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A risk assessment model to measure the difference in worker injury risk between corn and biofuel switchgrass production systems

Saxon James Ryan
Iowa State University

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Saxon J. Ryan

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Gretchen A. Mosher, Co-Major Professor
Charles V. Schwab, Co-Major Professor
Jeffrey D. Wolt

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ABSTRACT

Keeping workers safe presents a continuing challenge in the agricultural industry. Risk assessment methodologies have been used widely to better understand systems and enhance decision making with a goal of reducing injuries and fatalities. This research applies probabilistic risk assessment to human safety in two agricultural production systems, taking into account uncertainties such as equipment variation, working schedules, and weather conditions. A comparative model was developed because it can be scaled up or down based on available data and allow inputs from categories defined broadly or specifically as necessary. In this model, risk is calculated by multiplying the probability of exposure to a hazard and the probability of injury, given that an exposure to the hazard has occurred. The probability of injury and exposure values are derived from the USDA Census and from the Survey and Bureau of Labor Statistics data from 12 states in the Midwest for each year from 1996 to 2011. The exposure and injury data were used to build probability distributions that were randomly sampled using a Monte Carlo simulation. The output of the simulation demonstrates that corn has a higher risk of worker injury than biofuel switchgrass over a ten year period in the Midwest. A Monte Carlo simulation and a sensitivity analysis were run to determine the greatest contributing factors to worker injury risk within each production system. Harvest operations in both corn and biofuel switchgrass production systems were determined to be the greatest contributing factor to worker injury risk.

CHAPTER 1. INTRODUCTION

Year after year agriculture fatality rates remain one of the highest of all the industries across the United States (OSHA, 2013). Not only are agricultural injury and fatality rates high, rates of injuries and fatalities are likely under reported (Leigh, Du, and McCurdy, 2014). Extensive research to enhance agricultural safety has been completed, but there has been limited examination to determine what parts of agriculture pose the greatest worker injury risk. Furthermore, Schaufler, Yoder, Murphy, Schwab and Dehart, (2014) found that research addressing safety, specifically in the increasing field of biomass production, hasn't been thoroughly investigated.

Risk assessment tools have been used in various industries to enhance the safety of systems (Clemons & Simmons, 1998, Shyur, 2008, Mitropoulos & Namboodiri, 2011, & National Aeronautics and Space Administration, 2011). However, the field of agriculture has seen limited risk assessment implementation to enhance safety. There have been previous studies, such as Kingman and Field's (2005) investigation on the specifics of grain engulfment using Fault Tree Analysis, but this looked at one specific task rather than an entire production system. Broad studies investigating worker safety risk of entire systems over regions have yet to be pursued.

Although there are many risk assessment tools such as Fault Tree Analysis, Event Tree Analysis, and Risk Assessment Matrices that have their own purposes, other tools may be a better fit for assessing risk of a system over a region. Using the basic concept of risk, a product of exposure and effect, a Monte Carlo simulation was used to calculate the difference in worker safety risk of two production systems across the Midwest.

The Monte Carlo simulation samples data gathered in an attempt to analyze all possible outcomes. This method requires exposure and effect data for the Midwest region and the production systems being analyzed. In agriculture, the major difficulty with this method is the relatively limited amount of agricultural injury data.

A comparative risk assessment model between corn and biofuel switchgrass was chosen in part because it required less data. Comparing the difference in risk between corn and biofuel switchgrass systems rather than calculate the total risk of each system would require only that data on differences between the two systems be analyzed. Equivalent tasks would not need to be included in the model because the probabilities would cancel themselves out when calculating the difference in production systems.

Project Objective

The objective of this project was to develop a comparative risk assessment model to identify the production system with greater worker injury risk between two production systems in the Midwest. The Midwest as defined by U.S. Census Bureau (2013) includes North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, and Ohio. The comparative risk assessment model was intended to:

- Facilitate a relative comparison of risk values between the two production systems
- Use available published data
- Adjust and modify data using transformative processes to best align with input variable measurement units

- Scale up or down easily to allow more or less information to be added into the model

Research Questions

The research was conducted to answer two questions.

