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A Quantitative Analysis for Improving Harvest Productivity for Biomass Crops

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To the Graduate Council:

I am submitting herewith a thesis written by Magen Elizabeth Shedden entitled "A Quantitative Analysis for Improving Harvest Productivity for Biomass Crops." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

James A. Ostrowski, Major Professor

We have read this thesis and recommend its acceptance:

Jamie B. Coble, Mingzhou Jin, Erin Webb

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

A Quantitative Analysis for Improving Harvest Productivity for Biomass Crops

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Magen Elizabeth Shedden
May 2018

DEDICATION

I would like to dedicate this work to my grandparents, Russ (Guppie) and Martha (Gum) Shedden. Gum passed away during my second semester in graduate school. While I was taking care of her during her final hours I was explaining the parts on the New Holland forage harvester that needed repair and maintenance, which is discussed in Chapter II. My grandparents taught me that education and faith are the two things that no one can take away from you. This work is dedicated to my grandparents.

ACKNOWLEDGEMENTS

I would like to thank God for giving me the opportunity, knowledge, ability, and perseverance to complete this degree. He gave me the endurance to overcome all obstacles and challenges faced during my time in graduate school. Without Him this achievement would not have been possible.

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Research would have not been possible without The Center for Renewable Carbon at the University of Tennessee where Dr. Tim Rials and Jessica McCord were pivotal in research success. Also, Devon Bryant and his family were crucial for Miscanthus research. Their cooperation, generosity, and state-of-the-art farming practices were fundamental for this work. Additionally, The State University of New York College of Environmental Science and Forestry where Mark Eisenbies, Tim Volk, Daniel Pegoretti, and Karl Hallen played critical roles in willow data collection, harvest operations, and research. This work was not possible without their assistance and contributions.

Finally, I express my profound gratitude to my family and friends for their steady encouragement throughout my academic career. With the sincerest gratitude, thank you!

ABSTRACT

Harvest cost is a major concern for making biomass a viable option. Unproductive time in-field significantly contributes to this cost. Variability of harvest timeliness is largely due to maneuvering equipment in-field, operator experience, equipment failures, and field and crop conditions, among other reasons. These are particularly important for farm management to know how to best handle interruptions during harvest. Consequently, there is a serious need to better account for harvest untimeliness. For this research, the crops of interest are Miscanthus and shrub willow. These crops are attractive for several reasons. They do not compete with cash crops because they grow on marginal land and have the potential normalize feedstock qualities. In general, three aspects of harvest productivity will be focused on, which include: equipment maneuverability at the headlands, operator performance, and equipment reliability. More specifically, maneuvering equipment during harvest operations can have a significant impact on production cost; therefore, the fieldwork pattern is critical for optimal productivity and a cost-efficient harvest. Harvest pattern influences time wasted due to excessive unproductive time and distances traveled during operational tasks. Equipment is maneuvered at the skill of the operator. Often, operator experience is a bottleneck for operations and a key factor influencing productivity. In addition, unproductive times are largely due to repair and maintenance on the equipment caused by unexpected harvest complications. The uncertainty of these factors cause inconsistency in productivity. It is crucial to achieve optimum harvest efficiency for the feasibility of the biomass supply chain. Evaluating these aspects will allow us to better understand and model for these limitations.

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INTRODUCTION

Biomass is natural material that is animal and plant matter or remains of these organic materials. Biomass has a high concentration of carbon, hydrogen, and oxygen, which makes it an attractive energy source for heat, electricity, and fuel. Biomass is a building block for energy and is an alternative to fossil fuels. However, feedstock production is critical to the bioenergy supply chain. There are multiple feedstock sources, but for the purposes of this research Miscanthus and shrub willow will be focused on. Miscanthus is a warm-season grass. It is a high yielding crop with a low nutrient requirement (Williams and Douglas). Harvest operations for Miscanthus require a windrower to cut and condition the crop followed by a tractor towing a baler to package the material into a bale for easy handling and storage. The low moisture content of this crop at the time of harvest does not require a dry down period, so the material can be baled immediately after it is cut. Multiple harvests can be achieved from a single planting. Similarly, willow shrub is a short rotation woody crop (SRWC), which utilizes a coppice management system that allows multiple harvests from one planting, where harvests are every three to four years (Eisenbies, Volk, Posselius, et al.). For SRWCs a single-pass cut and chip technique is the preferred conventional harvest method. Here, a forage harvester equipped with a hydraulically driven woody coppice header processes the material and blows the processed chips into collection equipment which operates alongside the harvester. These crops are attractive for several reasons. They do not compete with cash crops because they can be grown on marginal land. Growing an energy source on land that cannot be used for other agricultural purposes will allow associated agricultural industries to prosper. Rural development would be stimulated by providing jobs through harvest and logistic operations (Abrahamson et al.). Farm managers, farmers, operators, and other skilled labor play a key role in the success of the biomass agricultural sector. Singlehandedly, these crops have the potential to increase rural economies and advance agricultural industries. For instance, improved and innovated machinery will need to be designed, fabricated, and tested for the production of biomass crops. Moreover, harvest operations will employee more operators and equipment to be purchased to meet the commercial scale demand. All in all, biomass is broadening the agriculture.

Research Purpose and Significance

In the bioenergy supply chain, harvest costs account up to one-third of the total delivered biomass cost (Eisenbies, Volk, Posselius, et al.). This cost is a major concern for making biomass a viable option. Agricultural machinery has direct and indirect costs associated with harvest operations. The largest direct cost is due to the high capital cost of machinery. Recently, technology, advancements, and higher powered equipment have given rise to an already elevated direct cost (Sopegno et al.; Spekken and de Bruin). Indirect costs are associated with the variable costs of harvest operations. Ultimately, a reduction of unproductive time during harvest would decrease indirect costs (Spekken et al.). Unproductive tasks include: servicing, maneuvering equipment in-field and near field boundaries, and repairing equipment. These responsibilities cannot be avoided, but it is important to reduce the excess time spent during these tasks. Harvest delays are costly.

The variability of harvest timeliness is largely due to maneuvering equipment in-field, operator experience, equipment failures, field and crop conditions, among other reasons. These are particularly important from a planning perspective given how potential harvest interruptions could impact harvest operations and scheduling. For the purposes of this study, harvest timeliness due to turning equipment in the headland space, operator performance, and equipment reliability caused by unscheduled harvest delays will be evaluated. Uncertainty of these factors cause inconsistency in productivity. It is crucial to achieve optimum harvest efficiency to build a cost-efficient the biomass supply chain.

Maneuvering Equipment at the Headlands

Maneuvering equipment in-field can have a significant impact on production cost; thus, fieldwork pattern is critical for operational efficiency (Spekken et al.).Space required to maneuver equipment at the field boundaries and the time consumed maneuvering equipment both add to an elevated harvest cost. Excessive nonproductive travel and time are frequently due to sub-optimal fieldwork patterns (Zhou et al.). Prior to harvest, a fieldwork pattern is established, which is defined as the ordered traversal sequence of in-field tracks by the machine (Zhou et al.). The entire field will be coved by the machine starting with the machine operating along the field boundary, which creates the headlands. Headland space is influential for harvest operations as the number of turns, distance traveled to turn, and time spent turning are factors effecting field efficiency. Given the uncertainty of harvest operations, some nonproductive time is unpredictable, yet some of it can be reduced with the proper fieldwork pattern.

With the increased importance on agriculture and technical advancements, route planning is a current topic of interest. Current machinery equipped with auto-assist have raised an interest in field coverage planning, harvest optimization, and productivity for precision agriculture. Consequentially, numerous research studies have been conducted in this area. One study minimized the total nonproductive travel distance for an optimized fieldwork pattern (Jensen et al.). Reducing field complexity in order to reduce the number of turns in a field has also been evaluated (Oksanen and Visala). A method for choosing the best orientation of parallel tracks for minimizing time wasted turning between tracks was evaluated (Spekken and de Bruin). Another study looked at the most suitable turning pattern between adjacent tracks (Cariou et al.). Machinery limitations were evaluated to reduce nonproductive travel distance in field (Bochtis and Vougioukas). This research was later built on, studying various driving directions to optimize the sequence of turns (Bochtis and Oksanen). Generally, a decline in nonproductive travel and time would reduce production costs.

Operator Experience

Operational efficiency is crucial to reach optimal productivity and thus a cost-effective biomass feedstock. A skilled equipment operator is essential for a highly efficient performance during harvest operations. It is important to better understand how field performance and variations in performance levels impacts harvest feasibility. Given that most bioenergy crops do not require a dry down period all harvest operations are completed at once. Multiple pieces of equipment operating at the same time require operators to work together. This team scenario impacts operational efficiency because harvest is only as productive as the least efficient operator. Fatigue and stress, environmental factors, work history, equipment, among other factors all impact an operator's skillset for any situation during harvest operations. It is noted that experience level can change based on equipment; a highly skilled operator running a forage harvester may not be as comfortable operating a tractor and baler. In addition, downtime, repair, and maintenance are all influenced by operator experience Operator experience is a major bottleneck for field operations.

As agricultural equipment has changed throughout the years, it is necessary that the operator's skillset evolve with the changing control paradigms of the power machinery. Additionally, a skilled performance is characterized by anticipation of variations throughout the operation coupled with the ability to cope with disturbances without disrupting productivity (Bernold). A highly skilled operator not only improves production reliability, but it also can reduce repair and maintenance equipment costs. It is important to better understand how operator performance impacts harvest feasibility and downstream impacts in the supply chain.

Repair, Maintenance, and Reliability

With the increased importance to reduce harvest costs, management of agricultural machinery is central for farm management (Afsharnia et al.). Classifying breakdowns is beneficial to the operator to help prepare for breakdowns in-field and potential spare part requirements (Al-Suhaibani and Wahby). It is also important for the agricultural machinery industry to help them identify issues and improve design and fabrication of equipment (Al-Suhaibani and Wahby). Failure of the equipment to function can be a major contribution to production losses and high maintenance costs. Agricultural equipment is a repairable mechanical instrument that is prone to repeated breakdowns and deterioration (Afsharnia et al.). Reliability of farm equipment is mainly affected by the annual use, repair and maintenance policies, and operating environment (Lips). Breakdowns that occur during harvest are not part of scheduled maintenance and routine checkups, which occur before or after working hours; these breakdowns can happen at any time during operations.

For agricultural machinery, repair and maintenance costs attribute up to 15% of the total streamlined cost (Calcante et al.). Typically, these costs are incorporated in the annual operating cost and increase as the equipment ages, which is used as a criteria to determine the optimal time to replace machinery (Calcante et al.). However, repair and maintenance costs are difficult to estimate for several reasons. They are variable among machines, operating conditions, crop types, operator handling, and the unavailability of good record keeping (Abubakar M.S., Zakari M.D., Shittu S.K.). It was concluded that age and annual use of the equipment are significant factors that impact annual repair and maintenance costs, and such short service intervals coupled with a high annual utilization is advantageous for cost savings (Lips). The expenditure necessary to repair is expensive, but the impact on productivity can be more costly. One of the most important factors during harvest is timeliness. Equipment breakdown can be add to the elevated harvest cost. Therefore, there is a need to have an optimal maintenance strategy such as replacement, repair, and inspection (Ahmad et al.).

Previous Research

Previous studies have identified headland space as an operational constraint, analyzed harvest patterns to reduce the number of turns by finding the best turning patterns, conducted trials to simplify turns to reduce nonproductive travel distance, and optimized routing of field equipment to reduce cost; however, increasing headland space by the fieldwork pattern for improved productivity has not yet been performed. Additionally, developments in agriculture machinery with the emphasis on field productivity have underestimated the importance of an experienced operator. In fact, some turns in the headland space can be demanding and time consuming, and how these turns are handled is solely dependent on operator skill (Spekken et al.). A major challenge in the biomass sector is the need for more skilled operators. Evaluating this need will allow better understanding to best account for these limitations. Current frameworks and models need to be updated to more accurately estimate harvest costs provided the range in operator experience. A better understanding of how operator performance influences and cost will provide more real-world approach in modeling harvest operations.

Current supply chain models account for harvest equipment repair and maintenance costs by using cost indexes from outdated equipment. The majority of the research data collected is from the 1970s, so it does not account for current prices or new and advanced equipment. A substantial pitfall for accurate and up-to-date repair and maintenance costs is repair data, and few analyses for repair and maintenance have been complete in the last twenty years (Lips). The American Society of Agricultural and Biological Engineers (ASABE) have evaluated repair, maintenance, and reliability for farm equipment by crop type and field size. However, these data sets were only for certain crops and do not include equipment specifics. Similarly, farm management methods primarily focus on the accumulated repair and maintenance costs over the estimated machine life. These costs are simplified and formulated as a fraction of the capital cost of the machine (Lips). However, there are several issues with the repair and maintenance factor. For instance it does not account for advancements in the equipment, improvements to the replaceable parts, nor does it account for predictive maintenance aids given by sensors and monitors on-board the equipment. Consequently, there is a serious need to better account for untimely breakdowns and machine reliability of modern equipment.

Primarily conventional crops have been evaluated the performance of harvest, collection, and transportation operations. Moreover, headland space depends on the field and harvest pattern and productivity is dependent on the operator's skillset. Fieldwork pattern is one of the few parameters that can be controlled throughout harvest. To date, no work has evaluated the impact of headland space and operator experience for biomass crops. Additionally, no work has been done to estimate the cost of operational delays in biomass crops using probabilistic risk assessment. It is important to better understand these factors and their impact on harvest timeliness and cost.

Objectives and Conclusion

Three main aspects of harvest productivity will be focused on in this research, which include: 1). Maneuvering equipment in the headlands, 2). Operator performance, and 3). Reliability of harvest equipment. Unproductive time in-field is a major cost contributor. Consequently, there is a serious need to better account for harvest untimeliness for biomass crops and modern harvest equipment. Two harvest scenarios will be analyzed, which are: 1). Miscanthus harvested by Massey Ferguson windrower and tractor towing a large square baler, and 2). woody biomass crops harvested by a New Holland forage harvester equipped with a custom woody coppice header. Miscanthus operations will focus on the impact of headland space and operator experience while willow operations will evaluate the cost of harvest delays for unscheduled repair and maintenance. The objective of this research is to analyze harvest unproductive time and delays as well as define field work patterns for increased headland space, operator experience levels, and categories for harvest delays. Then, the optimal headland space for turning equipment at the field edge and variation between operator experience levels will be identified, and the financial impact of overall harvest system reliability with the associated financial impact will be provided.

