of bale tie-off events. Individual bale drop locations were integrated into larger harvest areas to determine total bales per unit of area harvested. When combined with an average mass per bale the in-field yield of biomass material could be directly calculated and enabled the determination of effective material capacity.

Software Analysis and Filtering

Geographic information system (GIS) software was used for direct spatial analysis of the collected harvest data. Each machinery specific parameter was associated with a specific GPS location and recorded as a new attribute with a one second temporal resolution. GIS software allows for fast and efficient spatial querying of machinery performance data and can be automated to provide specific reporting functions. Attributes can serve both categorical and continuous variable roles. An example of a categorical variable would be the binary on/off state of the tractor rear PTO which determines the engaged state of a rotary powered implement. An example of a continuous variable would be vehicle speed which changes throughout the field operation. All GIS examples presented in this paper were completed using the SMS Advanced GIS software package commercially available from Ag Leader Technology (Ames, IA). Figure 1 shows an example output from a baler dataset that shows the travel speed for each second of operation in the field.

Figure 1: Example attribute map of baler speed data

Case Study Data Set

From the 2,300 acres that were harvested in the fall of 2010, five representative fields were selected to demonstrate the GIS based machinery performance methods presented in this paper. The harvest operations in these fields included windrowing, baling, and stacking at the field edge. All data was generated during the fall 2010 corn harvest in central Iowa. Experimental treatments were predefined within production fields and included 20 acre blocks of harvest area to ensure sufficient steady state conditions. Results presented in this paper are summary results for individual treatment zones. Additional statistical analysis of all treatment zones across the experimental season can be used to conclude specific production differences between harvest equipment systems.

GIS data analysis also enables identity preservation of treatments factors in machinery productivity experiments. In the field shown in Figure 1, a change in swath width is visible between the right third and the remaining left section of the field. This indicates a change in experiment or operation. A reference of the related windrowing dataset shown in Figure 2 confirms the operation change and shows that a rake operated in the left portion of the field and a flail chopper operated in the right third creating a larger windrow and thus a larger swath width. Understanding, documenting, and querying the dataset in relation to these different field zones was essential for accurate evaluation of baler performance under these separate production scenarios.

Figure 2: Example map of windrowing operational area

Results

Area and material capacity calculations require vehicle speed, functional width, harvest rate, and efficiency to be known. GIS sampling strategies and queries were used to accurately assess each of these core parameters. Specific query tools enabled segmentation of steady state and total field operation time which supported direct assessment of capacity values. Results for each of these core parameters is presented in this paper with examples focused on biomass harvesting operations. However, the methods used are generic and can be applied broadly to other agricultural machinery operations such as sprayers, planters, tillage tools, and grain harvesting equipment.

Area Selection

Spatial data analysis allows the selection of data points based on geographical area. This spatial selection function is useful in the examination of performance parameters. Some performance metrics require a query of data at different levels of machine operation. Geographical location, speed clues, and engagement indicators can help software distinguish between different levels of operation. These engagement indicators could be a specific CAN message, a sensor input, or even an aftermarket switch. Example indicators include non-zero PTO speed, hydraulic flow, or thresher speed.

Specific metrics are only associated with the steady state, functional activity of the machine. In this case the dataset is filtered to include only the area in the central section of the field that has a positive engagement indicator. Other management terms are associated with all active data points throughout the field. This spatial selection would include the activity on the headlands of the field in addition to the steady state points in the center of the field.

Operational Speed

Field speed is the average rate of machine travel in the field during an uninterrupted period of functional activity (ASABE, 2005). This occurs while the vehicle is traveling in the steady state, central section of the field. In order to determine the average field speed of the equipment, spatial software was used to query the steady state, functional data. If appropriate CAN data for the engagement state is available, the query can be performed by directly utilizing this information. Otherwise, ground speed can serve as an alternative engagement indicator. Low or zero speed data indicates non-operational data that needs to be removed. It is advisable to also screen for low speed data even if a CAN engagement parameter is used to select active production areas. A distribution of vehicle speed within this interior field area often highlight anomalies associated with real field operations (Figure 3). Breakdown and other real stoppage events will result in recorded data points with zero actual velocity. These low speed data points represent interruptions in functional activity and should not be included the determination of field speed.

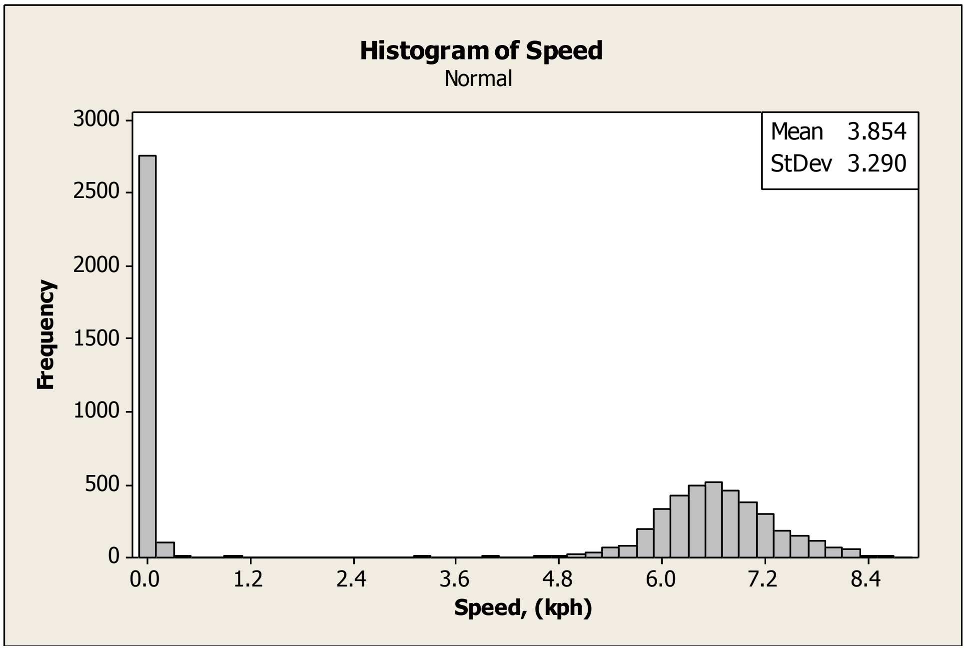

Figure 3: Example speed data histogram before stoppage filtering

Data filtering methods on the queried steady state area of the field were used to remove outliers at or near zero velocity. Through inspection of several field speed histograms, 2.5 mph was chosen as the standard threshold velocity for biomass harvesting operations to delineate between active and inactive field states within the central operating area. This velocity fell below the active speed range for all equipment analyzed. After these points are filtered a mean can be obtained that represents the field speed as defined by ASABE S495.1. Figure 4 demonstrates a mean that accurately represents the travel speed of the tractor while operational in a specific experimental zone.

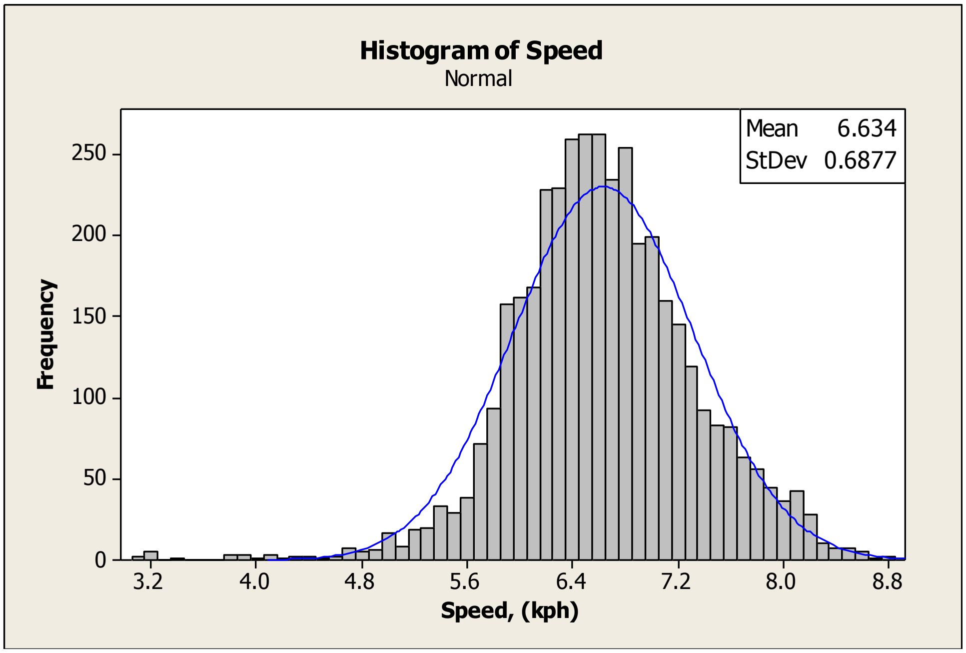

Figure 4: Example speed data histogram after stoppage filtering

A comparison of five randomly selected field zones within the case study data set was conducted to evaluate the impact of zero speed events within field scale experimental trials. Results, shown in Table 2, indicate that the frequency of stop events are random, but do have a significant influence on the calculated average vehicle speed. A large number of low speed events will have an impact on the reported average.

Table 2: Impact of filtering on five experimental zones

Experiment Number	Raw Speed Data Sample Count	Raw Speed Data Mean	Raw Speed Data Std Dev	Filtered Speed Data Sample Count	Filtered Speed Data Mean	Filtered Speed Data Std Dev
1	6875	3.854	3.29	3965	6.634	0.6877
2	802	5.41	2.19	687	6.26	0.7074
3	2810	3.172	3.503	1262	6.953	1.126
4	5420	1.521	2.239	1654	4.858	0.5717
5	4071	3.272	2.09	2993	4.427	0.947

Operational Width

Operational width, or effective width, is the width across the implement over which the machine actually works (ASABE, 2005). This is the width of the implement that is actually utilized on an area of the field not previously covered. Measurement of operational width should occur in the central section of the field during regular operation. This measurement can be easily accomplished in most GIS software packages by using a distance measurement tool. The software measurement tool can be used to measure the distance across a series of regular passes in a direction perpendicular to the travel direction. Figure 5 shows a GIS tool being used to obtain the desired distance. The tractor in Figure 5 example traveled through the field with a bearing of 0.0 or 180.0 degrees.