- Do biofuel switchgrass production systems have a greater worker injury risk than corn production systems in the Midwest?
- What is the greatest contributing factor to worker injury risk in corn and biofuel switchgrass production systems in the Midwest?

CHAPTER 2. LITERATURE REVIEW

Agriculture's Injury Problem

Agricultural occupations are ranked among the most dangerous occupations by the Occupational Safety and Health Administration (OSHA, 2013). The fatality rate for agricultural workers was nearly 25 per 100,000 workers as compared to the fatality rate of 3.5 per 100,000 workers for all occupations in 2011 (OSHA, 2013). Agriculture has a history of high fatality rates. Between 1992 and 2012, the fatality rate ranged from 22.2 to 32.5 per 100,000 workers (Bureau of Labor Statistics, 2012). These fatality rates do not include youth under the age of 16, so the actual level of fatalities are likely much higher. This is especially relevant when the research of Leigh, Du, and McCurdy (2014) is considered. They estimate that up to 73% of crop related farm injuries are not reported, meaning that the rate of injuries and fatalities, as well as the potential savings in human lives and costs associated with these, could be much greater than reported above.

According to the National Safety Council (2013), the average cost of a non-fatal injury for all occupations is approximately $37,000, the average fatal injury cost of all occupations is approximately $1,390,000, the estimated number of agricultural non-fatal injuries was 120,000, and the number of agricultural fatal injuries was 543. Using these figures from 2011, a cost of $5.2 billion can be estimated as a result of injuries and fatalities for the agricultural industry in a single year. A better understanding of safety risks in agricultural operations has worker safety as well as financial benefits to the agricultural industry.

Risk Assessment

Risk is calculated using two terms, a probability of occurrence and the impact of a given scenario occurring (Vose, 2008). Clemons and Simmons (1998) describe risk as the product of the probability of an event and the severity of that event. Certain risk assessment tools assist in quantifying the probability of an event and use a subjective severity to calculate risk, while others use both a subjective probability and severity (Clemons & Simmons, 1998). There are several challenges in applying risk assessment tools in agriculture. The first challenge of using risk assessment in agriculture is selecting the appropriate tool. There are a variety of risk assessment tools available.

Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) are tools that calculate a probability of occurrence based on logic, but provide no insight for quantifying the effect of an event (Clemons & Simmons, 1998). Fault Tree Analysis (FTA) has been used to investigate the probability of a single outcome (e.g., grain elevator explosion) based upon Boolean logic. Event Tree Analysis (ETA) has been used to investigate multiple outcomes from a single initiating event (e.g., hydraulic pressure loss) based on binary yes-no logic (Clemons & Simmons, 1998). Both ETA and FTA provide an analysis of how events occur and the likelihood that they can occur. These tools are an appropriate choice when the scope is small because the number of causal pathways to investigate is limited.

Another commonly available risk assessment tool is a Risk Assessment Matrix (RAM). The RAM facilitates a subjective risk assessment using data collected by an analyst (Clemons & Simmons, 1998; U.S. DoD, 2012). A RAM displays subjective categorical probabilities and severities to label and identify risk (Cox, 2008). The risk output from the

RAM is effective in prioritizing risks within a single system. However, the subjectivity of the RAM limits the uniformity of the risk value across systems or between analysts.

Several industries such as mining, construction, and aviation use risk assessment methodologies to help prevent worker injuries (Ghasemi, Shahriar, & Sharifzadeh, 2010; Mitropoulos & Namboodiri, 2011; Shyur, 2008). A risk assessment helps managers better understand a system by quantifying the likelihood of an event occurring and describing the potential consequence if it does occur. Risk assessments are often used in complex systems to predict probable risk levels so that the probability of negative events such as injuries, fatalities, and catastrophic environmental impacts can be reduced (Clemons & Simmons, 1998). Risk assessment information also helps develop a more complete understanding of the system to improve safety decisions (Mosher & Keren, 2011). Risk assessment methods have not gained the popularity in agriculture relative to other industries since their development. Kingman and Field (2005) describe how risk assessment tools have been used to estimate risks in non-agricultural areas such as nuclear power plants and space missions, but also show that they can be used in agriculture to predict factors that can be manipulated to enhance human safety.