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CHAPTER I

AN EVALUATION TO IMPROVE HEADLAND SPACE WITH RESPECT TO MACHINE AND OPERATOR EXPERIENCE FOR A COMMERICAL SCALE MISCANTHUS HARVEST

This article was revised by the graduate committee and co-workers at the Oak Ridge National Laboratory. The student's involvement included: literature analysis and initial research setup, data collection, data processing, and data analysis. Help was received from several participants, which is outlined below:

- Devon Bryant- harvest operations and data collection
- Josh Price in the Office of Information Technology at the University of Tennessee – aid in statistical analysis in SAS
- Tony Rodriguez in the Industrial Engineering program at the University of Tennessee – aid in Python coding
- Noya Livine, Jessica McCord and Tim Rials at the Center for Renewable Carbon – aid in Farm Works Software input, facilitated and support research possibility
- Erin Webb and Bhavna Sharma at the Oak Ridge National Laboratory – research support and chapter edits, suggestions, and revisions

Abstract

Maneuvering equipment during harvest operations can have a significant impact on production cost; therefore, the fieldwork pattern is critical for optimal productivity and a cost-efficient harvest. Harvest pattern influences time wasted due to excessive nonproductive time and distances traveled during operational tasks. In addition, technology advancements and developments in agricultural machinery and autonomous equipment have underestimated the importance of an experienced operator. Previous studies have identified headland space as an operational constraint, but altering the fieldwork pattern to open up the headlands for additional space to maneuver equipment at the field boundaries has not been done. In this study, three harvest patterns were analyzed for a commercial scale Miscanthus harvest in Northeastern Arkansas, which include: 1). 2-pass, 2). 4-pass, and 3). 6-pass perimeter cut. There is an economic benefit to improving productivity and reducing nonproductive time spent turning in the headlands to make Miscanthus a viable biomass crop. Field data was analyzed to assess the impact headland space has on machine performance based on operator experience. After statistical analysis, it was determined that the ideal fieldwork pattern was a 4-pass perimeter cut, and field speed significantly impacts turn times. Additionally, operator experience was determined to be a key factor influencing productivity; a seasoned operator will be more consistent throughout harvest operations.

Introduction

Harvest consumes one-third of the total delivered biomass cost, which is significant given the multiple phases of the bio-energy supply chain (Eisenbies et al.). Efficiency and unproductive time lost during harvest impact this inflated harvest cost.

Harvest has direct and indirect costs associated with it, and a reduction in unproductive time spent in-field would decrease indirect costs (Spekken et al.). During harvest operations, unproductive tasks include: servicing equipment, maneuvering equipment near field boundaries, and excess travel time in-field. Improving field efficiency is essential to making biomass a viable option.

This study will focus on harvest operations for Miscanthus (*miscanthus giganteus*), a warm-season grass that is pictured in Figure 1. Miscanthus is an attractive biomass crop for several reasons. It has a low nutrient requirement with high potential yields and the ability to prosper on marginal land (Williams and Douglas). Unfortunately, there is a lack of experience cultivating and harvesting Miscanthus in the United States (Williams and Douglas).

Figure 1. Miscanthus biomass located in Northeast Arkansas.

During Miscanthus harvest, a windrower cuts and windrows the crop. Later, a tractor towing a baler packages the cut Miscanthus into a bale. The windrower has a zero-turn radius. However, turning for baling is limited to the steering angle of the tractor in addition to the baler in tow. The steering angle is the angle between the front of the tractor and the steered wheel direction, which is illustrated in Figure 2. This lengthy assembly considerably limits turning capacity. The turning capacity of the machine can easily surpass the space available to turn equipment at the field edge.

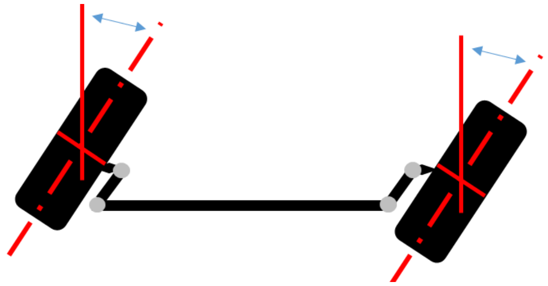


Figure 2. Steering angle diagram.

Excessive unproductive travel and time are frequently due to sub-optimal fieldwork patterns. In fact, a significant potential savings in both distance and time traveled were found for potato cultivation. In this study, savings for planting operations were 22.6% for unproductive distance traveled and 24.8% savings in unproductive time traveled, which led to an increase in field efficiency of 7.1% (Zhou et al.). Maneuvering equipment in-field can have a significant impact on production cost. A sub-optimal fieldwork pattern is the main cause of wasted time in field operations. Therefore, fieldwork pattern plays a crucial role in operational efficiency (Spekken et al.).

Prior to harvest, a fieldwork pattern is established. Fieldwork pattern is the sequence of tracks made in-field by the machine (Zhou et al.). The entire field will be covered by the machine starting with the machine operating along the field boundary, called a perimeter cut, which creates the headlands. It is important that headlands are opened to allow minimal crop damage during harvest operations by giving the equipment more space to turn. Typical harvest operations rely on a 2-pass perimeter cut fieldwork pattern; given a 13-ft. implement width, this pattern gives a 26-ft. headland space. This fieldwork pattern is illustrated in Figure 3.

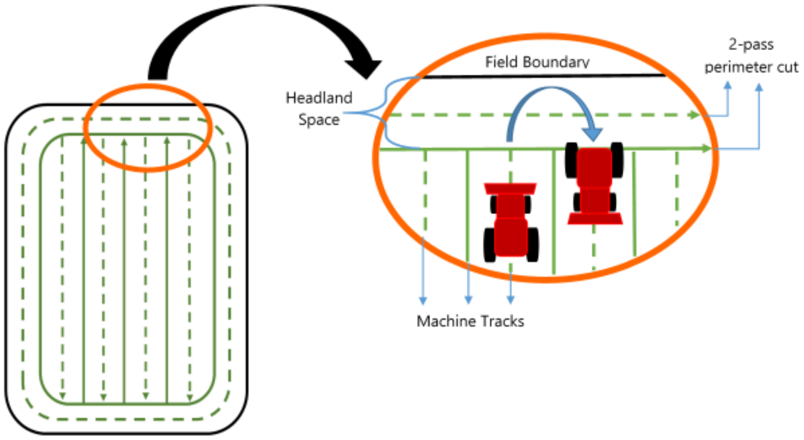


Figure 3. Typical commercial Miscanthus harvest fieldwork pattern.

Once the headlands are cleared, the machine operates in a straight row parallel to the long side of the field, which is the most common technique for a commercial harvest. These rows are called windrows. The windrows are where the primary cropping is done. Turning equipment occurs at the end of each windrow in the designated headland space along the field edge. Headland space is influential for harvest operations as the number of turns, distance traveled to turn, and time spent turning are factors effecting field efficiency. Field efficiency is the ratio of time the machine is processing the crop to the total machine harvest time (Jensen et al.).

$$Field\ Efficiency\ (\%) = \frac{Harvest\ Uptime}{Total\ Harvest\ Time}$$

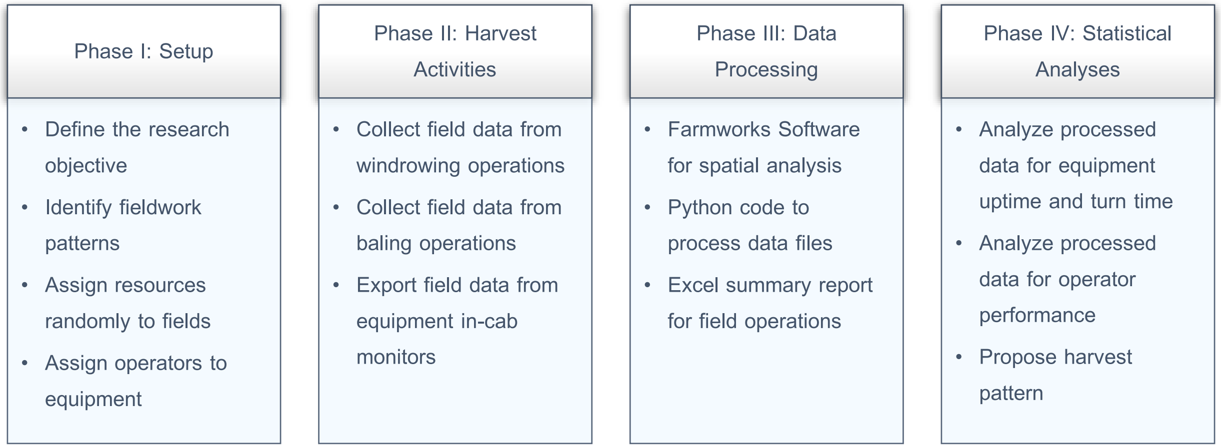
Space required to maneuver equipment at the field boundaries and the time consumed maneuvering equipment both add to an elevated harvest cost. For example, harvest uptime influences field efficiency, which impacts field capacity, and thus hourly cost for operations. Therefore, a reduction in downtime, and consequently an increase in uptime, would increase field efficiency and reduce overall operational costs. For any given harvest operation, field efficiency does not remain constant. It is influenced by: maneuverability, harvest pattern, field shape, field size, yield, soil condition, harvest system capabilities, and operator performance (Zhou et al.). Given the uncertainty of harvest operations, some unproductive time is unavoidable, yet some can be reduced with the proper fieldwork pattern.

Current machinery equipped with auto-assist have raised an interest in field coverage planning, harvest optimization, and productivity for precision agriculture. Consequently, numerous research studies have been conducted in this area. For example, one study minimized the total unproductive travel distance for an optimized fertilizing operation. It found optimizing fieldwork patterns led to a savings in the total travelled distance by 5.8% to 11.8% (Jensen et al.). Reducing field complexity to reduce the number of turns in a field was evaluated by classifying field plots (Oksanen and Visala). A method for choosing the best orientation of parallel tracks for minimizing time wasted turning between tracks was evaluated for spraying and manure distribution operations; the results found that in smaller fields turns between tracks can be optimized to reduce turning time by 50% (Spekken and de Bruin). Another study looked at the most suitable turning pattern between adjacent tracks, and found that a reverse turn maneuver is the most promising when the operation calls for an implement in tow (Cariou et al.). The most common headland patterns were evaluated in order to minimize the unproductive distance traveled; these results found using an optimal harvest pattern can reduce total unproductive distances by 50% (Bochtis and Vougioukas). This research was later built on, studying various routes to optimize the sequence of turns (Bochtis and Oksanen). All the studies reported a decline in unproductive travel and time would reduce production costs.

Previous studies have identified headland space as an operational constraint, analyzed harvest patterns to reduce the number of turns by finding the best turning patterns, conducted trials to simplify turns to reduce nonproductive travel distance, and optimized routing of field equipment to reduce cost. However, increasing headland space by fieldwork pattern for improved productivity has not yet been performed. Additionally, given the developments in agriculture machinery with the emphasis on field productivity it is important not to underestimate the importance of an experienced operator. In fact, some turns in the headland space can be demanding and time consuming, and how these turns are handled is solely dependent on operator skill (Spekken et al.). Headland space depends on the field and harvest pattern and productivity is dependent on the operator's skillset. Fieldwork pattern is one of the few parameters that can be altered from field to field. In this study, operational efficiency of two harvest operations, windrowing and baling, are examined to determine the impact headland space has on productivity and how this field efficiency changes based on operator experience for a commercial scale Miscanthus harvest in Northeastern Arkansas.

Methodology

The methodology consists of four main phases: 1). Setup, 2). Harvest activities, 3). Processing, and 4). Analyses. These stages are outlined in Figure 4. Performance data from field operations was collected for each piece of equipment in operation. Field data was processed to determine the operational state of the machinery throughout the study period. These operational states were categorized as either productive or unproductive tasks. For each fieldwork pattern, tasks were evaluated. Then, an ideal fieldwork pattern for headland space was determined from the results.



Phase I: Setup

- Define the research objective
- Identify fieldwork patterns
- Assign resources randomly to fields
- Assign operators to equipment

Phase II: Harvest Activities

- Collect field data from windrowing operations
- Collect field data from baling operations
- Export field data from equipment in-cab monitors

Phase III: Data Processing

- Farmworks Software for spatial analysis
- Python code to process data files
- Excel summary report for field operations

Phase IV: Statistical Analyses

- Analyze processed data for equipment uptime and turn time
- Analyze processed data for operator performance
- Propose harvest pattern

Figure 4. Outline of the four methodology phases to achieve research objectives.

Phase I: Setup

To evaluate the impact headland space and operator experience has on field efficiency, three fieldwork patterns, two harvest operations, and two operator experience levels were evaluated. The fieldwork patterns and equipment fleets were randomly assigned to fields by the farm manager. Fieldwork patterns consisted of a 2-pass, 4-pass, and 6-pass perimeter cut. A 2-pass perimeter cut opens up the headlands by two passes of the 13-ft. wide windrower. This fieldwork pattern gives a headland space of 26 ft. Similarly, a 4-pass and 6-pass headland space would be 52 ft. and 78 ft., respectively.

Equipment Specifications

Field operations were conducted by Hesston by Massey Ferguson equipment. Two equipment fleets were utilized to complete harvest, including: two WR 9770 machines, two 8660 series tractors one towing a 2170XD large square baler and the other towing a 2270XD large square baler. These balers are the same, but the 2270XD is one model year newer. The equipment is pictured in Figure 5. Machine pairings for each equipment fleet and equipment costs are given in Table 1.

Table 1. Miscanthus equipment information.

Equipment Operation	Equipment Fleet I	Equipment Fleet II	Capital Cost ($)
Windrowing	WR 9770 – 220 hp	WR 9770 – 220 hp	175,000
Baling	MF 8660 Series Tractor – 260 hp 2270XD Large Square Baler	MF 8660 Series Tractor – 260 hp 2170XD Large Square Baler	207,000 170,000

The WR9770 has a 6.6-liter AGCO Power Tier 4i engine and is equipped with e3 SCR clean air system to comply with EPA emission regulations. Four valves per cylinder to boost horsepower (hp) for high-capacity mowing at 220 hp (“There ’ S Hay . And Now There ’ S Hesston Hay The All New WR Series . Cutting-Edge Header to Tail .”). The TwinMax header with RazorBar assist allows double crimping of the crop for advanced conditioning. Electro-hydraulic technology for the engine and drive functions are operated by an onboard computer terminal. Real-time data is collected and displayed in-cab by the FieldMax monitor system, which gives the operator immediate feedback for machine performance features. For baling operations, the Massey Ferguson 8660 Series tractor is equipped with the 8.4-liter turbo-charged AGCO Sisu Power engine which outputs 260 hp (“The Industry’s Leading Baler Leads the Way Again.”). The tractor is equipped with a similar FieldMax monitoring system. In tow are high density balers that produce a 3 ft. X 4 ft. X 8 ft. bale. Both balers have the extended length OptiForm bale chamber allowing for a high, uniform density bale. The equipment is pictured in Figure 5; the image to the left is the WR9770 series windrower, and the image on right is the tractor towing a large square baler.