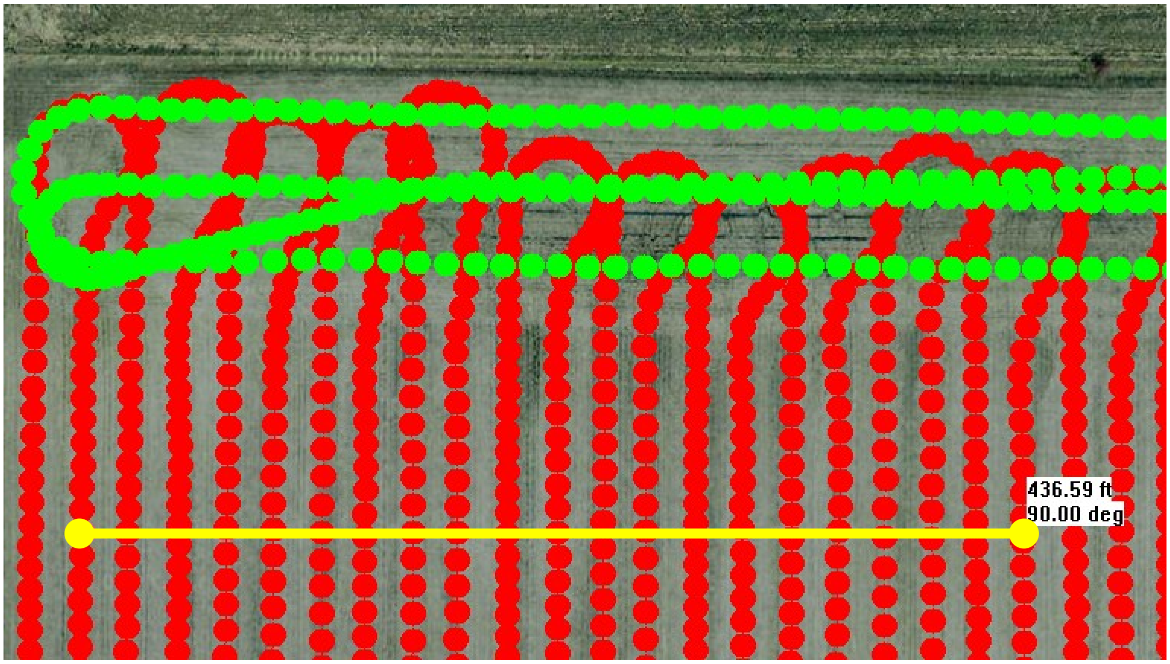

Figure 5: A GIS measurement too being used to measure operational width

The distance should be measured across several passes through the field for two reasons. Software tools are more accurately used across longer distances and thus data quality is improved. Measurement across several passes allows an average of the experimental zone to be taken in one step which improves data collection efficiency and reduces sample noise. The distance measured divided by the number of passes measured provides an accurate evaluation of the effective operating width.

Effective width can be compared to the theoretical operating width of the implement. Difference between effective and theoretical operating widths is not a metric of equipment capacity, but rather a measure of equipment operator skill. These two values can be used to calculate the swath efficiency of that operation. Swath efficiency was calculated for each experiment using this developed equation:

$$E_s = 1 - \frac{w_t - w_e}{w_t} \quad (1)$$

where E_s = swath efficiency, decimal

w_t = theoretical swath width, m

w_e = effective swath width, m

Although overlap efficiency is a part of the overall field efficiency, it is beneficial to calculate separately. The implementation of an automated GPS guidance or steering system can eliminate overlap and effectively improve this term to one. Consequently, the overlap efficiency can be used by precision agriculture professionals to determine payback on guidance equipment implementation.

Harvest Rate

Harvest rate is a description of how much material, or crop, is being processed per unit of time. This term takes on a variety of forms in different harvesting systems. In the biomass harvesting case study, the harvest rate refers to the amount of corn stover that was processed or baled in one hour. This rate could be calculated in a common mass per time format and reported as tons of stover per hour. Baling systems present a second harvest rate metric associated with individual bale creation. The harvest rate could be expressed in the unit per time value of bales per hour.

The unitized approach is an option that can be calculated using GIS data exclusively. When a baler nears the end of a bale, a series of discrete events execute to complete one bale and start the next. The baler control system senses and controls these events through signals transmitted on the ISOBUS network on the baler. These signals, recorded by the logging equipment, can be used to discern the number of bales created in the experimental zone.

Some of the ISOBUS VT messages listed in Table 1 can be used to distinguish the bale end event within the GIS software. The bale count messages will increase by one at bale end while the flakes per bale messages will reset to zero.

ISOBUS VT messages are only transmitted across the bus when the value changes. For example, after bale number 1234 is complete, one message will be sent that indicates the bale count is 1234, instead of a message containing this information transmitted at a continual rate. This allows a simple sample count query in the GIS software package to return the total number of bales created in an experimental area.

This area based measurement necessitates an assessment of time required to harvest the area. ASABE S495.1 defines field time as the time spent in the field from the start of a functional activity to the end of the functional activity. However, ASABE EP496.3 clarifies that field time does not include repairs, preventive maintenance, or daily service. Thus, field time is the time spent underway in the central part of the field and on the headlands. If a complete data set is available, field time can be obtained by performing a query including headlands and filtering out low speed points as described previously. The number of data points active after filtering was recorded as the number of seconds required to complete the zone. This calculation of field time was available due to the 1 hertz recording frequency of the logging equipment. With both pieces of information, the total number of bales and the field time, the unitized harvest rate can be calculated in bales per hour.

In order to evaluate harvest rate on a mass per time basis, additional sensor information is necessary. Sometimes sensor technology can be used to calculate a mass based harvest rate in real time. Grain combines have integrated sensing technology that is able to measure the flow rate of material through the combine. This flow rate of material is synonymous with a mass based harvest rate.

Theoretical Area and Material Capacity

ASABE S495.1 defines theoretical field capacity as the rate of performance obtained if a machine performs its function 100% of the time at a given operating speed using 100% of its theoretical width. This term, which defines the maximum area capacity of a machine, is designed to be the best that the equipment can perform. The theoretical area capacity of the machine is measured in an area per time value, for example, hectares per hour.

This standard expands to describe a theoretical material capacity which combines the area capacity term with crop yield. The material capacity value describes the material processing rate of the machine. After combination with yield, the hectare per hour term is transformed into a ton per hour term. Whether an area capacity or a material capacity values is used depends on the type of equipment under analysis. Both types of capacities were used in the assessment of the corn stover harvesting example. The area capacity term is appropriate for windrowing equipment where width is the prevailing factor. However, baling performance is better related to crop throughput and thus it is better to use a material capacity for baler evaluation.

Theoretical field capacity is not designed to account for any non-productive time in the field. Turning on headlands and swath overlap is not included in this term. The operating speed calculated previously is a good fit for theoretical capacity evaluation. This speed was calculated from operational data points in the central, steady state portion of the field. The theoretical area capacity is the product of operating speed and maximum implement width. The theoretical material capacity can be determined by calculating the product of the area capacity and the average yield of the material harvested. Table 3 provides an example of the two types of theoretical capacities calculated for a single baler.

Table 3: Example baler theoretical capacities

Experiment Number	Theoretical Area Capacity (ha/hr)	Theoretical Material Capacity (ton/hr)
1	4.7	14.8
2	5.0	15.0
3	5.9	14.3
4	6.7	14.9
5	5.7	14.3

Effective Area and Material Capacity

Effective field capacity is a term that describes actual machine performance as completed in a field. This is a term that allows managers and operators to understand what sort of capacity can be realistic obtained during equipment operation. However, effective field capacity is not designed to account for all non-productive events necessary to complete harvesting operations. According to ASABE Standard EP496.3, field efficiency accounts for swath overlap, operator ability, turning, and field characteristics. Road travel, major repairs, preventive maintenance, and daily service activities are not included. The standard describes effective field capacity simply as the theoretical field capacity multiplied by the field efficiency. This method requires the use of an assumed field efficiency selected from a wide range of possible values.

As with the theoretical capacity, the effective capacity can be calculated on an area basis as well as a material basis. The units of effective area capacity are hectares per hour while material capacity values are reported in tons per hour. Spatially collected data provides an opportunity to calculate the effective field capacity directly from production data rather than make field efficiency assumptions. An area measurement GIS software tool can be used to calculate the area of the field that the implement was functional in. If the entire field was harvested, the area value for calculation is the same as the size of the field. The effective capacity term includes turning on headlands and overlap, but does not include non-operational, low speed data points. The field time described previously as a part of harvest rate evaluation is also an appropriate term for effective capacity evaluation. The effective field area capacity is equal to the area factor divided by the time factor.

Effective material capacity can be calculated from a field level as well. In order to understand the total mass of stover collected the unitized harvest rate in bales per hour can be combined with an average bale mass. This bale mass is not a value that can be accurately collected using available real time sensors. This metric depends on external values provided by the user. This external term can transform the harvest rate into the effective material capacity in tons per hour.

Efficiency

ASABE S495.1 describes field efficiency as the ratio between the effective field capacity and the theoretical field capacity. The overall field efficiency can be accurately calculated from the spatially determined field capacity values. This term incorporates the inefficiencies associated with regular, in-field machine operation. Turning on headlands, swath overlap, operator skill, and field conditions are incorporated as part of this metric. Transportation between fields, machine repair, preventative maintenance, and daily service is not included as part of this term. A calculation of field efficiency for windrowing operations in five example fields is shown in Table 4. This term can be useful to managers with the knowledge that allowance for service and breakdown is required in addition to the field efficiency term. Updated field efficiencies can be used to help transform the easily obtained theoretical field capacity to the more useful effective capacity on new or different equipment.