Agricultural Statistics and Data

The complexity and variation of agricultural cropping systems makes the use of conventional risk assessment tools challenging (Clemons & Simmons, 1998; Ericson, 2005). For example, a manufacturing operation may have fewer concerns about weather variation than a construction or agricultural operation. Other industries may have company or governmental regulations that make them similar from site to site while the agricultural industry has relatively little regulation from farm to farm. Wilkins, Engelhardt, Bean, Byers and Crawford (2003) describe how OSHA-exempt farms do not follow tractor rollover protection regulations set by OSHA. This along with other regulations that go unenforced add to the variation between farms. Furthermore, farm incident data and cost data are difficult to obtain in order to determine exposure and effect values for the calculation of risk (Rautiainen & Reynolds, 2002). The limited regulation and lack of uniformity of agricultural operations makes it difficult to obtain finite agricultural injury data that could be used in risk assessment tools such as FTA or ETA in solving system problems.

Current injury data are found in small-scale case studies as well as large-scale national studies and surveillance reports. Case studies such as those found in the Iowa Fatality and Assessment Control Evaluation program (FACE) collects specific information on individual occupational fatalities and has little information on non-fatal injuries. FACE is a useful program in determining the specifics of fatal injuries, especially agricultural injuries in Iowa (NIOSH 2014). The FACE program is found in other states such as Nebraska, Minnesota, Iowa, Missouri, Wisconsin, Michigan, Indiana, and Ohio, but investigations can vary from state to state in a manner that one state may focus more on a specific industry (NIOSH, 2014).

A study done by Gerberich (1998) provides acute injury information from Minnesota, Wisconsin, South Dakota, North Dakota, and Nebraska. Although the information is not as specific as the FACE data, it does include specific data about machinery-related injuries for 5 Midwest states. Data from Gerberich (1998) do not provide a range of years, which limits the ability to identify patterns or provide multiple data points year after year to sample from.

Another source of injury data is the Bureau of Labor Statistics (BLS), which has injury and illness data categorized by state and year in useful categories, one being crop production. However, the BLS data do not contain categories for corn and biofuel switchgrass that would allow differentiation between injuries in the two production systems. Even so, the BLS data categorized by year and state can be combined with the specific injury information from Gerberich (1998) to estimate crop specific acute injury incidents. Gerberich (1998) has injury counts related to machine type that were used to calculate a percentage of injures related to specific machine types. The calculated percentages were then used to distribute BLS injury data to estimate an injury count for each machine type, each state, and year. These injury counts were sorted into corn and switchgrass production systems based on the types of machines that were used in each production system. Gerberich (1998) data were then used to distribute the BLS injuries into corn and switchgrass related acute injuries. This distribution of BLS injury data using information from Gerberich (1998) transformed the data so that it could be used to determine the difference in worker injury risk between corn and biofuel switchgrass production systems.

Monte Carlo Simulation

A Monte Carlo simulation is a method of determining all possible outcomes by accounting for all values that each variable can hold (Vose, 2008). The Monte Carlo simulation weights each case or value by the probability of occurrence (Vose, 2008). This means that each of the variables, inputs to the algorithm that an analyst is attempting to compute, in each production system have a probability distribution that are sampled by the Monte Carlo simulation. Each of the probability distributions in the model are sampled in a manner that reflects the probability distributions shape. For each sample, or iteration, a single value is calculated with one value drawn from the input variable distributions. This process is repeated with multiple iterations until the set amount of iterations have been completed. Ultimately, the output reflects a frequency distribution that represents the likelihood of values that could be generated by the model (Vose, 2008). The number of iterations is generally defined by the risk analyst (Vose, 2008), and should be sufficient enough to have a repeatable output distribution. A repeatable output distribution has small changes even when running many more iterations. In this risk assessment, probability distributions will be fit to exposure and injury data that have been obtained and the output frequency distribution will reflect the likelihood of injury under a variety of scenarios.