Figure 5. Massey Ferguson machinery used for 2015 Miscanthus harvest.

All machinery was equipped with the Global Positioning System (GPS) Topcon System 150 to collect data. Machine performance data was collected in real-time, recorded, and stored by the onboard AGCO FieldMax monitor at one-second intervals. At the conclusion of harvest, all data was exported from the in-cab monitor using a standard Universal Serial Bus (USB) thumb drive.

Phase II: Harvest Activities

Harvest operations used in this analysis were conducted between December 2014 and February 2015. During this time of year, harvesting Miscanthus is done without a dry down period because the moisture content is below 20% (wet basis). The low moisture content allows baling to begin immediately after enough cut material is on the ground to be processed. This harvest technique allows for simultaneous windrowing and baling operations. In this study, three harvest patterns were evaluated, which include: 1). 2-pass, 2). 4-pass, and 3). 6-pass perimeter cut.

It is important to note, the windrower in equipment fleet I did not operate the entire harvest season. It needed a major repair in January 2015. The coupler on the header which housed the roller conditioner was damaged, and significant downtime was associated with this repair. Some data from this windrower was included in this study prior to when it was taken out of operation for the repair. Thereafter, this piece of equipment was taken out of operation, and the windrower in equipment fleet II harvested the remaining fields. Multiple operators were employed with different levels of experience. Experience level was defined as either experienced, more than 3 years, or inexperienced, less than 3 years of experience in the particular equipment they would be operating during harvest. Operators were ranked for each piece of machinery, such that a seasoned windrow operator may not be experienced in the tractor towing a baler.

Traditionally, the most skilled operator drives the baler assembly as it is the more demanding operation. Baling is more difficult for several reasons. For instance, there are two pieces of equipment, the tractor and baler, for the operator to maintain during harvest. The tractor does not have steering assist like the windrower, and the tractor is towing a 27-ft. baler, so the operator has to be more strategic when driving and turning equipment. Concurrent operations created a team scenario in each field. Without a dry down period, harvest can only be completed as fast as the least productive operation. Each team of operators worked together to complete harvest. In total, 44 fields of various shapes and sizes were evaluated; all fields were in Northeast Arkansas. Field sizes ranged from 3 acres to 160 acres; the average field size was approximately 50 acres. The average yield was 7.2 harvested tons per acre with an average moisture content of 11.18 % wet basis. The conclusion of harvest accomplished Phase II of this project.

Phase III: Data Processing

To begin Phase III, data files downloaded from each piece of equipment were imported into Farm Works Software. Farm Works is a division of Trimble Ag Software, which is compatible with AGCO systems. Unit compatibility allows machine parameters to be collected in real-time and recorded during operations. Data was collected in 1 second increments while the machine engine was engaged. These shape files were opened through the AGCO platform within Farm Works, converted, and exported as Excel.csv files. Spatial field images for various machine performance parameters were obtained with the precision mapping capability; a subset of these images can be seen in the Appendix. The properties tab in Farm Works saved the information loaded from the task controller which indicated, field, total harvested acres per field, total harvest time, and operator. Once converted, an Excel spreadsheet represented a single harvest operation, windrowing or baling, for a field. All spreadsheets were analyzed using Python programming language, and simplifying assumptions were made. These assumptions include:

- There was an optimal predetermined field entrance and starting point for field operations
- Field operations were performed in straight and parallel tracks
- Turns were generalized; turn type was not considered
- Field condition was approximately the same for every field, so it was neglected
- Fields were primarily flat, so field slope was neglected
- Various field sizes and shapes represented different levels of complexity

Operational tasks were determined by changes in machine performance parameters; tasks under consideration were: field efficiency, turn time, and other unproductive time. These unproductive times include idling for machine servicing, such as: machine adjustments, machine warm-up for hydraulic lines, refueling, reloading baler twine, cleaning and unclogging equipment. The changes in machine parameters evaluated are outlined in the Appendix. All data points were productive based on latitude, longitude, field speed, and engine speed. Similarly, turns were determined by a change in directional heading. The heading indicator, collected from the directional gyro, data indicates heading direction based on 360º. It is important to note, the heading indicator will change overtime due to the rotation of the earth, which is approximately 15º per hour. However, slight deviations in heading degrees within a windrow is seen for the baler because the operator had to adjust, move right or left in row, to make a uniform bale.

The final summary of results computed in Python were compiled and exported into a single Excel document. This spreadsheet included: field efficiency (%), turn time (%), other unproductive times (%), average field speed traveled (mph), average fuel consumption (gal/hr), average bale moisture content (% w.b.), and average bale weight (tons). Fuel consumption was only recorded for the windrower. Additionally, significant downtime caused by the damaged windrower in equipment fleet I was omitted from the dataset by assigning a binary value, 0 = no breakdown and 1 = breakdown when the windrower was not immediately repairable. Data analyzed was without breakdowns consuming more than 25% of the total harvest time.

Phase IV: Statistical Analysis

Five statistical analyses were performed to understand the Python results. This evaluation was computed in SAS based on split plot repeated measures with covariates. To be more specific, a mixed effect with repeated measures ANCOVA test for fixed effects, regression analysis, spearman correlation, Mann-Whitney U, and Kruskal-Wallis tests were calculated. Repeated measures were set by space as windrowers and balers operated within the same field. Parameters under evaluation included: field efficiency, turn time, other nonproductive time, field speed, and harvest pattern of 2-pass, 4-pass, or 6-pass perimeter cut for equipment type. Perimeter cut served as the headland space determinant. All statistical analyses were performed at an alpha level of 0.05. No transformation was required for uptime; however, a log transformation of the data was necessary to evaluate turn times. No heterogeneous variables were evaluated and thus all statistical criteria were met. SAS residual outputs for the analyses performed are presented in the Appendix.

Upon initial statistical evaluation, operator experience was found to be a major contributor to productivity. The influence operator experience has on harvest operations was evaluated. An inexperienced operator was one that had less than three years of experience, and an experienced operator was defined as having three or more years of experience. Miscanthus harvest was fulfilled in a team setting, thus a team experience rating was assigned to the data. All baler operators were seasoned, and so the variability in experience originated from the windrower operators. To complete these analyses, a mixed effect repeated measures ANCOVA and Mann-Whitney U calculations were performed. Multiple categorical and continuous with repeated measures over space and nonparametric independent two sample T-tests were calculated to appropriately represent operator experience within each team scenario.

Results

The results from this study align with previous studies. For instance, an increase in excess travel distance to turn farm machinery at the headlands increases turn times. Additionally, unproductive time increases as field size increases. However, this study identifies the optimal space to turn equipment during harvest operations based on the fieldwork pattern. Previous studies also noted, machine maneuverability is influenced by the operator. This study quantifies the variability among different skill levels.

Headland Space

Analyses included paired equipment in their respective fleets and individual machinery for their operations. First, field efficiency for the different headland spacings will be discussed. Figure 6 illustrates the average operational efficiencies for the paired equipment at each harvest pattern. Fields with a 4-pass and 6-pass perimeter cut show a lower overall field efficiency. Additional machine servicing was required (e.g. refueling, reloading baler twine, etc.), and thus the unproductive times are higher. It was determined that headland space does impact uptime in-field for the paired equipment fleets, at a p-value of 0.0142.

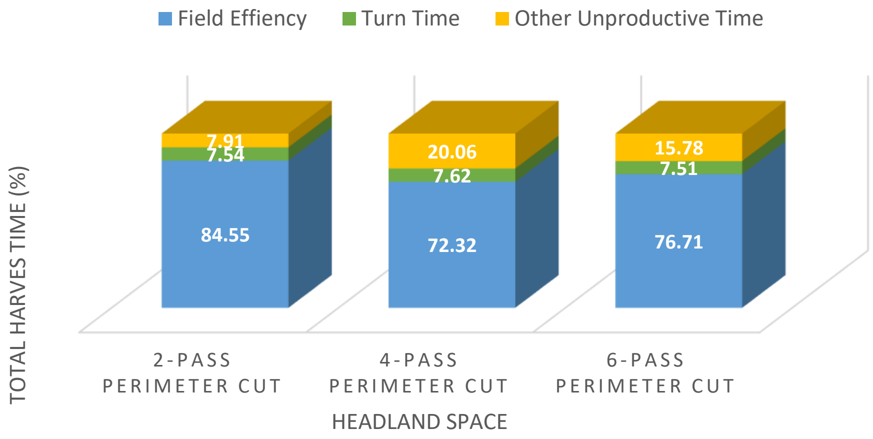


Figure 6. Operational task breakdown for the combined equipment fleets for each fieldwork pattern for increased headland space.

The paired data was further examined on an equipment type by perimeter cut interaction, shown in Figure 7 and outlined in Table 2. There was no statistical significance between fieldwork patterns for the baler and the windrower for the 2-pass harvest pattern. The windrower field efficiency for the 4-pass perimeter cut was statistically different from the others. This low field efficiency was due minor header repairs and adjustments. Minor repairs were initially made, and it remained in operation until was no longer functioning; at this time, it was taken out of operation completely. Figure 7 shows productivity by equipment type. The baler was significantly more efficient compared to the windrower; this efficiency can be explained by operator experience. Both baler operators were seasoned and were consistently more efficient. Thus, there was no statistical difference between cuts for the baler. Looking at these parameters in conjunction, the best headland space width was determined by field efficiency. Solely based on field efficiency, a 2-pass perimeter cut for the windrower and a 4-pass perimeter cut for the baler is ideal. A 4-pass fieldwork pattern for the baler is ideal. A 2-pass fieldwork pattern, opened the headlands 26 ft., did not leave enough space to turn the tractor and baler at the headlands and caused the operators to make two-point turns, which consumed more time. A 6-pass fieldwork pattern, gave the operator ample space to turn the equipment; however, the operator used the extra space to turn the equipment which caused excess travel distance for turning. Even though additional space was convenient for the operator to turn the equipment at the field edge, it was not efficient. Only one harvest pattern can be selected; a 4-pass perimeter cut to increase productivity is preferred.

Figure 7. Field efficiency by equipment type for different harvest patterns for increased headland space.

The spearman correlation analysis for the windrower determined field size impacted field efficiency, at a p-value of 0.0031. This was explained by field size also influencing other unproductive times, at a p-value of 0.0028. Therefore, the larger the field the more time will be spent in-field servicing the machine, such as refueling.

For the baler, the average field speed was seen to impact uptime at a p-value of 0.0036. This relationship can be explained by the impact speed has on turn times, which is illustrated in Figure 8. For the paired data, headland space did not impact the average field speed traveled. This relationship was determined by the Kruskal-Wallace test. Evaluating the mean ranks reported a p-value of 0.6454 which found it was not an influential parameter. In general, the average operational speed was consistent throughout the various fields and fieldwork patterns. The average speed traveled by the windrower was 5.8 mph and just over 6.0 mph for the baler. Specifically evaluating the effect headland space has on turn times, average speed was significant. In fact, the paired equipment data showed that field speed was a crucial factor to reduce turn times in the headlands, at a p-value of 0.0001. For every 1 mph increase in average field speed traveled a 1.66% increase in turn time can be expected.

Table 2. Field efficiency by equipment type and fieldwork pattern.

Equipment	Fieldwork Pattern	Field Efficiency Estimate (%)	Field Efficiency: Least Squares Mean Letter Grouping[1]
Windrower	2-pass cut	75.12	A, C
Windrower	4-pass cut	47.36	B
Windrower	6-pass cut	63.82	A
Baler	2-pass cut	88.89	C
Baler	4-pass cut	88.93	C
Baler	6-pass cut	85.70	C

[1] LS means with the same letter are not significantly different.

A log transformation of the turn data was performed. A Type III Test for mixed effects showed, additional headland space did not reduce turn times for the paired equipment or individual operations of the windrower and baler with a p-values of 0.6623, 0.2978, and 0.6513 respectively. There was no difference between a 2-pass, 4-pass, and 6-pass perimeter cut; however, the type of equipment used is a crucial limiting factor, at a p-value of < 0.001, represented by the different letter groupings in Table 2. It was expected that the windrower and baler would have significantly different turn times. The windrower has a zero-turn radius compared to the tractor, with a 55º steering angle, towing the 27-foot baler. It is understandable that this lengthy assembly would require a wider space to proficiently maneuver in the headlands. Equipment was also evaluated individually. Additional headland space to reduce turn times for the windrower was not impactful at a p-value of 0.4311, but it was for the baler at a p-value of 0.0023. As field speed increases so does turn time.

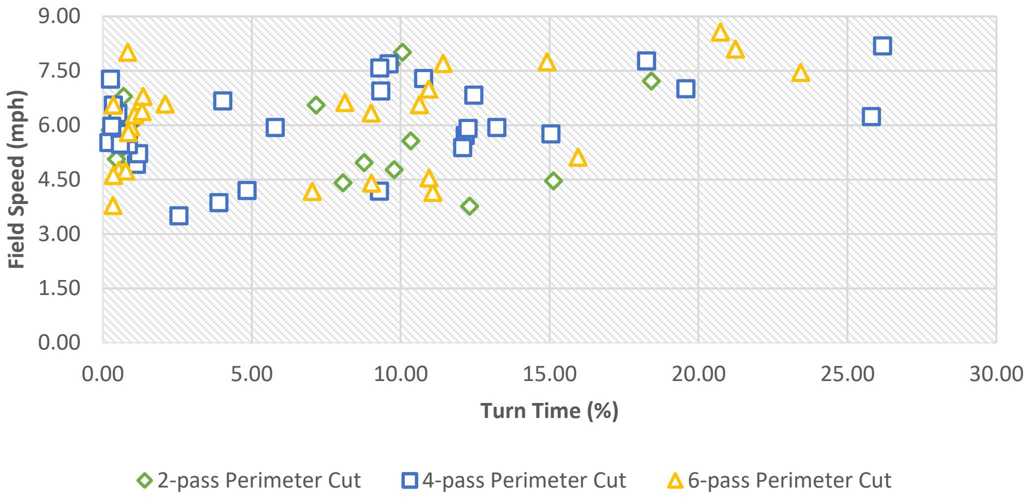


Figure 8. The impact average field speed traveled has on the percentage of turn time for harvest operations.