Table 4: Windrower field efficiency calculation for five example fields

Experiment Number	Theoretical Field Capacity (ha/hr)	Effective Field Capacity (ha/hr)	Field Efficiency
1	5.24	4.62	0.88
2	5.46	4.66	0.85
3	4.69	3.74	0.80
4	4.84	4.02	0.83
5	5.23	4.25	0.81

Fuel Consumption

While understanding the timing aspect of harvest operations is essential for decision makers, fuel use is also a notable consideration as fuel consumption contributes to the variable cost of an operation. Understanding the fuel consumption characteristics of field machinery is more straightforward than understanding the capacity of the machine. The primary fuel use occurs while the equipment is in full operation within the experimental zone. Therefore, a spatial query of data excluding headlands and non-operational data points provided an appropriate source of information for this metric. Fuel consumption is an available message on the CAN bus that was recorded with the logging equipment. Details of this message are displayed in Table 1. This value was averaged to provide an understanding of fuel consumption rates in each experiment. The volume per time metric is suitable for most equipment although this value can be transformed to other useful terms. For example, Table 5 shows an example from corn stover collection where a L/ton term was calculated from the product of the L/hr fuel consumption rate and tons/hr harvest rate. This type of term can provide additional value to economic models.

Table 5: Average baler fuel consumptions for five example fields

Experiment Number	Fuel Consumption (L/hr)	Fuel Consumption (L/ton)
1	27.94	1.27
2	24.35	1.64
3	21.89	1.04
4	21.91	1.66
5	22.33	1.64

Conclusion

The use of Global Positioning Systems has brought about a new era of machinery management data collection. The ability to accurately time and track equipment spatially eases and improves the data collection process. This information is further improved by harnessing the operational data streams available on controller area networks. Linking position to operational data allows for more in-depth analysis than previously possible.

GIS software can be used to perform queries and extract data for machine performance analysis. Standard queries and filters for each performance metric were developed to ensure analysis conforming to ASABE standards for machinery management. Definition of the parameters for each metric facilitates the future automation of spatial data analysis.

In order to calculate in-field parameters like operational speed and fuel consumption the GIS software was used to remove headland areas and non-engaged data points. The data was then filtered to remove low speed data points before the average of speed or fuel consumption was made. These values can then be used for calculation of management terms like theoretical area and material field capacity. For entire zone parameters like effective field capacity the same low speed filtering process was completed, but on a selection of data including the headlands. The measurements made within the GIS software were direct inputs into calculations of performance metrics.

GPS data alone allows a number of management terms to be evaluated including field speed, effective swath width, overlap efficiency, and theoretical field capacity. With the addition of CAN data logging additional performance metrics like harvest rate, effective field capacity, field efficiency, and average fuel consumption can be calculated.

Performance metrics provide farm operators and industry managers with information necessary to plan and organize field operations. The importance of accurate, realistic information is increasingly important as operations are scaled to multiple machines and larger harvesting areas. This type of capacity, efficiency, and fuel consumption information is essential to the continual development and improvement of agricultural industries.

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CHAPTER 3: LOGISTICAL AND PRODUCTIVITY ANALYSIS OF MULTI-PASS CORN STOVER HARVESTING SYSTEMS

A paper to be submitted to *Applied Engineering in Agriculture*

Kevin Peyton, Matthew Darr

Abstract

Renewable fuel production is essential to improve the energy independence of the United States. Cellulosic ethanol is renewable fuel that is gaining feasibility and traction in the commercial fuels industry. This fuel can be produced from agricultural residues or dedicated energy crops widely available in the Midwestern United States. The biofuels industry is already moving to meet federal biofuels mandates and to establish a biomass feedstock supply chain. Two companies have scheduled to build dedicated cellulosic ethanol refineries in Iowa. This initial phase of a biofuels supply chain is currently in its infancy and will require significant efficiency improvements and enhancement to current methods to ensure profitability. The resulting harvest costs, transportation costs and material quality all have significant impact on the cellulosic ethanol industry.

Current equipment developed for the hay and forage industry can be used to harvest corn stover in a multi-pass configuration. Two windrowers, two square balers, and a bale collection system were evaluated as part of a 2010 experimental corn stover harvest. Understanding the performance characteristics of this repurposed forage equipment is critically important for the continued development of the cellulosic ethanol industry. An examination of machine operation allows researchers to calculate management parameters

like field capacity, field efficiency, and fuel consumption. Standardized management metrics can be used to develop economic models and help managers estimate operating costs associated with process scale up.

A systems level analysis of the equipment combinations indicate that at an industrial scale the type of windrowing equipment has a significant impact on the capital, labor, and variable costs associated with harvesting activities. With accurate performance data on specific equipment, modelers can evaluate the impact of different harvesting scenarios. This can help certify that the production methods are practical, achievable, and sustainable.

Introduction

Renewable fuel production is essential to improve the energy independence of the United States. The Midwestern United States is already heavily involved in lowering the dependence on oil through the production of renewable fuels like ethanol. Ethanol derived from corn grain is already an important part of the nation's renewable transportation fuel portfolio. Cellulosic ethanol is another fuel that is gaining feasibility and traction in the commercial fuels industry. This renewable fuel is created from the cellulose and hemi-cellulose available in fibrous plant materials. The Energy Independence and Security Act of 2007 mandates that cellulosic ethanol increase in production through year 2022 (EISA, 2007). This act requires that cellulosic fuel production meet a volume capacity of 250 million gallons by 2011 and a further increase to 16 billion gallons by 2022.

The ability to economically harvest and transport biomass feedstock is essential to the development of commercial scale cellulosic ethanol production in the Midwestern United States. This initial phase of a biofuels supply chain is currently in its infancy and will require significant efficiency improvements and enhancement to current methods to ensure profitability. The resulting harvest costs, transportation costs and material quality all have a significant impact on the cellulosic ethanol industry. The long term sustainability and cost competitiveness of the cellulosic ethanol industry will be directly related to these harvest and transportation activities.

The Midwestern United States has already experienced industry movement to meet these federal biofuels mandates and to establish a biomass feedstock supply chain. Two companies have scheduled to build dedicated cellulosic ethanol refineries in Iowa. POET Biorefining announced the development of a 25 million gallon per year cellulosic ethanol facility slated to begin production in 2013. This facility will generate renewable fuel from corncobs, leaves and husks, the material left after grain harvest and commonly referred to as corn stover (POET, 2011). A second company has also selected Iowa as the location for a cellulosic ethanol facility. DuPont Cellulosic Ethanol (DCE) has purchased land and is launching programs to develop a corn stover supply chain throughout central Iowa. DCE has developed a pre-commercial facility in Tennessee that is currently generating ethanol from cellulosic sources. This same technology will be used in the Iowa commercial scale facility (DDCE, 2011).

Corn stover is a viable cellulosic ethanol feedstock due to its widespread available in the Midwestern United States. While it is important to maintain partial residue cover in the field for erosion control and organic matter return, a portion of this residue can be harvested with manageable effects. A joint study conducted by the United States Department of Energy and the United States Department of Agriculture indicates that corn stover is an underutilized source of cellulose with approximately 75 million dry tons available for harvest at a sustainable collection rate (USDA, 2005). Sokhansanj reports that only about 6% of stover is currently harvested (Sokhansanj et. al,2002).

Iowa already leads the nation in biofuel production capacity and is poised to play a large role in the development of cellulosic biofuels as almost a quarter of the harvestable corn stover in the nation is located in Iowa (Tyndall et. al,2011). Tyndall found that currently only 17% of Iowa's farmers who participated in a survey are interested in harvesting biomass, however, an additional 37% are undecided. This indicates that increased understanding and education will be essential to the success of the cellulosic ethanol industry in Iowa.

Current equipment developed for the hay and forage industry can be used to harvest corn stover. This equipment lends itself to multiple, separate operations to accomplish a specific element of harvest. A multiple pass corn stover collection system would require a combine to first harvest the grain, then a windrower would merge corn stover on the ground into strips on the field followed by a baler that would collect the corn stover in the merged strips and produce individual bales. Flail style choppers and bar rakes are two common equipment solutions used to form a windrow. Multiple baler types are available for densification of the windrowed material. Round balers, small square balers, and large square balers have been evaluated for use in corn stover (Tyndall et. al,2011).

Understanding the performance characteristics of this repurposed forage equipment is critically important for the continued development of the cellulosic ethanol industry. An examination of machine operation allows researchers to calculate management parameters described in ASABE Standard S495.1. The parameters can be utilized to determine optimal equipment sets and design efficient harvesting systems (Buckmaster, 2006), (Sogaard et. al, 2004). These equipment performance indicators can also be used by farm owners and industry managers to aid in machinery selection and implementation of support equipment (Taylor et. al, 2002).

Standardized management metrics can also be used to develop economic models and help managers estimate operating costs. Tools like Iowa State University Extension's *Ag Decision Maker* utilize performance data to estimate crop production costs. Extrapolation of performance terms into cost estimations or scale up models necessitates the accurate evaluation of performance parameters such as harvest capacity and fuel consumption rate.

Windrowing and baling is only part of the corn stover process. Bale collection and transportation is a significant portion of the cost associated with biomass collection (Sokhansanj et. al, 2002). The ability to efficiently collect and transfer corn stover bales to storage will be an important consideration for Iowa farmers and industry developers due to the high volumes and short time interval of a commercial corn stover harvest.

Harvest timeliness is an important factor in industrial corn stover collection. A cellulosic ethanol plant of the size that POET and DDCE are considering will require 300,000 – 400,000 tons per year in order to operate at capacity. At a sustainable target harvest rate of 2 ton/ac, this will require the partial harvest of corn stover from over 150,000 acres within the same period as grain harvest. The combination of two passes of harvesting equipment and the operation of bale collection equipment over this area represents significant organization, management, equipment, and labor costs. A critical assessment of realistic cost and time requirement metrics for all aspects of a corn stover supply chain will improve the ability of farmers and industry leaders to make informed decisions and will lead to a more economically viable biomass feedstock supply.