Fitting a probability distribution to the exposure and injury data fills the gaps that are present assuming the data follow the curve of the fit distribution. The Monte Carlo simulation samples the distribution rather than the exact input data. Sampling the probability distribution rather than sampling the data itself allowed values to be included in the simulation that would be in the tails of the distribution or where gaps exist between data points. The Monte Carlo simulation provides more information by accounting for every possible value that each variable's distribution can hold (Vose, 2008).

The output of the Monte Carlo simulation showed each value that was generated in an output frequency distribution. The output frequency distribution showed the range of values and the likelihood of each value that the model can produce with the input data. In terms of risk interpretation, this type of result provides analysts and mangers with more information such as a distribution of values with likelihoods to interpret rather than a single value to make better informed choices allowing the interpretation of the chances of a specific risk level.

CHAPTER 3. METHODS AND PROCEDURES

This research was conducted to answer two questions. The first, between switchgrass and corn production systems, which has a greater worker injury risk? The second, what is the greatest contributing factor to worker injury risk in corn and biofuel switchgrass production systems in the Midwest?

Clemons and Simmons (1998) define risk as the product of probability and severity of an event. The probability of an event is the likelihood that an exposure to a hazard will occur within a selected period of time. In this research, exposure to a hazard was a measure of how much contact the workers in the production systems have had with the hazards on a per-acre basis. The severity was measured in a single level of damage, the probability of an injury. The units of risk were defined by the units of the two terms. In this research, the two terms are probabilities; therefore, the resulting risk units are probability values.

Figure 1 is a graphical conceptual model that illustrates how worker injury risk was determined for a production system. The exposure and injury data were first transformed to meet the requirements of the model namely, distributing injury data into specific corn and biofuel switchgrass production systems and operations and calculating the likelihood of exposure in each production system. The transformed data were then entered into the stochastic risk assessment model where input probability distributions are fit to exposure and injury data and multiplied to output a frequency distribution of worker injury risk that was calculated using a Monte Carlo simulation.

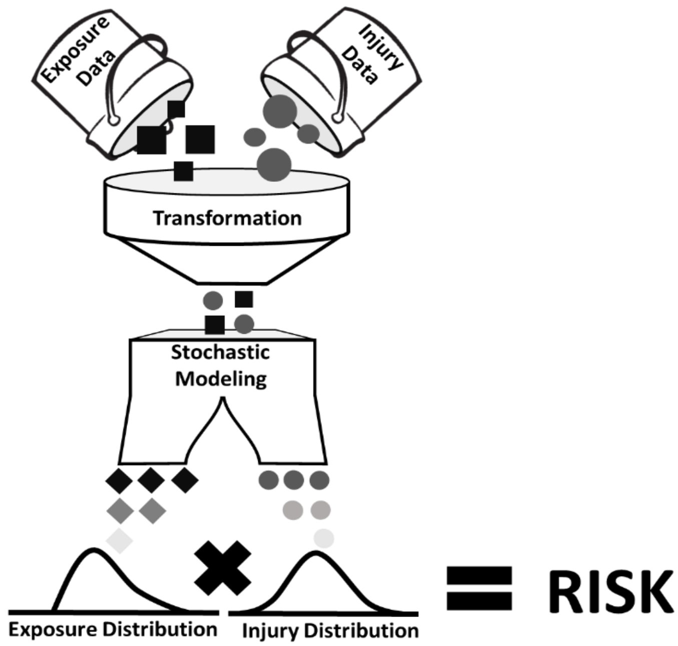

Figure 1. Graphical representation depicting the process in which risk is calculated for each production system

To accomplish the project objectives, five steps were completed. These steps include:

1. Formulation of the problem

   A – Identification of data sources

   B – The probability of exposure

   C – The probability of injury

   D – Distributing data using time and machine type

2. Build a spreadsheet model with appropriate risk algorithms

3. Build deterministic calculations to validate model

4. Calculate stochastic model and sensitivity analysis

   A – Defining distributions

   B – Monte Carlo simulation

   C – Sensitivity analysis

5. Determination of the greatest contributing factor to worker injury risk

1 – Formulation of the problem

The goal of this risk assessment was to enhance the understanding of human safety risks from Midwest corn and biofuel switchgrass production systems by modeling the probability of exposure and injury inherent to each production system. To facilitate this, relevant information such as the life cycle and data sources were identified for inclusion in the model. Boundary conditions, confounding factors, and assumptions of the risk assessment were also specified as described in this problem formulation.