Only one fieldwork pattern per field can be selected for harvest operations. Due to machine capabilities, turns for the windrower are miniscule, a 4-pass perimeter cut would be optimal for reducing time to turn the baler. This perimeter cut would allow ample room to move the baler at the field edges. The added space in the 6-pass perimeter cut gave the operator additional room to turn which increased the nonproductive distance traveled and increased time spent in this task. However, this additional 26 ft. of headland space could be ideal for other types of harvest equipment, field obstacles, or field boundary limitations.

Operator Performance

Operator experience was evaluated as a team component. An experienced team consisted of both an experienced windrower and baler operator. An inexperienced team was comprised of an inexperienced operator on the windrower paired with an experienced operator on the baler. All team scenarios had at least one seasoned operator. To analyze the impact operator experience on field operations, multiple categorical and continuous repeated measures ANCOVA statistical method was used. A Type III test for fixed effects found that operator experience is statistically significant, at a p-value of 0.0416, for field efficiency during both windrowing and baling operations. The operational time breakdown for experience level is given in Figure 9.

A higher turn time can be seen for the experienced operator at 10%; however, this difference was not statistically significant in comparison, at a p-value of 0.3740. Therefore, operator experience was not seen to impact turn time. The same held true for other unproductive times in-field, at a p-value of 0.6062. Specifically looking at baling operations, an experienced team was noticed to have higher yields. The Mann-Whitney U test, with normal approximation, concluded that experienced operators tend to have higher yields at a p-value of 0.0125. The means procedure was used to identify the trade-offs between an experienced and inexperienced operator in a team harvesting scenario. These results are outlined in Table 3.

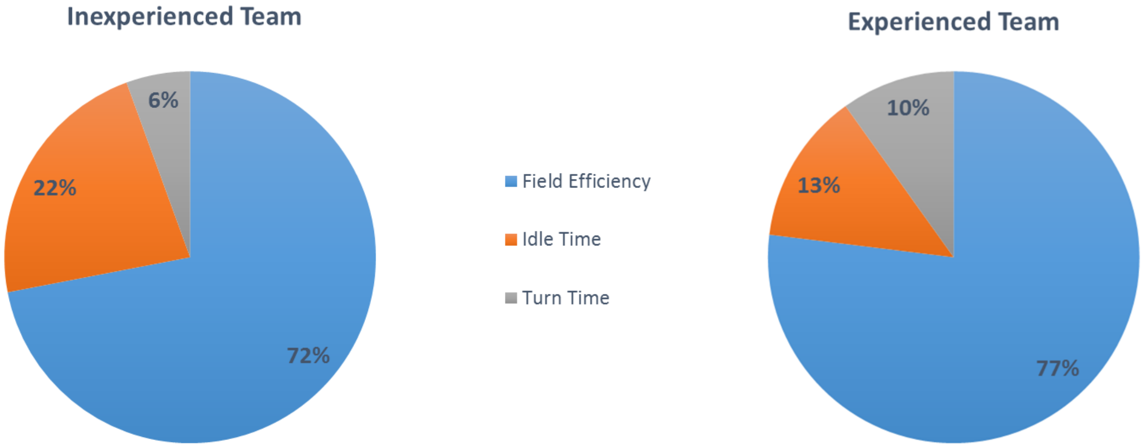


Figure 9. Operational time breakdown for operator experience levels in a team setting for Miscanthus harvest.

An experienced operating team is more productive at an average field efficiency of nearly 77%. Looking at the inexperienced team results, the high median and maximum efficiencies are not surprising due to the experienced operator's skillset in this team pairing. The inexperienced team had less variation between the median and the maximum field efficiency, which can be explained by the inexperienced operating team was less distracted during harvest. For example, given an experienced and inexperienced team, the experienced team will be side tracked more. Management decisions, harvest interruptions, and repairs will require the expertise of the experienced team. Harvest interruptions that cause unproductive time in-field will necessitate help from an experienced over an inexperienced operating team, which leaves the inexperienced team able to harvest undisturbed. An additional 12% in variability in field efficiency was seen with a less experienced operator. With an inexperienced operator uptime can deviate approximately 35%; however, only 22% variability in productivity can be expected with an experienced team of operators. This variability may change with a tighter window for experience level. For instance, if an experienced was defined as one year or more of operating experience in a specific machine, more variability might be expected.

Table 3. Field efficiency results based on operator experience for all harvest operations.

Team Experience Level	Minimum Field Efficiency (%)	Mean Field Efficiency (%)	Median Field Efficiency (%)	Maximum Field Efficiency (%)	Standard Deviation (%)	Coefficient of Variation
Inexperienced	19.19	71.98	84.95	96.10	25.02	34.76
Experienced	36.55	76.94	81.74	98.09	17.17	22.33

Conclusion

Maneuvering equipment in-field can have a significant impact on production cost. Fieldwork pattern is critical for operational efficiency. Headland space depends on the field and fieldwork pattern. A 2-pass perimeter cut is the most common way to open the headlands to provide space to turn the machinery at the field edge. In Arkansas during 2015 Miscanthus harvest, field trials were conducted to compare the impact of headland space on various operational parameters for various field shapes and sizes. Three harvest patterns were analyzed, which include: 1). 2-pass, 2). 4-pass, and 3). 6-pass perimeter cut. The harvest pattern influences time wasted due to excessive nonproductive time and distances traveled during operational tasks. There is a potential economic benefit by improving the machine productivity and reducing nonproductive time spent turning at the field boundaries. Maneuvering the windrower in the tight headland space is not an issue, but it is a limitation for the tractor towing a baler. The purpose of this study was to compare the impact of headland space on harvest uptime and turn time during Miscanthus harvest to identify productivity trade-offs between harvest equipment and operator experience. After analysis, a preferred 4-pass perimeter cut harvest pattern is suggested to utilize all productive land and create ample space to efficiently maneuver equipment at the field edge. With an inexperienced operator uptime can deviate approximately 35% from expected, which is 12% more than expected with a seasoned operator. It would be beneficial to follow up with the impact of additional headland space to various types of machinery and field collection equipment. Also, evaluating operator experience for different agricultural equipment and harvest operations with a dry down period would be useful.

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Appendix

Farm Works field images

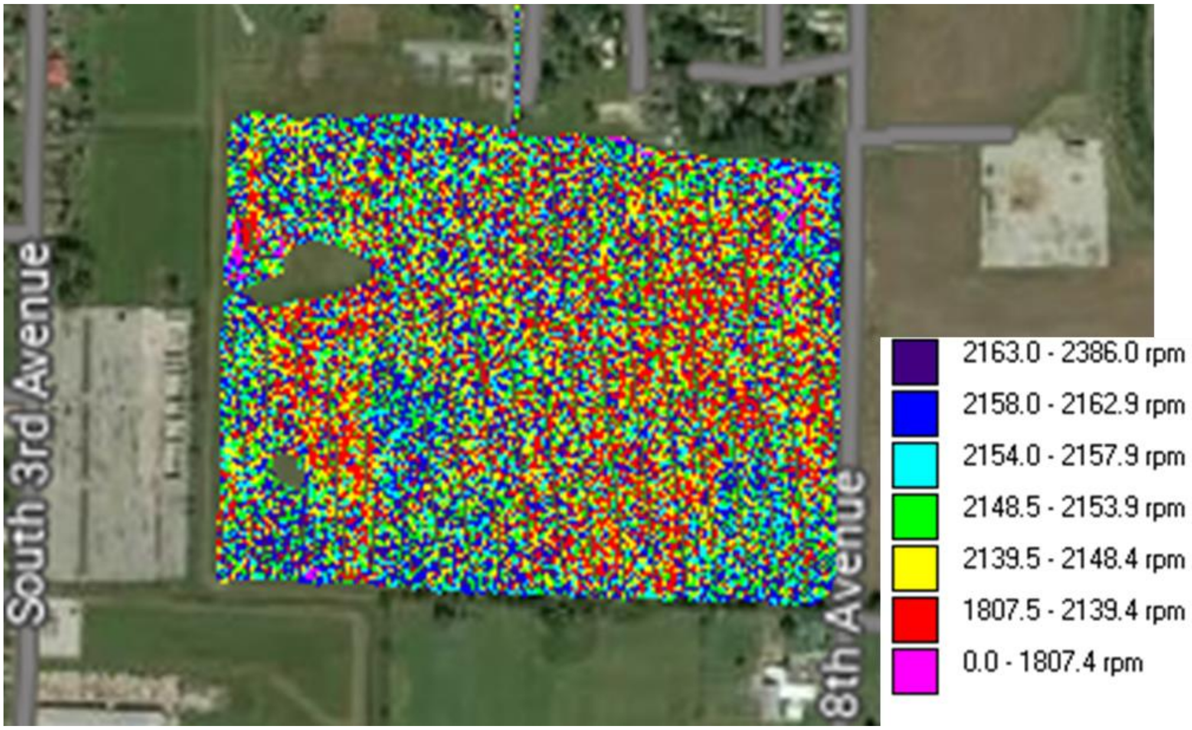


Figure 10. Engine speed spatial analysis for Miscanthus harvest.

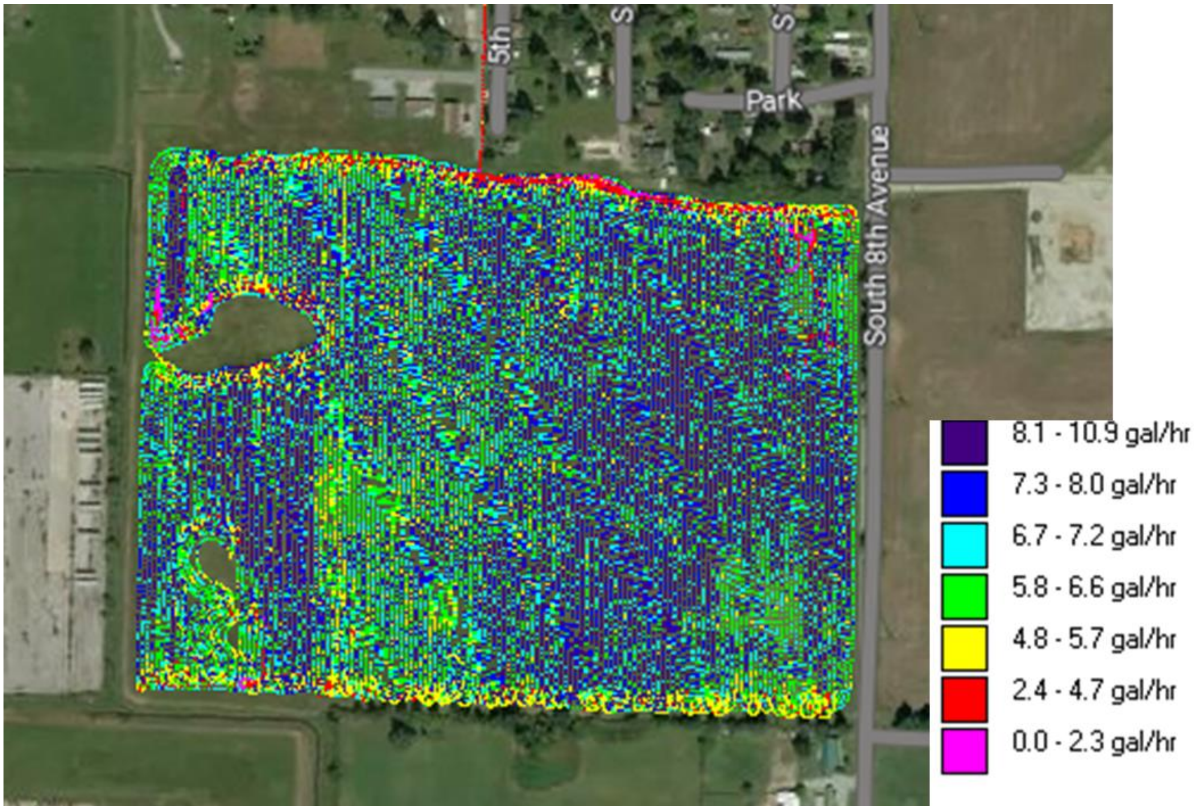


Figure 11. Fuel consumption spatial analysis for Miscanthus harvest.

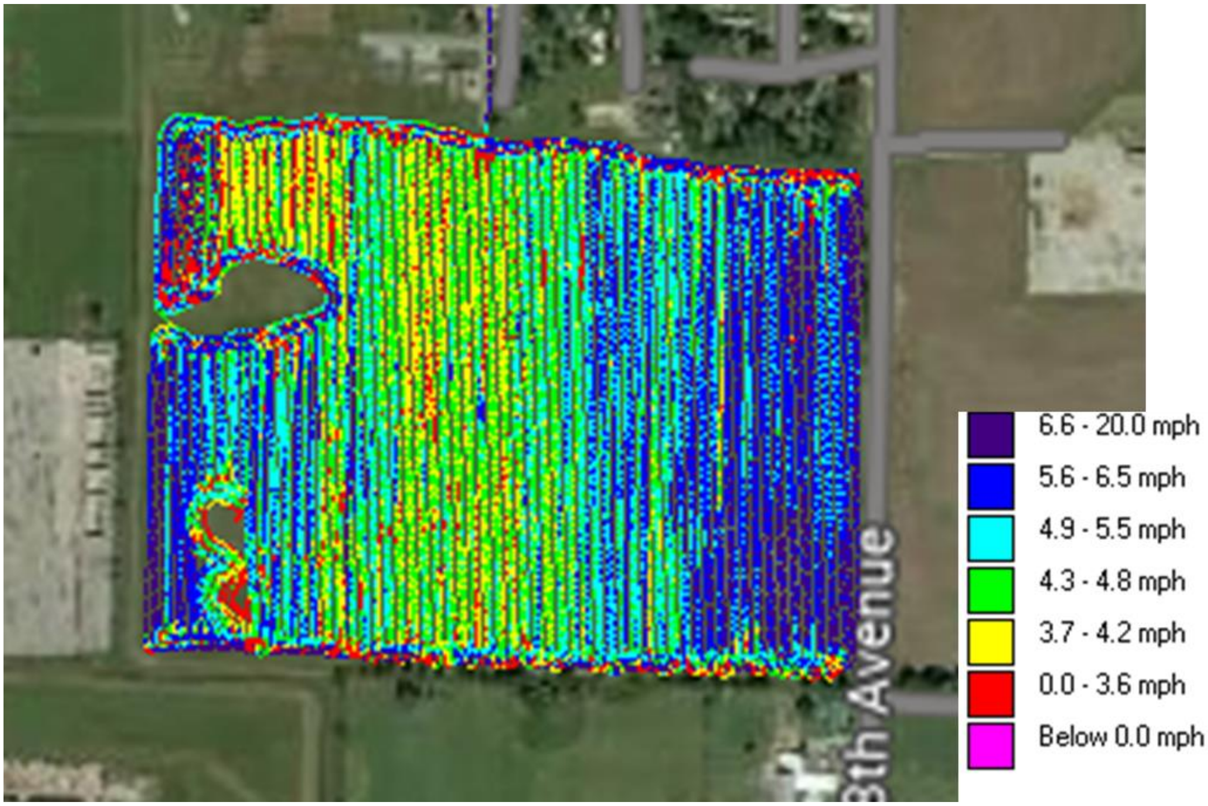


Figure 12. Field speed spatial analysis for Miscanthus harvest.