Research Objective

A significant need exists for accurate and detailed corn stover harvest and collection performance information. The objective of this research is to quantify and provide detailed information on the performance of corn stover collection equipment during industrial scale harvest operations. Spatial data evaluation will be used to directly assess the productivity of multi-pass baling systems. The metrics developed through this research can be used to develop accurate economic models and productivity estimates to help design and structure a corn stover supply chain in central Iowa.

Methods and Materials

A production scale research harvest of approximately 2,300 acres was designed to develop metrics for multi-pass corn stover harvesting performance using commercially available equipment. The multi-pass corn stover collection system begins with a windrowing operation to collect the material from a swath through the field into a single, narrow windrow. This is followed by the baling operation which densifies the material from the windrow into a bale. The final stage of the experimental evaluation was the bale collection systems used to move the bales from throughout the field to the field edge. An experimental plan was developed to measure the effects of different equipment combinations on the harvesting system. The specifications for each of the three types of equipment are explained in the following sections of this document.

Each power unit in the experiment was instrumented with logging equipment that recorded GPS and CAN signals. The loggers accessed several key parameters including position, travel speed, engine speed, and fuel consumption rate. Spatial data analysis allows for detailed measurement of field management characteristics. This data was analyzed using GIS software to create reports of machine performance. Chapter 2 details the procedure used to calculate management metrics including field capacities, swath widths, average fuel consumption, and several other terms.

Windrowers

Two windrowing systems were evaluated as part of the 2010 harvest. The Twinstar model 2027-G2 basket rake, pictured in Figure 6, was used for raking operations. A hydraulically powered basket rake is well suited for partial corn stover collection as the height can be modified to control collection rate and soil contamination. This rake has a maximum operating width of 8.2 meters (27 feet) and was pulled with an 89 kW (120 hp) Challenger MT475B tractor.

The MT475B was the only tractor in the experiment in which the logging system was not able to record CAN. This prevented the recording of an implement engagement message. In this case the speed data was used to determine machine engagement. The GPS signal allowed for timing data to be collected for analysis of the majority of the performance metrics as described in Chapter 2.

Figure 6: Twinstar hydraulically powered basket rake in corn stover

In this study the powered basket rake was compared to a type of machine that was designed for use in corn stalks. The flail shredder, sometimes known as a stalk chopper, is used to mitigate residue problems by reducing the particle size of infield residue. Some flail shredding systems have been improved to include windrowing capabilities on the shredder. The shredder used in the 2010 study was a Hiniker 5620 Windrower model with a 6.1 meter (20 ft) operating width which is pictured in Figure 7. A 151 PTO kW (205 hp) Challenger MT645C tractor was used to pull the shredder. The side discharge feature of this system allows the operator to combine two passes from opposite travel directions into a single windrow. The data collected from the shredder was analyzed using the procedure outlined in Chapter 2.

Figure 7: Hiniker windrowing flail shredder in corn stover

Balers

The baler is the core biomass collection machine and the heart of multi-pass harvesting operations. The baler collects loose material from a windrow and bundles the material into a denser package that can be easily moved and transported. Bales created by the baler come in a variety of sizes and shapes including round and rectangular. Each size and shape of bale has a place and purpose where that particular package is best utilized. Large rectangular bales measuring 3 feet by 4 feet by 8 feet provide a unit that can be moved and transported safely and easily within industrial biomass supply chains. This was the prevailing factor in the selection of the 3 foot by 4 foot size baler that was used in the 2010 study. Many production balers create a similarly sized large square bale, but it is important to consider bales from different machines unique. Differences in the design and operation of each baler suggest that the bales from different balers need to be evaluated separately.

Two different brands of balers with significantly different operation were evaluated. The first baler evaluated was a Massey Ferguson MF 2170 square baler pictured in Figure 8. This baler had a recommended power requirement of 123 kW (165 hp) and was pulled with a 151 PTO kw (205 hp) Challenger MT 645C.

Figure 8: Massey Ferguson MF 2170 baler during the 2010 harvest

A baler from Krone was also evaluated during the 2010 harvest. This Krone 1290 XC/HDP baler, pictured in Figure 9, had a power requirement of 147 kw (200 hp) and was pulled with a slightly larger tractor. The tractor used was a 166 PTO kW (225 hp) Challenger MT655C. The Krone baler included the Krone X-Cut system which reduces the particle size of material entering the bale by implementing feed tines and a knife bank in the material intake stream. This extra function requires additional power beyond standard baler operation, but helps to generate a bale with different, and potentially more desirable, characteristics.

Figure 9: Krone 1290 XC/HDP baler during the 2010 harvest

Bale Collection

A variety of equipment is capable of moving bales across the field, but equipment developed for the hay and forage industry was specifically designed for this task and provides industrial scale productivity. This equipment gathers a number of bales from the baler drop locations and stacks these bales in an organized fashion. The 16K Plus Bale Runner manufactured by Morris Industries is a tractor towed unit designed to gather and stack bales. This system, shown in Figure 10, collects 12 bales from across the field and stacks them in 6 bale tall configurations at the field edge in a single cycle.

Figure 10: Morris Industries 16K Plus Bale Runner adding bales to a stack

Bale collection equipment randomly traverses the field and collects individual bales during each cycle. This random nature requires the use of slightly different analysis methods. Unit level metrics are the most appropriate for this type of equipment. The bale collection system performs independent of bale weight. For this reason, a bales per hour metric provides the most direct measure of productivity. GPS timing data was still used to calculated performance parameters in this case.

Moisture is an important consideration in corn stover harvesting as it impacts the overall quality of the feedstock. Moisture can impact the way material flows through machinery, the mass of the material being collected, and the storability of the corn stover. The harvest research work was conducted throughout the full harvest season with a range of stover moisture contents experienced. Although this factor is important, it was not used as a factor in the evaluated experiments.

The prescribed experimental plan specified the windrowing, baling, and bale collection operation for each experimental zone. These experimental zones were approximately 20 acre sub-sections of research fields. Table 6 details the number of zones and the area from which data was successfully collected for each piece of equipment. The baling systems are related to windrowing type and it was important to collect information from all four combinations of baler and windrower. Table 7 indicates the four combinations tested and the number of zones from which data was successfully collected. The Krone baler arrived later in the harvest season and was therefore included in fewer experiments relative to the Massey Fergusson baler.

Table 6: Summary of data collected

Equipment	Zones Completed	Acres Completed
Twinstar Basket Rake	15	320
Hiniker Flail Shredder	14	280
Massey Fergusson Baler	28	590
Krone Baler	9	220
Bale Collection	30	-

Table 7: Summary of baler experimental combinations

Windrower	Baler	Zones Completed
Twinstar Basket Rake	Massey Fergusson Baler	14
Twinstar Basket Rake	Krone Baler	5
Hiniker Flail Shredder	Massey Fergusson Baler	14
Hiniker Flail Shredder	Krone Baler	4

Results

The 2010 research harvest started September 14 and continued for 58 days into mid-November when wet conditions prevented any further baling. Weather in central Iowa was generally dry with 38 of the 58 days fully available for field work. The timing of the rain events is included as a part of Figure 11.

The infield equipment operation was performed by a custom harvesting team with extensive experience in corn stover baling. During the 38 days of baling the crew covered 2,300 acres across the central Iowa region. This area yielded a total of 6,500 bales of varying types and quality. Although research focused, effort was taken to ensure that field operation of the equipment was performed at typical production level. The moisture content of the baled corn stover dropped quickly at the beginning of the harvest season. Occasional rain events did affect the moisture content of the available material throughout the harvest period with spikes in stover moisture corresponding to discrete rain events.

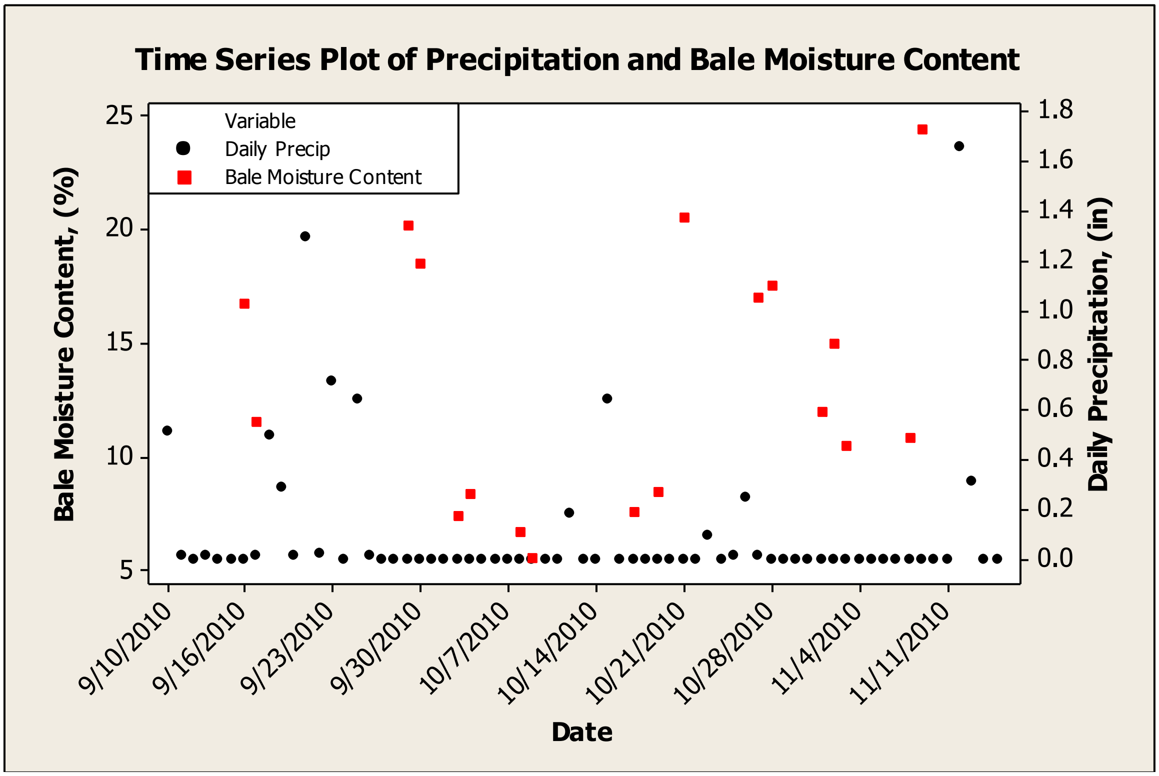

Figure 11: Bale moisture content over harvest season

Windrowing

Operational speed of the windrowing units was determined by the custom harvesting operators based on manufacturer recommendations and field conditions. Speeds were selected in the field to maximize performance of each piece of equipment and achieve the desired harvest rate. Harvest data indicates that the flail shredder was generally able to move across the field at a faster pace. Figure 12 demonstrates that although field conditions cause a moderate amount of variability, the shredder operates at higher average speeds. The small p-value in the ANOVA table shown in Table 8 indicates significant difference in operational speed between the two windrowing levels.