Three exposure scenarios were identified as operations for each production system: establishment, management, and harvest. Although each of the operations have specific worker activities within them, the operation level is what was used. Individual exposure scenarios are described in Table 1 for the three operations associated with corn and biofuel switchgrass production.

There are several identical worker activities in both corn and biofuel switchgrass production systems. The worker activities in both production systems would produce the same approximate level of risk. When calculating the difference in risk between the two production systems, identical worker activities added no additional information because the values cancel out. By observing only differences in the production systems, unnecessary collection of additional detailed information that would add no additional value to the output of this model was prevented.

Table 1. Characteristics of exposure scenarios for each of the three operations

Exposure Scenario Operations	Characteristics
Establishment	• Timeline is from March where fields are prepared to May when fields are planted for corn and biofuel switchgrass production systems. • Tillage is assumed to occur for each production system, in year one for biofuel switchgrass and each year for corn in the lifecycle • Workers are exposed to tilling, discing, cultivating, planting, and fertilizing equipment throughout preparation and planting in corn and biofuel switchgrass production systems. • Corn establishment activities reoccur every year. • Biofuel switchgrass establishment activities occur once every ten years, assuming establishment is successful the first year. • To cover the possibility that not all switchgrass will establish in the first year, an exposure value of 50% for switchgrass establishment operations was used in the second year. • After the second year, biofuel switchgrass establishment activities will no longer be necessary.
Management	• Timeline is from May until September. • Workers are exposed to spraying equipment each year for corn and biofuel switchgrass production systems. • Management activities occur once per year during the lifecycle of the analysis for corn and biofuel switchgrass production systems.
Harvest	• Timeline is from September to November. • Workers are exposed to harvest machinery such as combines, trucks, and gravity wagons in corn productions systems, and balers, and mowers in biofuel switchgrass production systems. • For corn, the harvest activities occur every year, once per year. • For biofuel switchgrass, harvest does not occur in the first year of the life cycle but will occur for each of the following 9 years.

Based upon when corn and biofuels switchgrass are established and harvested, production was assumed to begin in March and last through November, therefore, the risk calculation compared only worker activities falling within this timeframe. Risks outside of this time period were not included because they were assumed to be unrelated to production specific activities.

The life cycle for this analysis is ten years based on biofuel switchgrass, the longer of the two systems. Mitchell, Vogel, and Schmer (2013) describe switchgrass stands lasting at least ten years without being replanted. By choosing the longest lifecycle, the analysis captured all of the risks associated with the full life cycle for switchgrass. The corn production life cycle is less than one year and the establishment, management, and harvesting is repeated in the same way each year. For the purposes of this project, ten life cycles of corn were compared with one ten year life cycle of switchgrass. It was assumed that ten years of corn worker injury risk data were approximately equivalent whether the annual growth cycles were continuous corn or planted on a rotation with another crop.

A – Identification of data sources

It was necessary to identify relevant data sources that were usable for the risk assessment model. Exposure data were measured in acres, a base unit for production system data. As the acres of an operation increases, there is more work to be done. No matter who completes the work, exposure to hazards increases. Injury data were measured with injury counts. Farmer counts were also collected to calculate the probability of injury. Table 2 includes a summary of published public data that were used.