Figure 13. Directional heading spatial analysis for Miscanthus harvest.

Python Logic

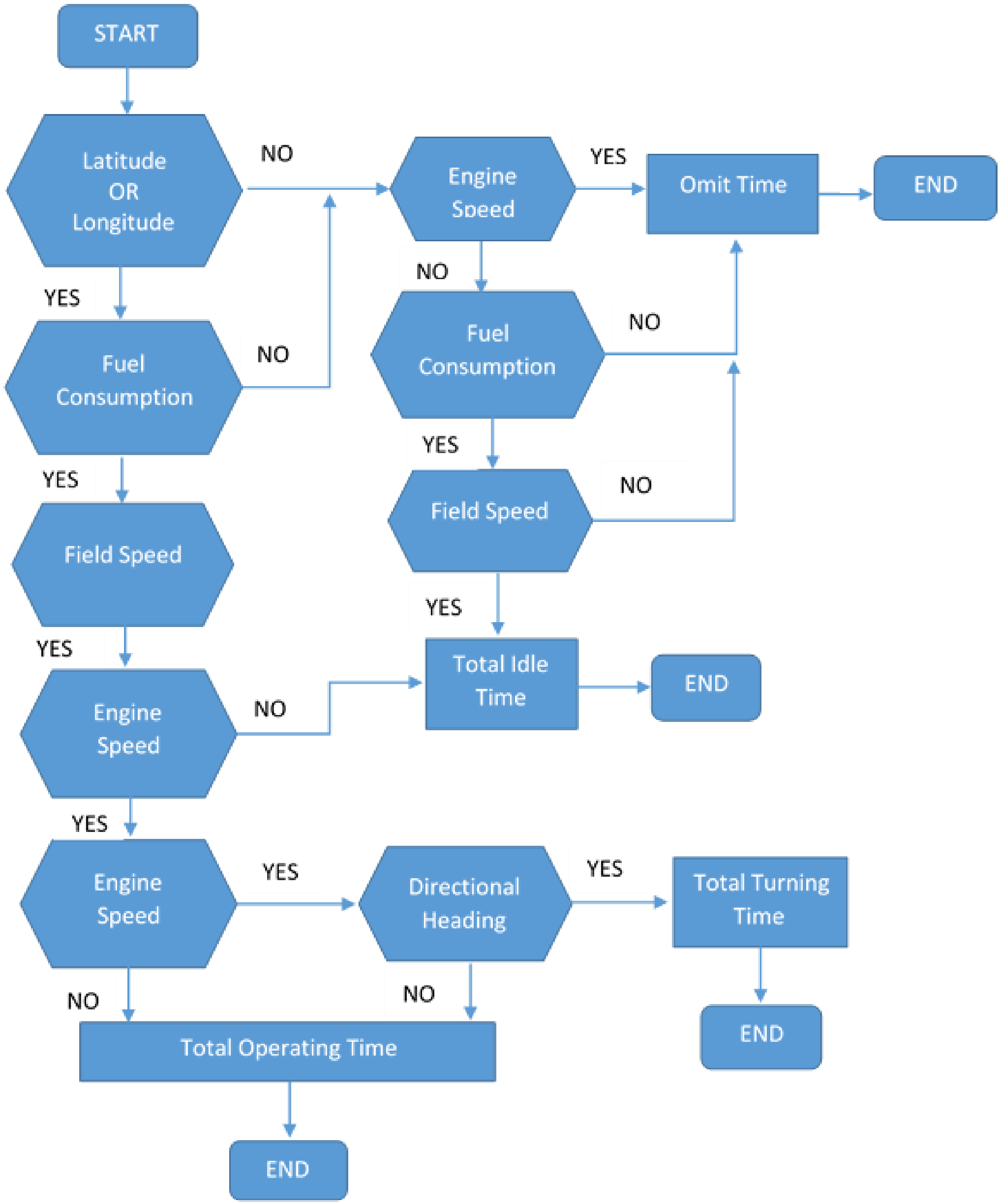


Figure 14. Python logic flowchart to determine operational tasks.

CHAPTER II

QUANTITATIVE RISK ASSESSMENT FOR REPAIR AND MAINTENANCE ON A NEW HOLLAND FORAGE HARVESTER DURING WILLOW HARVEST

This article was revised by the graduate committee and co-workers at the Oak Ridge National Laboratory. The student's involvement included: literature analysis and initial research setup, data processing, and data analysis. Help was received from several participants, which is outlined below:

- Mark Eisenbies, Tim Volk, and Daniel Pegoretti at the State University of New York College of Environmental Sciences and Forestry - harvest operations and data collection
- Christopher Muir in the Industrial Engineering program at the University of Tennessee – aid in Python and R coding
- Jamie Coble in the Nuclear Engineering department at the University of Tennessee – aid in probabilistic risk assessment
- Erin Webb and Mahmood Ebadian at the Oak Ridge National Laboratory – research support and chapter revisions, edits, and suggestions

Abstract

In the biomass supply chain, harvest is singlehandedly the largest cost in production of short-rotation woody crops. The capital cost of machinery is a major cost contributor, but downtime in-field adds to this expense. Unproductive times are largely due to repair and maintenance on equipment caused by unexpected harvest complications. Harvest delays are costly, and classifying these breakdowns is beneficial for farm management and operators. Additionally, identification of component failure is also insightful for the agricultural machinery industry to improve fabrication and design of equipment. Even though New Holland is an established equipment manufacture, the woody coppice header is a first-generation prototype; therefore, there is insufficient harvest repair data in mature woody crop conditions to estimate the reliability of components. The purpose of this study is to analyze the financial impact of harvest delays during a single-pass cut and chip operation utilizing a New Holland self-propelled forage harvester equipped with a woody coppice header and two collection fleets, which included a 140 hp tractor towing sugar cane wagon, for willow harvest in upstate New York. To accomplish this probabilistic risk assessment (PRA) is used. Logic for this quantitative analysis is modeled by a fault tree to include all potentially reasonable and quantifiable causes of delays during harvest operations. Based on field data collected, the main delay categories included: operational, mechanical, worker related, and miscellaneous delays; however, operational and mechanical are the most critical types. Unproductive delays during harvest operations were calculated to be 6 interruptions per hour. These interruptions consumed 28 hours of total harvest time. The hourly cost associated with breakdowns was $197.02, where fuel and labor costs accounted for $36.42 of this expense. This cost is significant. Quantitative analysis has a real application in the agricultural sector for estimating equipment reliability; results give an indication about harvest system reliability and identify critical components.

Introduction

Harvest operations for shrub willow, a short rotation woody crop (SRWC), are the primary focus for this study. Woody biomass is an attractive crop for several reasons. It does not compete with cash crops because it can be grown on marginal land. Willow is predominately farmed in the Northeast, and it has the potential to stimulate rural development (Abrahamson et al.). In this region, forests occupy approximately 67% of land area; therefore, there is a great potential for willow to create jobs (Eisenbies, Volk, Posselius, et al.). SRWCs use a coppice management system that allows multiple harvests from a single planting. Harvests are typically every three to four years and use a cut-and-chip method to get material into a desired, uniform quality (Eisenbies, Volk, Posselius, et al.). Harvesting, handling, and transportation account up to 60% of the total delivered cost for willow biomass (Eisenbies, Volk, Posselius, et al.). Unfortunately, harvest cost is the single largest cost contributor for willow at approximately one-third of the total delivered biomass cost (Mark Eisenbies, et al.). To help offset this cost, a custom forestry header was designed by Case New Holland to mount on current farm machinery for specialty SRWCs. The retrofitted equipment allowed for a cost savings, and preliminary research has been conducted to develop this robust header. However, there are some limitations to this first-generation prototype. Failure of the equipment to function is a major contribution to production losses and high maintenance costs. Therefore, there is a need for an optimal maintenance strategy (Ahmad et al.). Ultimately, reducing harvest cost is essential to making biomass a viable option.

Agricultural equipment has direct and indirect costs associated with harvest operations. The main contributor for direct expenses is the capital cost of machinery. Indirect costs are greatly influenced by downtime in-field often caused by unexpected harvest complications. A reduction in these unproductive times would decrease indirect costs (Spekken et al.). Unproductive times are largely due to repair and maintenance on equipment caused by harvest interruptions. An agricultural machine is a repairable mechanical system that is prone to repeated failures and deterioration (Afsharnia et al.). Typically, repair and maintenance costs are incorporated in the annual operating cost and attributed up to 15% of the total streamlined cost. These costs increase as the equipment ages, which is used as a criteria to determine the optimal time to replace machinery (Calcante et al.). In equipment repair and maintenance the expenditure necessary to repair is costly but also the impact on productivity and the fact that idle staff have to be paid increase this expense (Afsharnia et al.). In general, the performance potential of the machine is entirely influenced by maintenance and handling. Inadequate maintenance and repairs negatively influence machine performance throughout harvest and thus increases harvest cost.

The operational availability of an agricultural machine is defined as the period during which a machine can perform its function without any breakdowns (Afsharnia et al.). Breakdowns cause shortcomings during harvest. Reliability of farm equipment is mainly affected by the annual use, repair and maintenance policies, and operating environment (Lips). Failures and breakdowns that occur during harvest are not part of scheduled maintenance or routine checkups, which occur before or after working hours.

Rather, they can happen at any time during operations. Repair and maintenance costs are difficult to estimate for several reasons. These costs are variable among machines, operating conditions, crop types, operator handling, and the unavailability of good record keeping (Abubakar M.S., Zakari M.D., Shittu S.K.).

One of the most important factors during harvest is timeliness. Therefore, upkeep of agricultural machinery is essential for productivity. Classifying breakdowns is beneficial for farm management and the operator to prepare for breakdowns in-field and potential spare parts required (Al-Suhaibani and Wahby). It is also important for the agricultural machinery industry; it will help them identify breakdowns, pinpoint issues, and improve design and fabrication of equipment (Al-Suhaibani and Wahby).

With the increased importance to reduce harvest cost, several studies have modeled repair and maintenance costs for various farm equipment. The American Society of Agricultural Engineers (ASAE) evaluated repair, maintenance, and reliability for farm equipment by crop type and field size. Here, operational reliability is defined as the probability of satisfactory machine function over a certain timeframe ("ASAE D497.4 Agricultural Machinery Management Data"). In the Machinery Management Standard, failure data was collected by Midwestern farmers in 1970. Annual breakdowns were evaluated on an hourly basis for 100 acres, where the breakdown probability for machine system increased with an increase in farm size. Additionally, equations predicting reliability and operational downtime for a diesel engine were given ("ASAE D497.4 Agricultural Machinery Management Data"). However, these data sets were only for certain crops, they do not include equipment specifics, or account for machine updates and advancements.

Another study looked at repair and maintenance data for tractors based on job orders for 1988 to 1993. The data evaluated included: job date, tractor serial number, tractor power, type of work performed, number and cost of spare parts used, total labor requirement, related cost, and the total cost of the job order. Data was sorted and analyzed by ASAE and determined a cost ratio for each repair and maintenance category. This study found, the repair and maintenance cost ratio were directly related to the age of the tractor due to the availability of spare parts and the spare part working life. This trend was seen up to the tenth year, and a drop in the cost ratio was seen in the eleventh year. This decline in cost is potentially due major repairs made in the previous year which reduced necessary repairs in the eleventh year. This study concluded, increasing working hours for equipment decreases the operating cost per hour (Al-Suhaibani and Wahby). However, this conclusive study is dated. No equipment manufactured after 1993 was evaluated. There have been substantial changes in the agricultural machinery industry since the 1990s.

A similar study used a regression model to predict tractor failure rate of 300 tractors for Massey Ferguson, John Deere, and Universal manufacturers. Survey data was used to predict a repair and maintenance cost model for different tractor types. It was determined that equipment storage drastically influenced repair and maintenance costs. In fact, closed storage reduced annual repair and maintenance costs by 33.6%, 33.6%, and 29.6% for Massey Ferguson, John Deere, and Universal, respectively (Afsharnia et al.). For tractors stored outside, the electrical system caused majority of failures. Additionally the study noted, the lack of attention towards tractor care and maintenance was caused by poor skill, knowledge, and financial issues (Afsharnia et al.). In Switzerland a similar review was performed. In this study, surveys from 351 farms where detailed machine information and records for the last three years of operation were analyzed. It concluded similar findings to repair and maintenance costs documented in the ASAE Machinery Management Standard. For instance, age and annual use of the equipment are significant factors impacting annual repair and maintenance costs, and short service intervals coupled with a high annual utilization is advantageous for cost savings (Lips). However, there are several limitations to this study. For instance, there was a small sample size with only 18% of surveyed farms participating. Farm labor inputs for repair activities were not considered, productive time was not included, and all numbers were dependent on accurate, non-inflated costs, and no missing repair information from farm managers.

The competitiveness in the agricultural industry and energy market, the frequency of harvest, and the expense of farm machinery all give reason to better understand the sources of uncertainty in harvest operations for SRWC (Eisenbies, Volk, Espinoza, et al.). Farm management methods primarily focus on the accumulated repair and maintenance costs over the estimated machine life. These costs are simplified by using indexes from outdated equipment or estimated as a fraction of the capital cost of the machine (Lips). However, there are several issues with these repair and maintenance factors. For instance, it does not account for advancements in the equipment, improvements to the replaceable parts, nor does it account for predictive maintenance aids given by sensors and monitors on-board the equipment. A substantial pitfall for accurate and up-to-date repair and maintenance costs is repair data. Few analyses for repair and maintenance have been complete in the last twenty years. Consequently, there is a serious need to better account for untimely breakdowns and equipment reliability.

Previous studies have tested and evaluated SRWC single-pass cut and chip harvest; however, no work has been done to estimate the cost of operational delays with probabilistic risk assessment (PRA). PRA is a quantities analysis to determine what can go wrong and assesses strengths and weaknesses in a system. It will allow for better management and scheduling for harvest operations by defining types of harvest delays and identifying the sources for each delay. The objective of this study is to analyze the financial impact of harvest interruptions during a single-pass cut and chip operation utilizing a New Holland self-propelled forage harvester equipped with a woody coppice header and two collection fleets for willow harvest in New York. Logic for this quantitative analysis is modeled by a fault tree to include all potentially reasonable and quantifiable causes of unscheduled downtime during harvest.