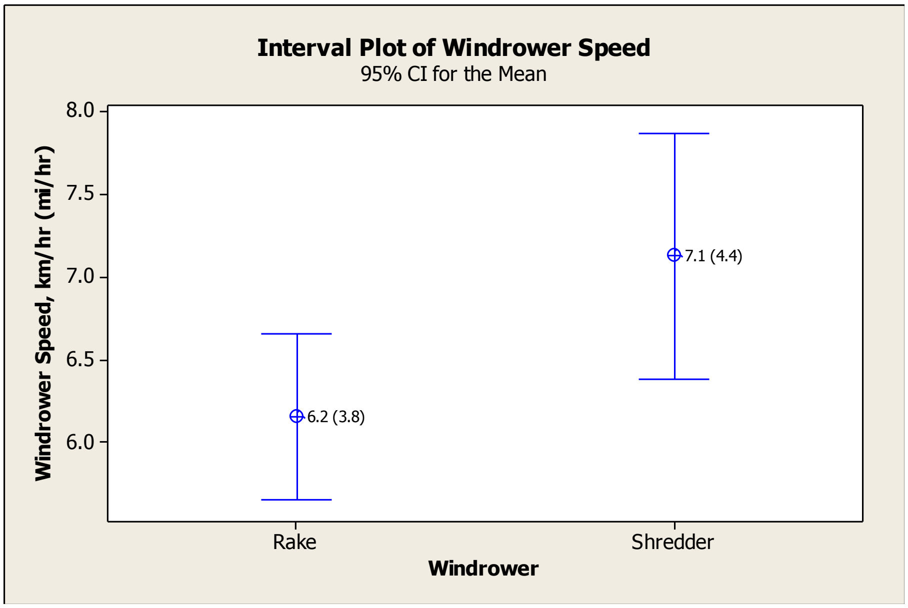

Figure 12: Operational speed of windrowing equipment

Table 8: ANOVA table for operational speed of windrowing equipment

Source	DF	Sum of	Mean Square	F Ratio	Prob. > F
Windrower	1	2.4774	2.4774	5.67	0.025
Error	25	10.929	0.4372		
Total	26	13.4064			

Although the shredder tended to have a higher field speed, it is important to note that the effective operating widths of the two pieces of equipment affect how much area is covered by that equipment. GIS data was used to calculate the effective swath width of each implement. The rake was able to consistently merge 7.3 meters of material into a windrow while the shredder merged windrows 5.9 meters wide. Although it produced a smaller windrow, the shredder was able to better maximize the operational potential of the equipment. The shredder achieved an overlap efficiency of 95 percent while the overlap efficiency of the rake was only 89 percent. Although the shredder traveled faster and was more efficient, the extra width of the raking system allowed it to produce a higher area capacity. Figure 13 shows both the theoretical and the effective area field capacities as defined in ASABE standard EP496.3 (ASABE, 2006). The theoretical area field capacity is based on maximum operating width and speed while the effective area field capacities are as measured by total time required to complete field operations. Table 9 and Table 10 list the ANOVA parameters for Theoretical and Effective field capacities for windrowing equipment. A sufficiently small p-value provides evidence of significant differences in theoretical field capacity across windrowing operations at the 5% level. However, a larger p-value indicates that the effect of the windrowing factor on effective field capacity is not significant at the same 5% level, but does indicate significance at the 10% level.

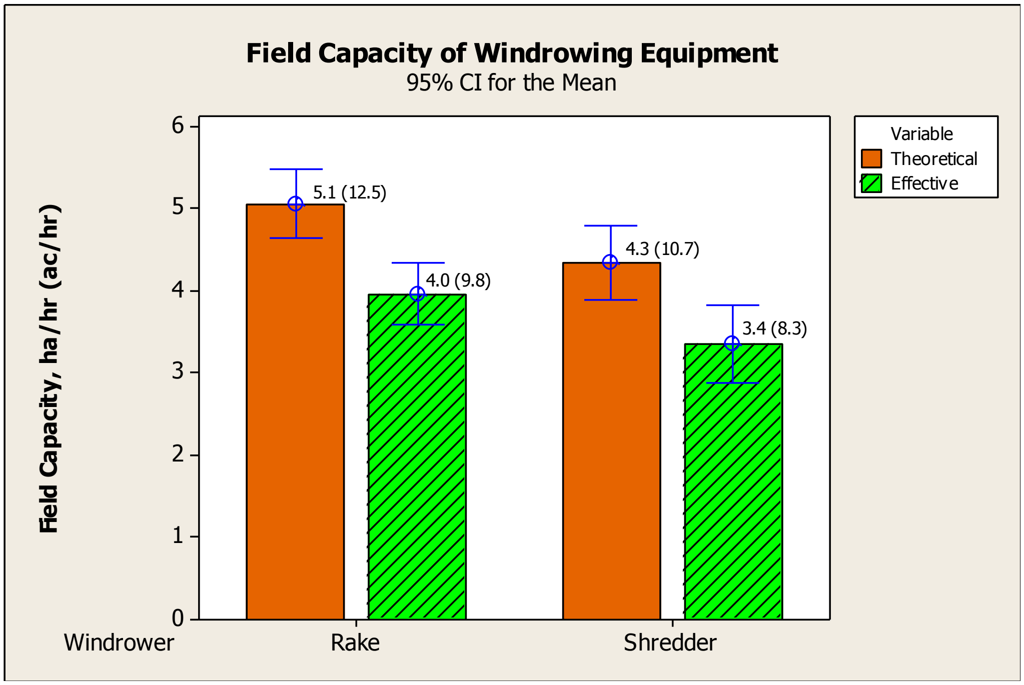

Figure 13: Field capacities of windrowing equipment

Table 9: ANOVA table for Theoretical Field Capacity of windrowing equipment

Source	DF	Sum of	Mean Square	F Ratio	Prob. > F
Windrower	1	3.4782	3.4782	6.42	0.018
Error	25	13.549	0.542		
Total	26	17.0272			

Table 10: ANOVA table for Effective Field Capacity of windrowing equipment

Source	DF	Sum of	Mean Square	F Ratio	Prob. > F
Windrower	1	1.9408	1.9408	3.34	0.079
Error	27	15.6994	0.5815		
Total	28	17.6403			

Fuel consumption is also an important metric in determining variable costs of the operation. Fuel use was not measured on the rake tractor, but was available on the tractor used with the shredder. Data for shredder fuel consumption data was collected and is displayed in Figure 14. The average fuel consumption rate for all fields was 23.1 L/hr.

Variability did exist with a minimum fuel consumption of 15.5 L/hr and a maximum fuel consumption of 28.9 L/hr.

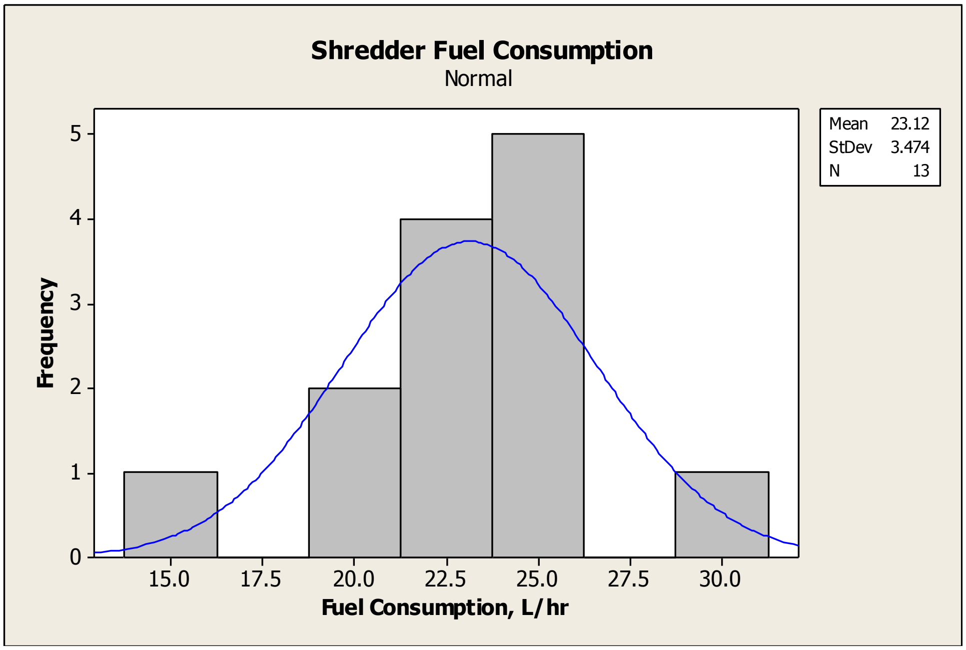

Figure 14: Fuel consumption of tractor pulling shredder

Baling

The two baling systems were both operated by the custom harvesting crew based on manufacturer recommendations and previous experience with corn stover baling equipment. Operational speeds were selected to best match the feed rate of material into the baler. Results indicate that the feed rate requirements were similar for both balers and that the windrower swath size is more dominant in the determination of baler operational speed. Figure 15 demonstrates no statistical difference between the mean speeds between balers under the same windrowing method that is reflected in the p-value of 0.86 for the baler factor in Table 11. A slight trend of higher operational speed under raked windrowing conditions is shown in Figure 15, but the p-value for the windrowing factor in Table 11 indicates low significance. This slight trend can be explained by the amount of material in the windrow. The side by side windrowing capability of the flail shredder allowed for 11.8 meters of the field to be combined into a single windrow for baler pick up. The smaller 7.5 meter windrow size of the rake may require the baler to increase speed to maintain an appropriate feed rate in some instances.