Table 2. Summary of published data used in the model by type

Type of data	Source of Data	Years
Acre Count	United States Department of Agriculture (USDA): Survey Program	1996-2011
Injury Count	Bureau of Labor Statistics (BLS): Archived State Occupational Injuries, Illnesses, and Fatalities	1996 - 2011
Farmer Count	United States Department of Agriculture (USDA): Census Program	1992, 1997, 2002, 2007

B – The probability of exposure

The probability of exposure (P(e)) is a measure of the likelihood that a worker will have contact with a hazard on a per-acre basis. The probability of exposure was calculated with equation 1 using a fractional relationship, where the numerator was the amount of acres where operations are performed and the denominator is the total amount of acres where operations could be performed. This method was selected because not all acres have each operation performed (establishment, management, and harvest) each year. Using a fractional proportion facilitated the normalization of the data, allowing for a more valid comparison between the two systems.

$$P(e) = \frac{Number\ of\ Acres\ where\ Operation\ is\ Performed}{Number\ of\ Acres\ where\ Operation\ Could\ be\ Performed} \quad (1)$$

Where $P(\text{e})$ = probability of exposure

The exposure data were compiled by searching records from the United States Department of Agriculture (USDA) to determine the acres grown and harvested for corn and biofuel switchgrass. Production data were drawn from USDA Survey program field crop data reports. Corn data from 1996 until 2011 were utilized and information provided included acres planted and harvested. This provided a measurable unit of corn with acres planted and harvested for each state and year. No exposure data were found on crop management so it was assumed if the crop was established (planted) and harvested, it was also managed.

In equation 1, the denominator was set to the number of acres planted in each state and each year of the lifecycle according to the USDA Survey data. For corn establishment, equation 1 had a numerator and denominator that were equal because there was no published measurement of established acres. Therefore, an assumption was made that all acres of corn had establishment activities. Ultimately the numerator and denominator of equation 1 for corn establishment were equal, making the probability of exposure one.

The USDA Survey and Census program data do not include the number of acres of switchgrass produced. Similar grass style crop data was available but could not be used. Using similar grass style crops presented a problem by providing acre counts that made the probability of exposure values exceed one. The probability of exposure to biofuel switchgrass operations exceeded one because grass style crops are generally planted once every few years and harvested multiple times a year. This makes the numerator in equation 1 larger than the denominator. Because of this, probability of exposure values for biofuel switchgrass establishment, management, and harvest operations of each year and state were over estimated at a probability of one. Vose (2008) describes conservative assumptions as a tool to ensure that there are no unacceptable risks taken by users of the risk assessment results. In this case, conservative assumptions were used because there was no method to accurately estimate switchgrass exposure data. When over estimating the probability of exposure to a probability of one, the calculated worker injury risk will be inflated from an overestimated probability of exposure thus allowing decision makers to be conservative in their risk projections.

Harvest for the first two years in the lifecycle of biofuel switchgrass have modified probability of exposure values as seen in Table 3 because switchgrass is grown differently and may take multiple years to establish. In the establishment year (year one) of switchgrass there is no harvest, year 2 will require partial replanting with a partial harvest, and from year 3 on, there are no establishment operations but rather, full management and harvest operations.

Table 3. Biofuel switchgrass probability of exposure values by year and operation

Year	Operation	P(e)
	Establishment	1
1	Management	1
	Harvest	0
	Establishment	0.5
2	Management	1
	Harvest	0.5
3-10	Establishment	0
	Management	1
	Harvest	1

A sample of data used to calculate the probability of exposure for establishment, management, and harvest operations for each crop from 1996 to 2011 in each Midwestern state is displayed in Table 4. Data were then entered into equation 1 to calculate the probability of exposure.

Table 4. Example exposure data and probability of exposure calculation for Illinois

Year	State	Corn Acres Farmed	Corn Acres Planted	P(e) Corn Establishment	Corn Acres Harvested	P(e) Corn Harvest	P(e) Corn Management
2011	IL	12,600,000	12,600,000	1	12,350,000	0.980	0.980
2010	IL	12,600,000	12,600,000	1	12,400,000	0.984	0.984
. . .							
1996	IL	11,000,000	11,000,000	1	10,800,000	0.981	0.981

C – The probability of injury

The probability of injury (P(i)) was the second term in calculating worker injury risk. The probability of injury was calculated by equation 2 in a fractional relationship where the numerator was the number of workers injured performing an operation and the denominator was the total amount of people performing that operation.

$$P(i) = \frac{Number\ of\ People\ Injured\ Performing\ an\ Operation}{Number\ of\ People\ Performing\ an\ Operation} \qquad (2)$$

Where P(i) = probability of injury

Injury data were gathered from the Bureau of Labor Statistics (BLS) using the Archived State Occupational Injuries, Illnesses, and Fatalities from 1996 through 2011. (Bureau of Labor Statistics, 1996-2011). These data were the most consistent and representative of the total recordable cases for agricultural crop production in the Midwest.