Methodology

To effectively manage and improve harvest operations, a systematic method of examining harvest interruptions and equipment reliability is necessary. The methodology consists of four main phases: 1). Project setup, 2). Data collection, 3).

Data processing, and 4). Probabilistic Risk Assessment (PRA). These stages are outlined in Figure 15. Materials in the initial phases and analysis methods will be discussed in this section.

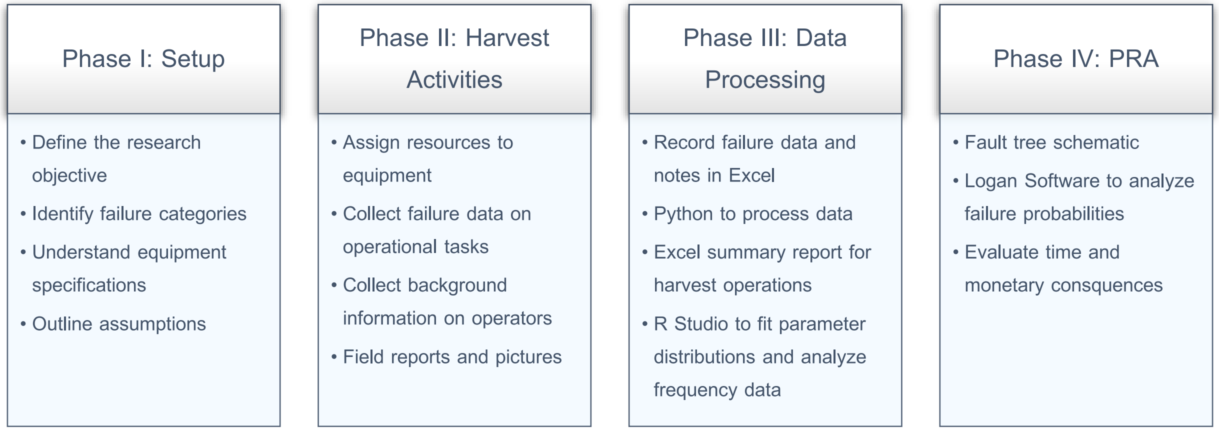


Figure 15. Methodology approach outline for assessing costliness of harvest delays for willow harvest.

Phase I: Setup

Operations for a single-pass cut and chip harvest were examined. The conventional harvest method is illustrated in Figure 16. The fieldwork pattern is represented by the flow of the arrows. A forage harvester equipped with a hydraulically driven woody coppice header cut and chips the willow into the desired particle size, and then material is blown into the collection equipment that operates alongside the harvester. Once full, collection equipment unloads material at the field-side for short-term storage. At least two collection fleets are employed. As one is unloading, the other will be collecting alongside the harvester. Then, the empty collection equipment will return to the forage harvester. This fieldwork pattern constraint differs from other forage crops. Machines operate straddling rows and cannot move across rows because the cut stems can damage equipment. Stems can puncture hydraulic hoses and cause flat tires. These fieldwork limitations impact operational efficiency and require separate analysis from other biomass crops.

Equipment Specifications

Single-pass cut and chip system for willow harvest was evaluated for a self-propelled forage harvester, FR 9080 series, equipped with a hydraulically driven woody coppice header, 130 FB Model. This custom header was designed and built to address previous issues for woody feedstocks. The header is equipped ¼ inch thick carbide-tip saw blades to effortlessly cut the trunk. The header design makes it robust for mature crops up to 5 inches in diameter. Stems are cut at least 2 inches off the ground at the forward speed of the harvester, dictated by an experienced operator, allows for a clean cut (Abrahamson et al.). Once cut, two turning vertical towers feed the tree into the horizontal rolls that feed the trunk into the cutter head. Then, material is fed into the chopper drum of the forage harvester where the industry exclusive Variflow crop processing system chips the willow to a uniform length quickly. The processed biomass is blown into collection equipment located beside the forage harvester. For this study, two collection fleets were employed. Fleets consisted of a 140 hp tractor towing a sugar cane wagon. The harvest equipment is illustrated in Figure 17, and equipment specifications are outlined in Table 4.

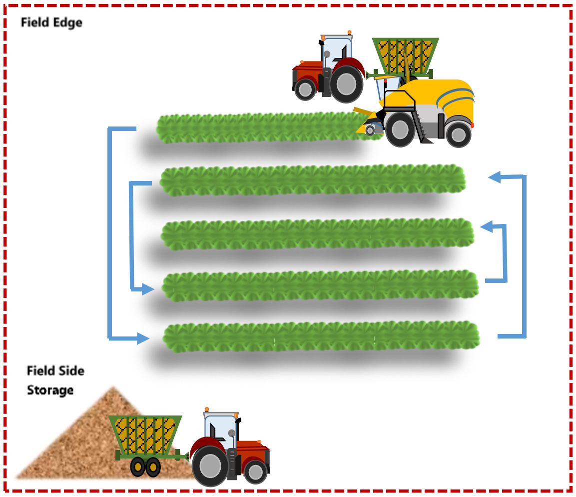


Figure 16. Fieldwork pattern for SRWC harvest operations.

Field operations were tracked using a combination of Global Positioning System (GPS) devices and the forage harvester was equipped with a GeoXM GPS unit with an external antenna for monitoring machine performance. Data was collected and recorded every second for the duration of harvest.

Phase II: Harvest Activities

Harvest began on September 5, 2017 in Jefferson County, New York. This site was composed of two separate farms, containing eight fields, which totaled 76.25 harvestable acres for Farm 1 and 103.7 for Farm 2. Aerial images were captured by Google Earth to show farm layout and field orientations for each labeled field, represented in Figure 18. The entire tillable field was not planted. A fraction of the field was left unplanted to give the forage harvester and collection equipment adequate room to maneuver in the headland space without damaging the woody crop or impacting regrowth.

Figure 17. New Holland self-propelled forage harvester equipped with a woody coppice header and two collection equipment fleets consisting of a tractor towing a cane wagon were utilized for 2017 willow harvest.

Table 4. Woody coppice harvest equipment specifications.

Equipment Type	Model	Capital Cost ($)
Forage Harvester	Self-propelled FR 9080 Woody coppice header FB 130	350,000 125,000
Collection Fleet 1	Tractor 4WD (140 hp) Sugar Cane Wagon	115,000 40,500
Collection Fleet 2	Tractor 4WD (140 hp) Sugar Cane Wagon	115,000 40,500

Figure 18. Various fields harvested in Jefferson County New York for 2017 willow harvest.

Throughout harvest, data was collected cumulatively, and individual equipment data was not collected; there is one dataset for the entire willow harvest. A holistic approach was applied for recording data because all operations were delayed if one piece of unit experienced a delay. For example, if a breakdown occurred specific to the forage harvester, but the collection equipment was functional it would also remain unproductive until the forage harvester was repaired. Inclusivity was necessary because a system delay was considered regardless of the explicit equipment that failed to function.

Field operations were carried out by experienced operators. There was no external direction given to the operator to harvest fields in a specific order; therefore, progression of harvest activities hinged at the discretion of the operator. Operations occurred simultaneously as the collection equipment drove alongside the harvester. These concurrent operations created a team scenario. This team of operators worked together to complete harvest. The operational objective was to optimize machine time throughout harvest. The average yields were 22.93 and 14.56 harvested tons per acre from Farm 1 and Farm 2, respectively. Harvest operations were completed in approximately 120 hours. The conclusion of harvest accomplished Phase II of this project.

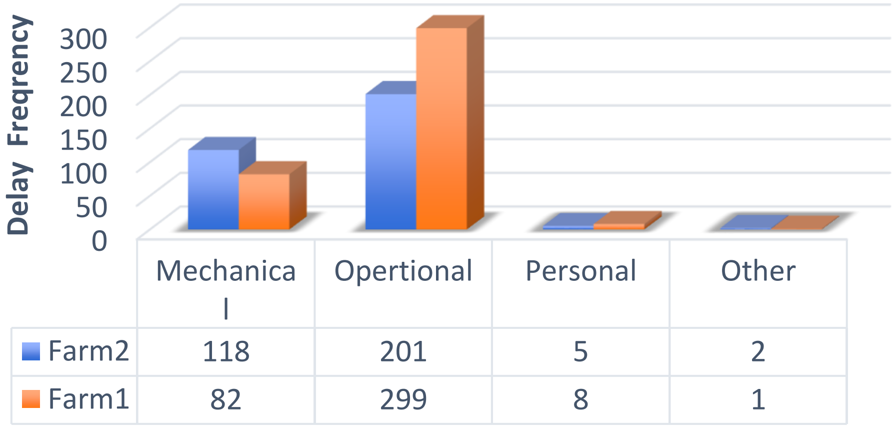
Phase III: Data Processing

Data and field notes collected during harvest operations were provided by a note taker, riding alongside the operator, who documented delays in real time with handheld GPS equipment. Delays were defined by the operator. Typically, operations were noted as idle at a period where the forage harvester's field speed was below 0.4 mph. At this speed GPS noise was indistinguishable between position changes (Eisenbies, Volk, Espinoza, et al.). Documented data was transferred into an Excel spreadsheet which included: location, date, timestamp, equipment type, delay category, source of delay, delay duration, and operator activity during delay. Insufficient reliability data has been collected on the prototype header in mature woody crop conditions. Therefore, field data collected in this study is invaluable. It is critical to estimate component reliability. Prior to data analysis, several assumptions were made. These assumptions include:

- All components were properly functioning at the beginning of harvest
- There was an optimal predetermined field entrance and starting point for field operations
- Field operations were performed in straight and parallel tracks
- Negligible operator error because all operators were experienced
- Negligible discrepancies between note takers in-cab recording data
- Delay are evaluated as integers

The initial data was filtered to outline harvest delay categories and their source. Unexpected equipment interruptions were divided into four delay categories: 1). Operational, 2). Mechanical, 3). Worker Related, and 4). Miscellaneous. Operational delays consisted of eight sub-categories, which included: field condition, material feeding issues, servicing, technical problems, waiting for other collection equipment, wildlife, communication with team members, and other operational delays. Field condition interruptions were commonly caused by vegetation impacting equipment operations, wet ground conditions, and stuck equipment. Technical delays were caused by the operator manipulating the onboard task controller located in the forage harvester, where the operator would load field settings, parameters, and record information, check machine settings, and export information. Other operational delays encountered included: adjusting the telescoping arm on the header, switching rows to harvest, and field findings. For example, part of the header fell off and was later found in-field which interrupted operations because the operator had to stop, get out of the cab to collect the missing part, and then repair the equipment. Similarly, there are seven sub-categories for mechanical delays, such as: engine, electrical, hydraulic, header, machine adjustments, metal detector alarm, and other mechanical failures. These categories are intuitive as mechanical delays are directly related to breakdowns on the different machinery sub-systems. Examples for unproductive time associated with the other mechanical delays category include repairing flat tires, cleaning the radiator vent and air filter. Worker related delays were due to personal phone calls or other personal reasons, like a bathroom break. Miscellaneous delays were unexpected downtime that did not fit into the other categories and commonly stemmed from management interruptions. The frequency for each delay category is shown in Figure 19. Operational and mechanical delays caused the most unproductive time in-field. These delays consumed 97% of the total delays.

Data was recorded at the time of delay occurrence, based on a time unit of hours. The cumulative data was evaluated; however, data was not divided into days since each day and field had the same operating conditions. Therefore, if harvest operations took place then conditions were met. It is important to note, if equipment is operating in a different region this would not be the case because soil types, field slopes, and other factors could be significantly different.



	Mechanica l	Opertional	Personal	Other
🟦 Farm2	118	201	5	2
🟧 Farm1	82	299	8	1

Figure 19. Harvest delay frequency by farm location.

The parameter defining equipment reliability is called the failure rate; it is known as the characteristic of delay occurrence frequency. To attain the delay frequency rate, Python was used. The data was formatted, compiled, and then exported into a single Excel spreadsheet. Python results allowed the data it to be easily read into R Studio for computational purposes. R Studio was used to fit data to a discrete parameter distribution. This distribution represents delay characteristics throughout harvest operations. This process is important because incorrect distribution identification impacts the cost of maintenance and repair and could cause potential production losses.

Frequency distribution of the quantitative data in R was performed by totaling observed delays for the entire harvest duration. Then, this range was broken into non-overlapping sub-intervals. The average delay frequency for a one-hour time window during harvest was computed, which was approximately 6 delays per hour. The next step was to use the fit the data to a parameter distribution. A Poisson distribution was evaluated. It gave a similar expected rate. Then, a Chi-square test was calculated, which gave a p-value of 0.5308. These statistics concluded that a Poisson distribution cannot be ruled out. A summary of these results are outlined in the Appendix. However, more data is necessary to confirm the distribution. In general, for the willow harvest timeframe the number of interruptions with their respective times were recorded, and the parameter, ƛ, was estimated as:

$$ƛ = {}^{n}/_{T_0}$$

ƛ = failure rate (number/hr)
n = number of harvest delays
T_0 = time period
As provided by (Coble).

Phase IV: Probabilistic Risk Assessment

Estimation of the probability, frequency, and magnitude of the harvest interruption evaluated from field data collected was performed in Logan Fault and Event Tree Software version 7.5.3. Risk analysis using fault trees is a well-established technique in machine maintenance and repair; it has a real application in the agricultural sector for estimating equipment reliability. The analysis objective is to: 1). Estimate delay probabilities based on real-time data collected, 2). Outline time durations of specific delays, and 3). Estimate the financial implications of downtime using a fault tree. These objectives represent a systematic process for a quantitative analysis. Adverse consequences and their associated probabilities arising from harvest interruptions and uncertainties were identified.

PRA is a stochastic approach where probability distributions were considered for the available field data. In this study, Homogenous Poisson Process (HPP) was used as the basic stochastic process. The objective was to quantify the frequency of the initiating delay event. HPP with the intensity of ƛ > 0 is a counting process with independent time increments (Coble). This distribution describes parameters that contribute to risk of the harvest uncertainties occurring. Consequently, it produced a risk distribution that characterizes a range that might be experienced during similar harvest situations. It is

important to understand how risk is calculated. Quantitative risk assessment relies on actual data, where:
Risk = <Si, Pi, Ci> , for i = 1, 2, … n
As provided by (Coble).

Such that it focuses on the probability estimation and the magnitude of loss for countable scenarios, which are estimated from field data as:

Risk = $\sum_{i=1}^{n} f_i C_i$
f_i = frequency of scenario i, i = 1, 2, … n
C_i = consequence of scenario i, i = 1, 2, …, n
As provided by (Coble).