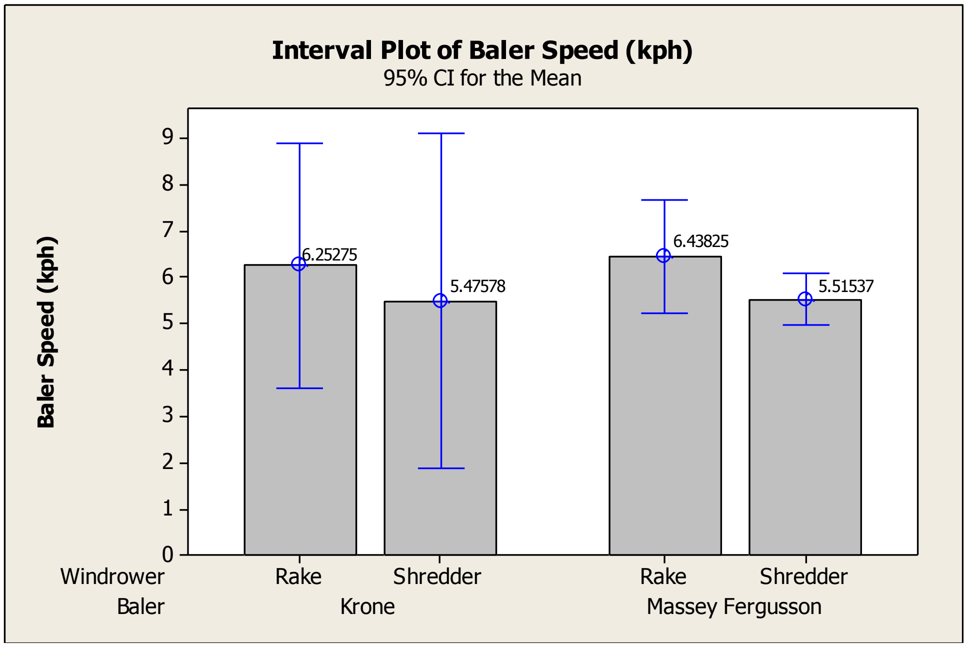

Figure 15: Operational speed of baling equipment

Table 11: ANOVA table for baler speed by windrowing and baling type

Source	DF	Sum of	Mean Square	F Ratio	Prob. > F
Windrower	1	5.433	5.536	11.66	0.208
Baler	1	0.105	0.105	0.03	0.861
Error	27	89.843	3.328		
Total	29	95.381			

The extra field width gained by the dual windrow system offered by the side discharge flail shredder provides a field capacity advantage to the shredding system. Both baling systems were able to realize a greater rate of field coverage behind a shredding system. The theoretical field capacity was calculated for the four baler and windrower combinations. Any overlap inefficiencies were attributed to the windrowing system and should not be attributed to the baling system. Equation 1, developed in ASABE EP496.3 was used to calculate theoretical area capacity, but the effective swath width of the implement was used in place of the implement working width. This substitution was implemented to prevent experimental variations in windrow size from biasing the calculation.

$$C_t = \frac{sw}{10} \tag{2}$$

Where C_t = theoretical capacity, ha/h

s = field speed, km/hr

w = implement working width, m

Figure 16 shows the trend of improved baler field capacity behind the shredder. The larger confidence interval in the shredder and Krone baler example is due to a low sample size of four experimental zones. This increased capacity for the baler to complete baling operations more efficiently behind a shredder is an important management decision when designing commercial scale biomass feedstock supply chains. The baling systems both have very similar field capacities under the same windrowing type, but vary between windrowers. This indicates that the windrowing type is the determining factor for field capacity which is supported by the small p-value for windrowing in Table 12.

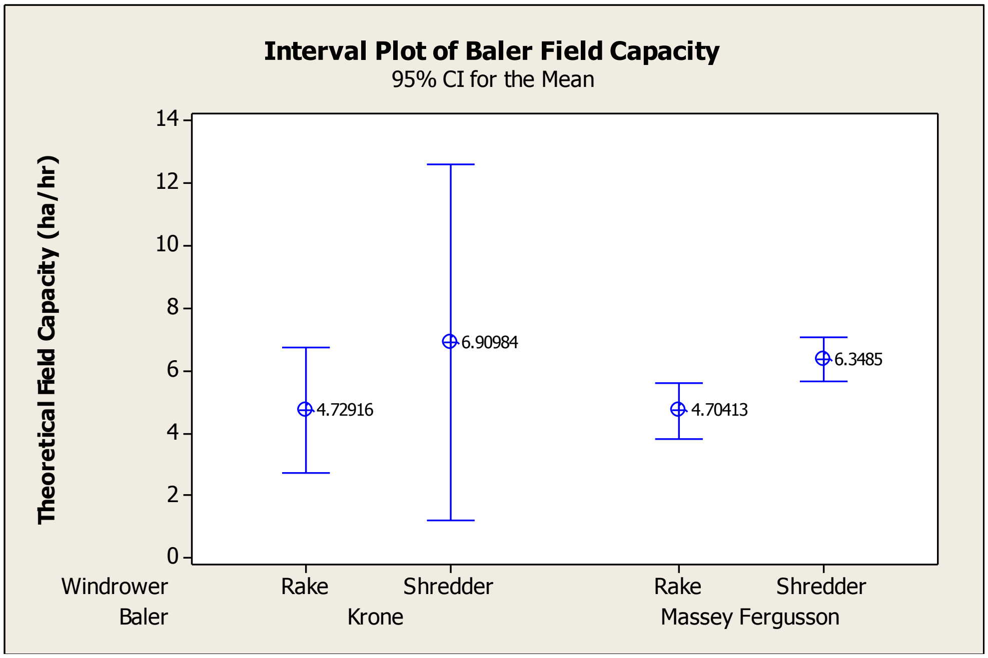

Figure 16: Theoretical field capacity of baling operations

Table 12: ANOVA table for baler theoretical field capacity by windrowing and baler type

Source	DF	Sum of	Mean Square	F Ratio	Prob. > F
Windrower	1	24.026	24.437	7.63	0.01
Baler	1	0.427	0.427	0.13	0.718
Error	27	86.49	3.203		
Total	29	110.942			

Although the field capacities of the baling systems are similar, the systems maintain important differences that affect the overall stover collection system. The X-Cut system and the higher plunger forces of the Krone baler create denser bales. Bales created by the Massey Fergusson baler contained, on average, 384 kg (844 lb) of dry matter while the Krone system generated denser bales with 508 kg (1117 lb) of dry matter per bale. More material per bale is highly desirable due to the inverse relationship with the number of bales that need to be collected, stacked, transported and stored throughout the entire stover collection system. Information presented earlier in this article indicates similar operational speeds and field capacities between the two baling systems. If field capacity similarities and bale differences are considered the Krone baler will generate bales at a lower rate than the Massey Fergusson baler. Effective bale production rates were calculated for each experiment conducted. The total number of bales created in each zone was divided by the time required to perform that baling operation. The results, shown in Figure 17, do show a higher bale generation rate for the Massey Fergusson as expected. This is supported by a low p-value in the ANOVA analysis for the baler shown in Table 13. It is also evident the windrowing type is not a significant factor. This measured rate accounts for all field efficiency variation and fluctuating field conditions.

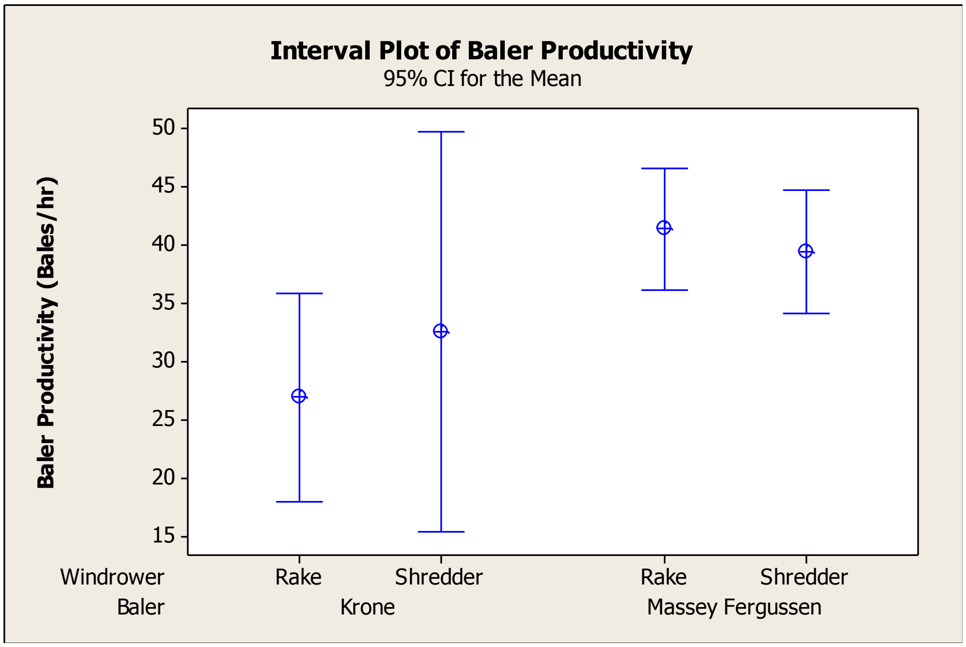

Figure 17: Bale production rate of two baling systems

Table 13: ANOVA table for bale production rate by windrowing and baler type

Source	DF	Sum of	Mean Square	F Ratio	Prob. > F
Windrower	1	25.9	44.3	0.36	0.553
Baler	1	644.7	644.7	5.22	0.029
Error	35	4325.6	123.6		
Total	37	4996.2			

The effective material capacity of each harvesting system can be determined as the product of the average dry mass per bale and the bale production rate. Material capacity, or throughput, is an excellent metric for comparison of baling systems. Supply chain design decisions should be made based on material capacity rather than area capacity because variability induced by fields, harvest seasons, and crop quality are all taken into account. A summary for effective material capacity is displayed in Figure 18. This figure, along with high p-values in Table 14, indicates that no significant differences exist between the four combinations of equipment.

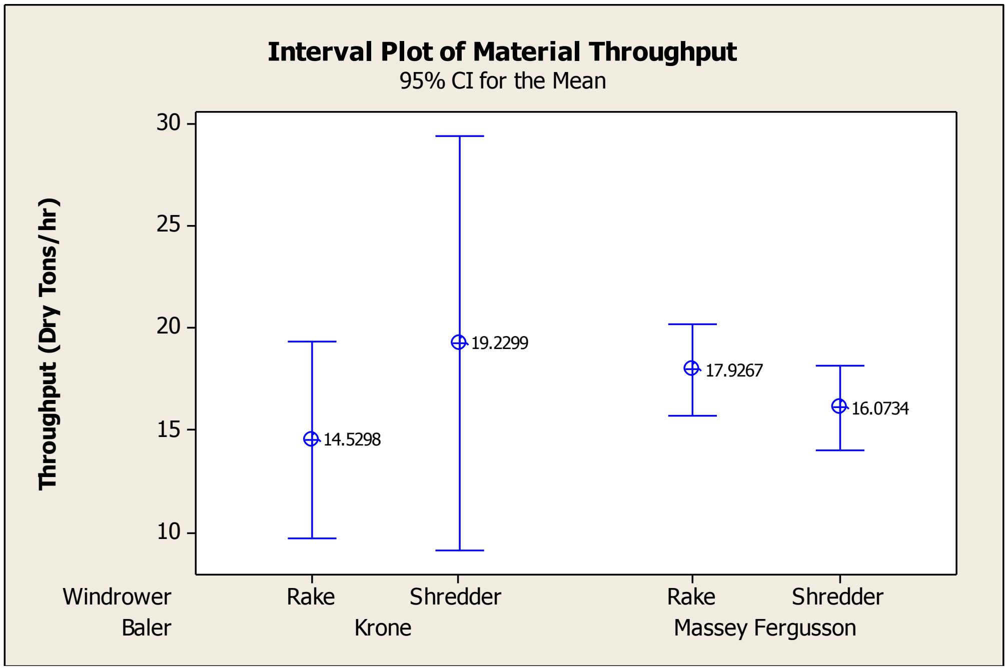

Figure 18: Material throughput for bale collection systems

Table 14: ANOVA table for material throughput by windrowing and baler type

Source	DF	Sum of	Mean Square	F Ratio	Prob. > F
Windrower	1	2.31	1.71	0.05	0.833
Baler	1	5.61	5.61	0.15	0.703
Error	37	1407.91	38.05		
Total	39	1415.83			

The fuel consumption for baler operation was monitored throughout the 2010 harvest season on both the Krone and the Massey Fergusson baler. As Figure 19 indicates, the tractor on the Krone baler used 80% more fuel than the tractor pulling the Massey Fergusson. This increase in fuel consumption corresponds to the increase in material capacity previously identified for these two baling platforms. Additionally, the Krone baler required extra power for the X-cut system which was unique to this baler.

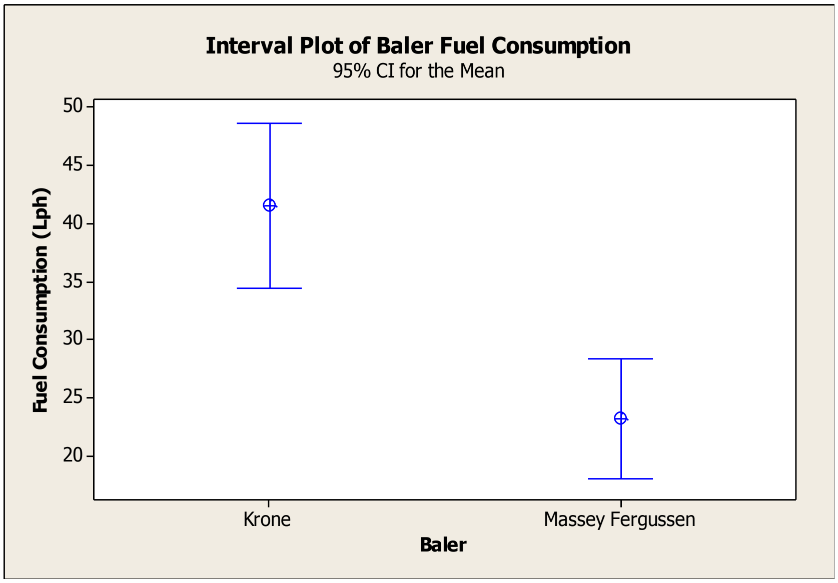

Figure 19: Fuel consumptions of two balers in corn stover

Similar trends exist when fuel consumption is evaluated on a material basis. The fuel consumptions metric was combined with the material throughput for each experimental zone. This liter per ton value displayed in Figure 20 can be very useful in estimating the baler fuel cost for a large corn stover collection operation as well as provide key information for bioenergy life cycle analysis.

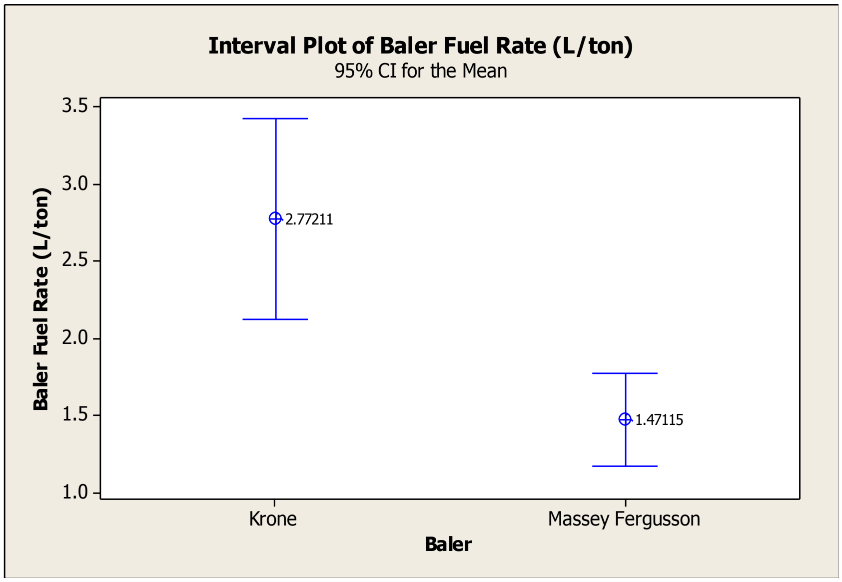

Figure 20: Baler fuel consumption for two balers on material basis

Bale Collection

Prompt removal of bales from the field is especially important in corn stover collection systems in the Midwest. Short harvest windows and fall tillage requirements necessitate dedicated bale removal systems. Understanding the capacity of these systems allows for better understanding of the machinery necessary for a stover collection supply chain. Manufacturers often indicate productivity values in bales per hour. This number is appropriate in comparison to a ton per hour or ton per area as the bale collection systems are not as affected by variable material properties such as bale density. However, performance does vary between different crop types so it is important to understand performance in corn stover.

Bale collection is a cyclical process of several operations instead of a linear activity like windrowing and baling. This requires an alternative spatial analysis process to obtain performance information. General performance data can be obtained by measuring the amount of time spent in the zone and the total number of bales stacked. A summary of each zone's performance in bales per hour is shown in Figure 21. The large variation in stack rate can be attributed to a variety of factors; operator skill, field size, and field shape all play important roles in determining the stack rate. During the 2010 harvest with varied conditions, the stacking equipment was able to obtain an average stack rate of 65 bales per hour. This considered the movement of bales from across the field to the field edge. Over the road transportation was not considered.

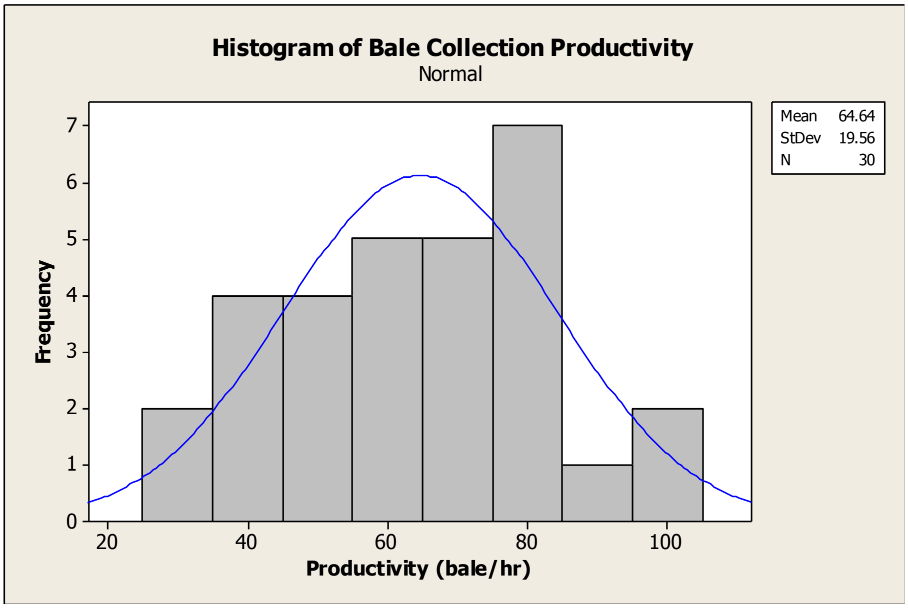

Figure 21: Productivity of a ProAg Bale Runner collection system

Similar variation exists in the fuel consumption data for the tractor pulling the ProAg Bale Runner. Figure 22 shows the average fuel consumption data for 32 of the experimental zones. The average fuel consumption rate was 17.5 L/hr with a minimum fuel consumption of 10.9 L/hr and a maximum of 31.0 L/hr.