To characterize risk, the frequency and magnitude of all delays were calculated. The initiating event was defined as a harvest delay. The frequency of the initiating event, calculated in Phase III, was found to be 6 harvest interruptions per hour. Then, probability of a harvest delay occurring from any given delay source was calculated by a fault tree. The consequence was evaluated as a monetary loss, in dollars per hour, as the opportunity cost of being productive. This financial loss consisted of a fuel and labor cost for the idle equipment and operators as well as the capital cost of the machinery as it sat in-field unproductive. Willow operations require custom harvest equipment; this equipment is rented on an hourly basis regardless if the equipment is sitting unproductive in-field or operating. It is important to note that the cost associated with the mechanical events do not include the part cost, if a spare part was necessary. The risk consequence is given below:

$C_i = \sum(L_T + F_T + M_T)$
L_T = Labor wage for all operators employed ($/hr)
F_T = Total idle fuel cost for all harvest equipment ($/hr)
M_T = Total machine cost for all harvest equipment ($/hr)

The summation of labor, fuel, and equipment expenses is the total hourly financial cost for a harvest delay. However, these costs will more expensive given the inclusion of the part replaced. For example, if a flat tire is replaced this total cost does not include the cost of the tire. Labor wages were based on data collected from the farm manager. The fuel cost is based on machine horsepower, and local farm grade diesel was purchase at $2.40 per gallon. Custom machine rates were set by the farm manager. All hourly expenses are outlined in Table 5. The total hourly expense is equivalent to $437.72.

Table 5. Hourly expenses associated with harvest delays.

Equipment Type	Labor Cost ($/hr)	Fuel Cost ($/hr)	Machine Custom Rate ($/hr)
Forage Harvester	20.74	25.85	300
Collection Fleet (Tractor & Wagon)	18.11	2.96	45

The purpose of a fault tree is to graphically illustrate logical connections between delays and their causes. It considers all possible combinations for a single delay where it starts with the top event and works down the tree to determine the various causes of that top event. Contributors of the top event are connected through logic gates. The probability of the top event occurrence is mathematically calculated with Boolean algebra for the probability of an individual system component, or basic event. Using Logan Software 18 minimal cut sets were found. Fault tree analysis is an inclusive method to evaluate all potentially reasonable and probability quantifiable causes of a harvest delay. This method provides a way to perform probabilistic analysis to determine critical delays modes during a single-pass cut and chip harvest operation. Results from the fault tree analysis given an indication about the harvest system reliability. In addition, it helps identify which components are more critical and costly than others. It is important to emphasize these limitations to improve harvest operations and reduce cost.

Results

For a single-pass cut and chip harvest for willow, fault tree analysis was used to evaluate the financial impact of harvest delays. The top event probability of a harvest failure was calculated to be 0.0689. The fault tree analyzed is shown in the Appendix. These results give an indication about the SRWC harvest system reliability and identify specific components that they are more likely to occur. This knowledge allows operators to better prepare and repair breakdowns in-field and allows for an optimal harvest scheduling.

The probability, consequence, and risk associated with each harvest delay event are given in Table 6. It is noticed that largest risks are associated with operational and mechanical delays. The most financially devastating risks are associated with feeding issues, the metal detector, waiting on other equipment, communication among team members, and header issues, which have a higher probability of occurrence. These delays are more significant and beneficial for management to understand the volume of time consumed in these tasks to reduce harvest cost.

Table 6. Outline of the various harvest delays and their corresponding probability, time duration, and financial impact.

Delay Category	Delay Source	Probability of Occurrence	Total Duration (hr)	Financial Risk ($/hr)
Miscellaneous	Miscellaneous	0.0042	2.40	10.93
Worker Related Delay	Personal Phone	0.0126	0.30	32.78
Worker Related Delay	Personal Other	0.0056	0.11	14.57
Operational Delay	Field Condition	0.0196	0.48	50.99
Operational Delay	Feeding	0.4008	3.39	1048.88
Operational -Delay	Servicing	0.0028	1.90	7.28
Operational Delay	Technical	0.0098	0.12	25.49
Operational Delay	Wait on Equipment	0.2095	12.42	546.29
Operational Delay	Wildlife Interruption	0.0028	0.09	7.28
Operational Delay	Communication	0.0293	1.50	76.48
Operational Delay	Other Operational	0.0224	1.06	58.27
Mechanical Delay	Engine	0.0028	0.25	7.28
Mechanical Delay	Electrical	0.0140	0.21	36.42
Mechanical Delay	Header	0.0237	2.52	61.91
Mechanical Delay	Hydraulic	0.0028	0.01	7.28
Mechanical Delay	Machine Adjustments	0.0014	0.02	3.64
Mechanical Delay	Metal Detector	0.2193	0.51	568.15
Mechanical Delay	Other Mechanical	0.0168	0.68	43.70

In Figure 20, looking at the individual risks of specific harvest interruptions, the most influential delays easily separate themselves. If the operator understands how to best respond to feeding issues, this cost can be reduced. Operator assessment of the situation and reactivity are critical. The optimal response might involve training or a simple adjustment in machine handling. Typically, the better prepared the operator is the faster operations will resume, and thus less resources are wasted. Not all harvest delays can be avoided, but proper planning and allocation of resources can alleviate the excess financial burden. For instance, waiting on equipment during harvest is inevitable. However, given the risk of it potentially consuming $546 per hour, it might be beneficial for management to higher another collection fleet at $45 per hour. Having another collection system in operation would reduce time the forage harvester is waiting on the other fleets to unload and return to operational status. This knowledge is invaluable insight for management.

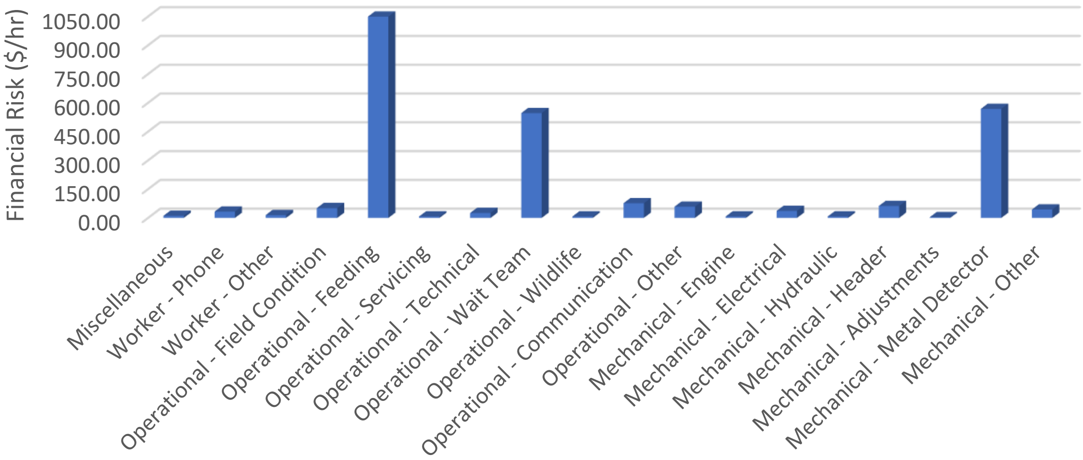
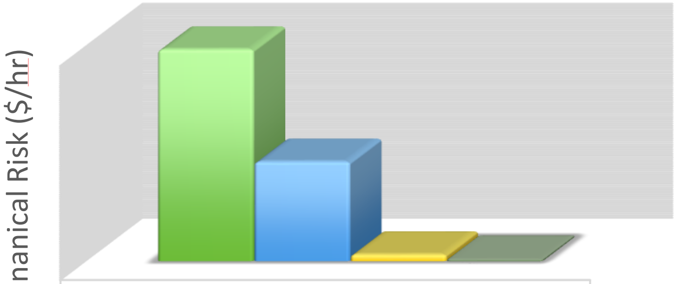


Figure 20. Failure events and their associated risk for harvest cost.

An overall view of the financial impact is illustrated in Figure 21. Operational and mechanical delays are the costliest. These categories alone account for approximately 97% of the total cost. This cost is significant considering no productivity was made while this expense was being incurred. Consequentially, these delay categories should be given priority for harvest scheduling and farm management practices. In addition, there have proven to be some limitations with the prototype header. It is beneficial to the equipment manufacturer to know the mechanical issues experienced for potential redesign for a second-generation woody coppice header.



	Harvest Delay
🟩 Operational	1486.51
🟦 Mechanical	698.61
🟨 Worker	47.54
🟩 Miscellaneous	11.00

Figure 21. Categorical breakdown of total harvest delay cost represented hourly.

Harvest delays consumed 28 hours of total harvest time, which was approximately 23% of the total time spent in-field. It is important to note, more time was spent performing unproductive tasks during harvest, such as turning at the headlands and driving to and from the shop and between fields. Therefore, the total unproductive time is larger than 23%. Times associated with each delay category are represented in Figure 22. The pie chart depicts the fraction of cumulative time each delay type contributed throughout the harvest duration. The most frequent delays are not necessarily the most time consuming. For example, miscellaneous delays only occurred 3 times throughout the entire harvest and consumed 15% of the time compared to 200 mechanical delays consuming 9% of the time. Most of the mechanical delays encountered during harvest could be identified easily, repaired promptly, and resume productivity. However, if a miscellaneous delay occurred equipment was unproductive for significantly longer. It is beneficial for scheduling purposes to be mindful that some delays are more time consuming than other, but they do not occur as often.

Some interruptions are unavoidable, but some are avoidable. In general, operational delays of machinery is the foremost contributor to the production loss of wasted resources. The harvest failure cost was calculated to be $197.02 per hour. Wasted fuel and labor accounted for $36.42 of this hourly expense. Harvest system reliability has not yet been evaluated for SRCWs, and it is significant. Harvest delays totaled at $23,589.05, which is comprised of a fixed cost for the machinery capital at $19,228.78 and variable costs consisting of fuel and labor at $4,360.26. At this substantial cost, it is not surprising to recognize how harvest costs can account up to one-third of the total cost of woody biomass.

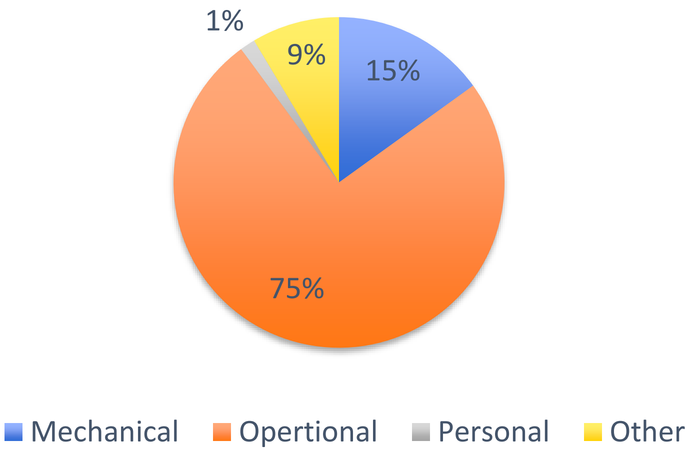


Figure 22. Breakdown of harvest delays based on time duration for repair.

Conclusion

For 2017 willow harvests, downtime in-field has proven to be a major expense. These delays are largely due to repair and maintenance on the equipment caused by unexpected harvest complications. Harvest operations were completed using a first-generation woody coppice header, and there are some limitations to this prototype equipment. There is insufficient failure data for the equipment in mature SRCWs to estimate component reliability; therefore, the data collected in this study is invaluable. The financial impact of harvest delays during a single-pass cut and chip operation were evaluated using PRA. This analysis is an inclusive method that provides a way to perform probabilistic analysis to determine critical delays modes.

Upon data collection, unexpected equipment delays, and breakdowns were separated into four main categories: operational, mechanical, worker related, and miscellaneous. A Poisson distribution was considered to describe the parameter behavior that contributed to the risk of harvest delays. A rate of 6 delays per hour was determined. Results from the fault tree analysis gave an indication about the harvest system reliability and identified critical components, such as: feeding, metal detector issues, waiting for equipment, communication, and header issues. A delay probability was calculated to be 0.0689, which gives an hourly expense of $197.02 and a total of $23,589.05 for harvest. This information is beneficial to for management purposes because it allows for improved scheduling and an optimal maintenance strategy. It is important to emphasize the equipment and operational limitations to improve productivity and reduce harvest cost. In future, more data should be collected to validate the Poisson parameter distribution. Additional datasets would build the framework to update parameter estimates for a best fit. In addition, separate data on collection fleet equipment and forage harvester equipment should be collected and analyzed to determine individual equipment costs for delay categories. It would also be beneficial to assess technological improvements and determine if they have led to less delays in-field due to the preventative maintenance capabilities at the operator’s fingertips.

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Appendix

R Studio Results – A Brief Clarification

Frequency of Delays based on 1-hour increments:
(6, 6, 1, 0, 1, 2, 1, 7, 7, 6, 6, 4, 6, 13, 8, 9, 4, 5, 4, 4, 6, 5, 3, 8, 4, 3, 5, 5, 3, 15, 7, 6, 6, 9, 8, 6, 7, 9, 7, 6, 6, 8, 7, 8, 7, 2, 4, 7, 8, 6, 8, 5, 7, 7, 2, 7, 6, 12, 15, 14, 11, 10, 2, 3, 4, 6, 7, 6, 10, 10, 3, 7, 4, 1, 1, 5, 8, 9, 1, 4, 8, 0, 0, 3, 2, 6, 3, 1, 2, 0, 0, 4, 1, 2, 2, 9, 14, 11, 1, 2, 2, 3, 7, 5, 3, 14, 11, 6, 9, 5, 9, 5, 21, 13, 16, 8, 3)
The mean of this data set is 5.957265

Fitting a Poisson distribution:
The expected rate is 5.9573, which is similar to the dataset mean
Pearson's Chi-squared test
X-squared = 150.99, df = 153, p-value = 0.5308
This means cannot conclude it is not a Poisson distribution

These tests were performed again for a negative binomial distribution; however, the fit was slightly worse at a p-value of 0.4865
These results were graphed to measure the shape of the data
A Poisson distribution was a slightly better fit and was used for PRA in this study

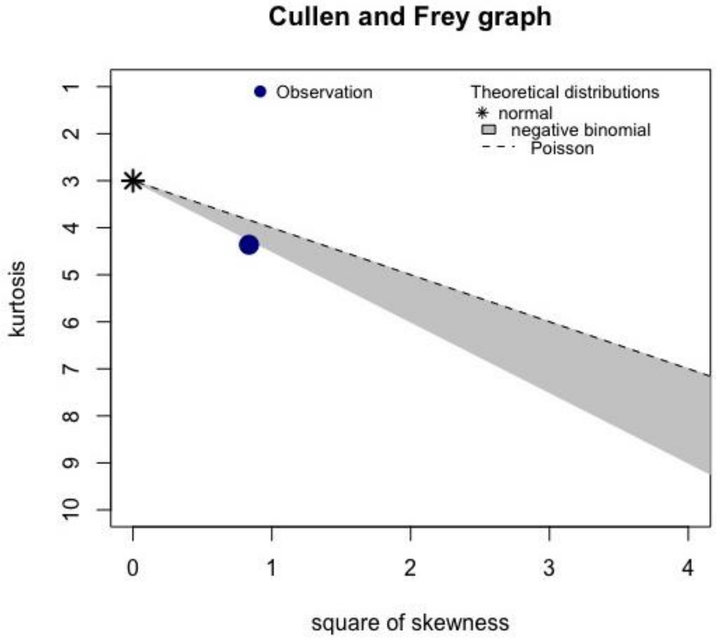


Figure 23. Shape of data graph for distribution fit testing.