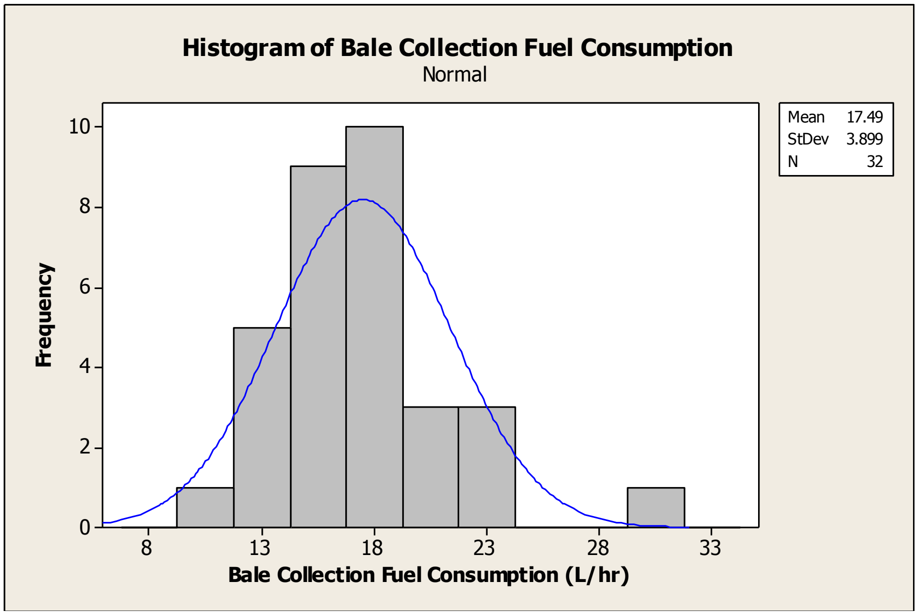

Figure 22: Average fuel consumption for bale collection operations

System Analysis

The information obtained from each part of the corn stover harvesting system can help provide insight into how a large scale harvesting operation should be structured. A consumer like a cellulosic ethanol plant needs a certain amount of material to operate for an entire year. If the sole feedstock is corn stover, this material must be collected in a relatively short harvest window. A case study was conducted to understand the scale of harvest machinery necessary to accomplish the collection of 100,000 tons of dry corn stover in one season. This value was selected as an example value and is approximately one third of the corn stover required to maintain full operation at one plant for a year. Several assumptions were necessary in order to complete this analysis. It was assumed that 30 working days were available for corn stover collection based on an examination of historical Iowa grain harvest length. It was also assumed that the windrower and stacker could operate for 11 hours each day and the baler could operate for 10 hours each day. These values were estimations based upon observations of in-field activity during the fall of 2010.

To complete this system analysis, it was necessary to use information external to the data collection system. The bale density typical of each baler was used to approximate the number of bales needed to package 100,000 tons of stover. In order to calculate the required equipment set for windrowing and baling, the mean effective material capacity in tons per hour for each piece of equipment was combined with the amount of stover collection required and the daily operational timing to determine the number of implements needed. The number of bales created in each scenario was divided by the bales per hour stack rate of the bale collection equipment and combined with operational time to determine the number of bale collection units needed.

In each scenario the total number of implements was summed to determine the number of tractors needed in each situation. This allots a tractor to each implement and assumes that implements do not share a tractor. Although economic models may optimize this practice, it is likely that this will remain the case due to the size and time requirements of the harvest. Table 15 summarizes the amount of equipment necessary to harvest this amount of corn stover within a single season harvest window.

Table 15: Number of units needed to harvest 100,000 tons of stover

Baler	Krone		Massey Fergusson	
Windrower	Rake	Shredder	Rake	Shredder
Bales Needed	178,891		236,967	
Windrowers Needed	18.0	29.4	18.0	29.4
Balers Needed	23.0	17.4	18.6	20.7
Stackers Needed	8.3		11.0	
Tractors Needed	49.3	55.1	47.6	61.1

When 100,000 tons of stover is transformed into harvesting requirements the scale of this activity becomes much easier to visualize. In order to harvest this amount of stover during a short harvest season, 45 – 65 sets of equipment will need to be deployed, depending on the final configuration. These differences in equipment requirements are an important part of supply chain development. Additional equipment represents additional capital and labor requirements. However economic impact modeling is necessary to determine if other external factors are of greater economic significance. Bale quality or bale quantity could become a factor that overrides the economics of a system.

For example, the number of bales in each system is a major factor. To help visualize the quantity of bales necessary at this scale of harvest, one could imagine the space needed to store these bales. If 200,000 bales were stacked six bales high and packed into a single stack, the bales would cover 25 acres. Each additional bale is another package that needs to be loaded, transported, and stored. The differences between these two systems results in an extra 1600 semi loads of bales and seven more acres of storage required. These system level differences are important considerations and affect the entire stover collection supply chain.

Conclusion

Production scale harvests like the one completed in 2010 are useful in obtaining realistic machinery management information. Tractors can easily be instrumented with data logging equipment to collect GPS and CAN data from the power units. GIS software can be used to extract management parameters from the spatial data collected from these loggers. These management terms are calculated in accordance with ASABE standards.

Analysis of the metrics calculated and the treatment factors associated with those metrics allowed for a system level analysis. Windrowing equipment is an important start to the multi-pass harvesting system. In the 2010 study, the basket rake was able to achieve a higher field capacity than the flail shredder. It was clear that the windrower characteristics have an impact on the field capacity of the baling systems.

The baler type has a significant impact on the entire corn stover harvesting system. The Krone baler was able to achieve a higher density bale. Although the Krone baler did have significantly lower bales per hour numbers, the higher density allowed the balers to achieve similar material throughput rates. This increased density appeared to come at a cost of increased fuel consumption. Although this increased fuel consumption raises the variable costs on this equipment, it is important to consider the impacts on the entire supply chain.

A systems level analysis of the harvesting operation starts to evaluate impact factors on the supply chain of industrial corn stover harvesting. It is clear that equipment selection at the windrowing and baling level have impacts on the labor and equipment requirements to harvest corn stover at a certain tonnage level. The analysis of this study was performed up to the field edge. It is important to note that the bale density can have a large impact on the corn stover supply chain. A lower density requires more trucking, storage, and handling costs that are associated with an increased number of bales.

The types of performance metrics determined in this study are extremely valuable in the development of economic and supply chain models. With accurate performance data, modelers can evaluate the impact of equipment selection on the entire system. It is important for work to continue to evaluate the impact of other harvesting systems and other operational interactions. Through the use of spatial data it is possible to evaluate performance metrics beyond what is defined in ASABE standards.

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CHAPTER 4: GENERAL CONCLUSION

General Discussion

It is clear that energy independence and reduced consumption of non-renewable resources is important to the United States. The mandates initiated by the United State Congress will ensure that the non-renewable transportation fuel industry will continue to grow into the future. Cellulosic ethanol is poised to be an important part of the growth in this industry. Multi-faceted research will have significant impacts on the shaping of this new industry. The need for detailed information about all parts of the cellulosic supply chain is driven by a desire to perform efficiently, effectively, and sustainably.

Corn stover is a significant source of cellulose in the Midwestern United States. Understanding the effort and expense associated with a partial corn stover harvest is essential to supply chain development. In Chapter 2, "*Using GIS Tools for Analysis of Machinery Logistic Parameters*", methods were developed to collect and analyze machinery performance data. The spatial logging equipment can be deployed on production equipment without a supervision requirement; this facilitates the collection of data from large experimental zones. GIS software has the capability to handle large datasets and manage multiple operations in the same experimental zone or field.

Chapter 2 defines the appropriate spatial queries and filters necessary to collect specific parameters necessary for management term calculation in accordance to ASABE Standards. The standardized queries established lend themselves to rapid analysis of machinery parameters. This enables evaluation of larger quantities of data which leads to better performances assessments. The standardized methods also lend themselves to implementation in automated systems that could measure parameters of interest in real time. The spatial analysis method of data collection facilitates evaluation of terms beyond the current management metrics defined in the ASABE Standards. As spatial performance analysis becomes more commonplace, standards could be updated and developed to account for the expanded functionality.

Currently published performance values list wide ranges of capacity and efficiency for generalized equipment operations. These wide ranging, general values are useful for small scale farming operations, but tend to be too broad for industrial harvesting operations. Chapter 3, "*Logistical and Productivity Analysis of Multi-Pass Corn Stover Harvest Systems*," provides calculations of performance metrics for specific harvesting scenarios. This type of unique performance measure is essential to the creation of biomass supply chains. The values determined as part of this research can be implemented directly into economic and impact models. These models can then provide realistic evaluations on the impact of different harvesting scenarios.

The accuracy of these models is important to industry efforts in the Midwestern United States. This will ensure success as harvesting operations are scaled from the meager 2,300 acres harvesting in 2010 to full production levels requiring partial harvest of over 150,000 acres. It is essential to understand the implications of each decision in the supply chain to certify that the prescribed and implemented methods are practical, achievable, and sustainable.

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