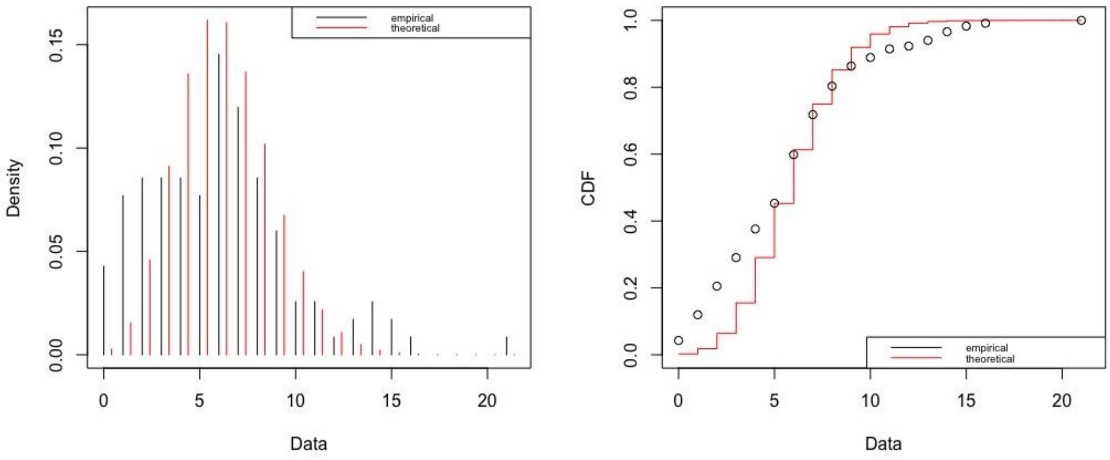
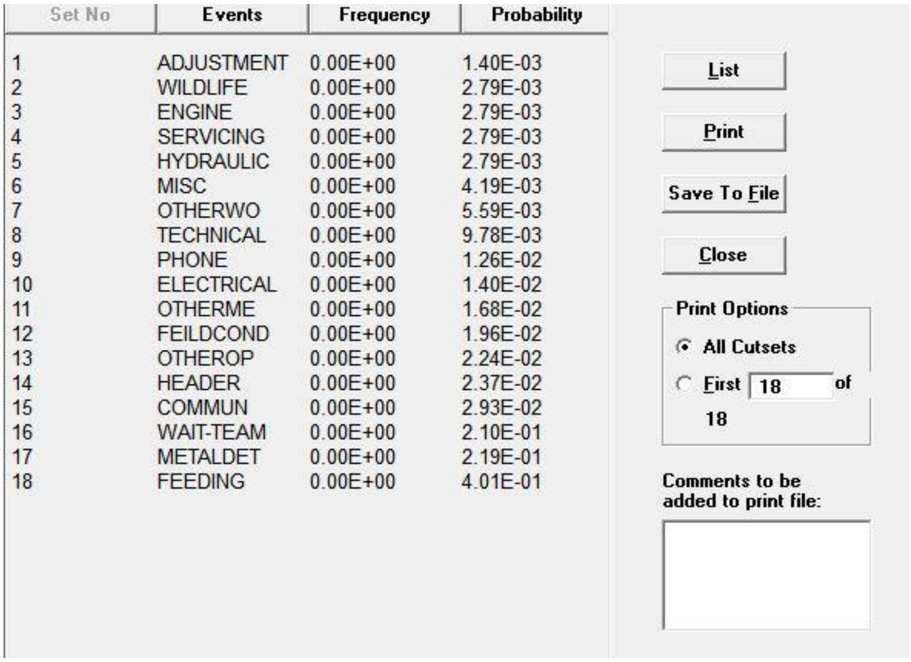


Figure 24. Empirical and theoretical distribution and CDF graphs of parameter distribution fit testing.

Fault Tree Analysis



Set No	Events	Frequency	Probability
1	ADJUSTMENT	0.00E+00	1.40E-03
2	WILDLIFE	0.00E+00	2.79E-03
3	ENGINE	0.00E+00	2.79E-03
4	SERVICING	0.00E+00	2.79E-03
5	HYDRAULIC	0.00E+00	2.79E-03
6	MISC	0.00E+00	4.19E-03
7	OTHERWO	0.00E+00	5.59E-03
8	TECHNICAL	0.00E+00	9.78E-03
9	PHONE	0.00E+00	1.26E-02
10	ELECTRICAL	0.00E+00	1.40E-02
11	OTHERME	0.00E+00	1.68E-02
12	FEILDCOND	0.00E+00	1.96E-02
13	OTHEROP	0.00E+00	2.24E-02
14	HEADER	0.00E+00	2.37E-02
15	COMMUN	0.00E+00	2.93E-02
16	WAIT-TEAM	0.00E+00	2.10E-01
17	METALDET	0.00E+00	2.19E-01
18	FEEDING	0.00E+00	4.01E-01

Print Options
● All Cutsets
○ First 18 of 18

Comments to be added to print file:

Figure 25. Logan Software fault tree analysis minimal cutsets for willow harvest operations.

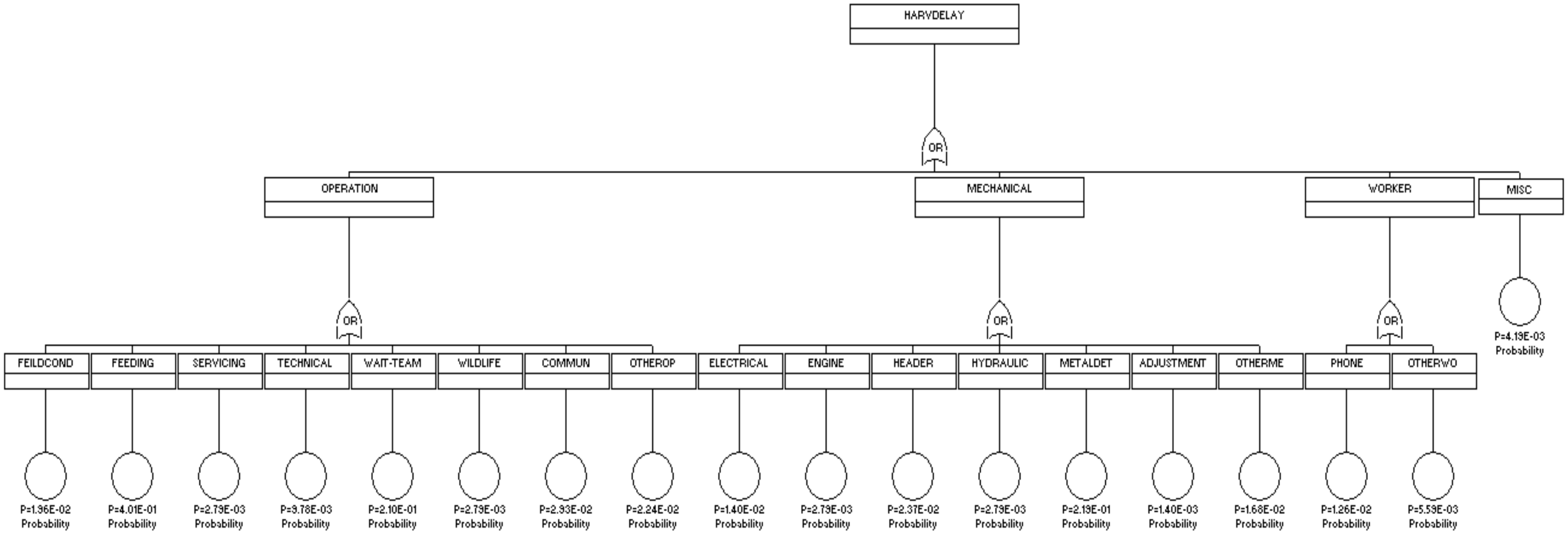


Figure 26. Logan fault tree for willow harvest failure data in 2017.

CONCLUSION

Harvest cost is a major concern for making biomass a viable option. Agricultural machinery has direct and indirect costs associated with harvest operations. The largest direct cost is due to the high capital cost of machinery. Indirect costs are associated with the variable costs of harvest operations, and a reduction in unproductive time would decrease indirect costs. During harvest, unproductive tasks include: servicing, maneuvering equipment in-field and near field boundaries, and down time for repair and maintenance. In order to make biomass a viable option, it is crucial to reduce the excess unproductive time. To be more specific, the variability in harvest timeliness is largely due to maneuvering equipment in-field, operator performance, equipment breakdowns, and field and crop conditions. There is a serious need to better account for untimeliness for biomass crops and modern harvest equipment. In this study, three factors impacting harvest productivity were evaluated, which included: maneuvering equipment in the headland space, operator performance, and equipment reliability. These are particularly important from a farm management standpoint to better assess the financial impact untimeliness has on total harvest cost and to advance scheduling and maintenance strategies during harvest operations.

Objective Overview

Biomass crops of interest for this research are Miscanthus and shrub willow. These biomass crops are attractive for several reasons. They do not compete with cash crops because they can be grown on marginal land. Additionally, they have the potential to increase rural economies. It is important to note that these crops have different harvest methods. Miscanthus harvest requires a windrower to cut and condition the crop followed by a tractor towing a baler to package the material into a bale for easy handling and storage. For willow, a single-pass cut and chip operations are the preferred conventional harvest method, where a forage harvester equipped with a hydraulically driven woody coppice header processes the material then blows it into collection equipment which operates alongside the harvester. In this study, Miscanthus operations focused on the impact of headland space and operator experience while willow operations evaluated on the cost of harvest delays and equipment reliability. The objective of this research is to analyze unproductive time during harvest. An ideal fieldwork pattern for increased headland space, the variability of operator experience, and harvest delay categories and their corresponding financial impacts were identified.

Outcome Summary

There is an economic benefit to improving productivity by reducing time spent turning in the headlands, evaluating operator performance, and equipment reliability to make biomass a viable option. Maneuvering equipment during harvest operations can have a significant impact on production cost; therefore, the fieldwork pattern was critical for optimal productivity. The fieldwork pattern influences time wasted due to excessive unproductive time and distances traveled during operational tasks. For Miscanthus harvest, productivity trade-offs were identified between harvest equipment and operator experience for three fieldwork patterns, which include: 1). 2-pass, 2). 4-pass, and 3). 6-pass perimeter cut. Maneuvering the windrower in the tight headland space was not an issue, but it was a limitation for the tractor towing a baler. Field data analyzed assessed the impact headland space has on machine performance based on operator experience, and the optimal fieldwork pattern was found to be a 4-pass perimeter cut due to turning the lengthy baler assembly. This preferred fieldwork pattern, created ample space to efficiently maneuver equipment at the field edge. In addition, field speed was a statistically significant factor influencing turn time with every 1 mph increase in field speed an increase in turn time by 1.66% was observed. Additionally, technology advancements and developments in agricultural machinery and autonomous equipment have underestimated the importance of an experienced operator. Study results showed a 12% larger variation in field efficiency with a less experienced operator. However, in a team setting, the experienced operator will get pulled away to help with other tasks while the less experienced operator will be left alone to work. Despite the distractions for the seasoned operator, the experienced operator will still be more consistent.

Results from willow harvest proved that delays are costly. Unproductive times caused by harvest delays are largely due to repair and maintenance on the equipment caused by unexpected complications. The financial impact of harvest delays during a single-pass cut and chip operation utilizing a self-propelled forage harvester equipped with a prototype woody coppice header and two collection fleets were evaluated with probabilistic risk assessment. For the data collected, probability distributions were considered to describe the parameters that contributed to the risk of each harvest interruption. In order to characterize risk, the frequency and magnitude of the financial consequence, a fault tree provided an inclusive analysis. Classifying breakdowns is beneficial to identify the most probable and costly interruptions. The most likely harvest delays were found to be: feeding, metal detector issues, waiting for other equipment, communication, and header problems. It was determined that 6 interruptions occurred per hour. The delay cost due to these interruptions was calculated to be $197.02 per hour, and the fuel and labor accounted for 18.5% of this expense. The total cost of harvest delays was $23,589.05. This is a substantial expense. There are some limitations to this prototype equipment. These results given an indication about the harvest system reliability and identified critical components. The information from this study is beneficial for management purposes to improve scheduling, allow the best allocation of resources during harvest operations, and provide an optimal maintenance strategy. It is important to emphasize these current limitations to increase productivity and reduce cost.

VITA

Magen Shedden was born in Knoxville, Tennessee on March 8, 1990. She was active on her family’s farm, an active member in 4-H and FFA where she showed livestock and competed on the National Skill-a-thon Team. With a passion for agriculture she continued to help manage her family’s farm throughout her academic career. After finishing high school in 2008, she continued her education by attending Pellissippi Technical Community College from 2008 to 2010. Thereafter, she transferred to The University of Tennessee from 2011 to 2014 where she earned a dual Bachelor’s degrees. One degree attained was in Food and Agricultural Business under the Agricultural Economics department, and the other degree earned was in Biosystems Engineering. Through undergrad she was active in Block and Bridle, an Animal Science club, Colligate 4-H, Gamma Beta Phi, and Taui Sigma. In addition, she was a member of the University of Tennessee’s Livestock Judging Team from 2011 to 2012, and a member of the University of Tennessee’s Wool Judging Team from 2013 to 2014. She had three separate internships at the Oak Ridge National Laboratory (ORNL) from 2012 to 2014 where she worked in the Environmental Sciences Division. After graduation, she accepted a job with the University of Tennessee where she worked from 2014 to 2016. Thereafter, she went back to work at ORNL and returned to school to earn her Masters of Science, and continues to manage the family farm.