In 2003, changes were made in how the BLS recorded injuries. From 2003 to 2011 injuries were recorded under the North American Industry Classification System (NAICS) code 111 for crop production. Prior to 2003, injuries were recorded under the Standard Industrial classification (SIC) code 01 for agricultural production crops. Total recordable cases from each year and state were used. Years without a crop production record or a number of injuries labeled as too small to display by the BLS were recorded as not available (NA).

The number of people performing an operation (P) was required as the denominator in the calculation of the probability of injury. The number of people that perform an operation was not available nor was the number of people farming corn or biofuel switchgrass from the USDA or BLS. An alternative approach was to assume that the number of farms was equal to the number of farmers producing corn or biofuel switchgrass crops. The number of farms was obtained from the USDA census. Furthermore, there was no count of farms producing switchgrass so data on farms of other grass style crops were substituted as an estimate instead. The category used for grass style crop farms was Forage - land used for all hay and all haylage, grass silage, and greenchop. The number of farms producing corn or grass style crops was acquired through USDA Census records published approximately every 5 years between 1992 and 2007 (USDA 1992, 1997, 2002, 2007).

D – Distributing data using time and machine type

The data from the Bureau of Labor Statistics (BLS) provided injury numbers in crop production but the numbers were not separated into production systems. The risk model required injury numbers specific to corn and biofuel switchgrass crop production. For this reason, data were transformed to estimate injuries associated with corn and biofuel switchgrass crop production systems by distributing the BLS injury data based on time and machine type.

Each injury count was first distributed by time (TD) to reflect the number of injuries between March to November, when switchgrass and corn are produced. Data from Gerberich, (1998) provided an injury count on a monthly basis for 5 Midwest states that were used for the time transformation. The portion of agricultural related injuries reported by Gerberich (1998) between March and November was 83.44% where all other months that were excluded made up 16.66%. The 83.44% was used to distribute the total number of injuries by state and year (IC) from the BLS data. Any injury count retrieved from the BLS was multiplied by .8344 to reflect the injuries occurring during the time of production from March to November.

The second part of the transformation was to distribute the time-based injury numbers into corn and biofuel switchgrass establishment, management, and harvest operations. These injuries were categorized into operations and crop types using the acute injury data from Gerberich (1998). Each type of machine in the study reported an injury count and a number of people involved. Dividing the number of injuries by the number of people exposed generated the second transformation factor for injuries, percent injury distribution by machine (MD), as seen in Table 5 and 6.

Table 5. Corn machine type injury data transformation values

Operation	Machine	# of Injuries	# of People Exposed	% Injury Distribution (MD)
Establishment				
	Corn/bean planter	3	9156	0.0327
	Tillage	15	13144	0.1141
			Establishment MD	0.1468
Management				
	Spraying equipment	3	8904	0.0336
	Manure spreader	3	8780	0.0341
			Management MD	0.0678
Harvest				
	Corn picker	1	2929	0.0341
	Self-propelled combine	13	8447	0.1539
	Pull type forage harvester	5	3980	0.1256
	Self- propelled forage harvester	1	889	0.1124
	Gravity box	1	6191	0.0161
	Forage wagon	1	4528	0.0220
			Harvest MD	0.4643

Table 6. Biofuel switchgrass machine type injury data transformation values

Operation	Machine	# of Injuries	# of people Exposed	% Injury Distribution (MD)
Establishment				
	Tillage	15	13144	0.1141
	Grain drill	9	10591	0.0008
			Establishment MD	0.1990
Management				
	Spraying equipment	3	8904	0.0336
	Manure spreader	3	8780	0.0341
			Management MD	0.0678
Harvest				
	Hay machine	4	4677	0.0855
	Mower	7	10834	0.0646
	Rectangular balers	3	5546	0.0540
	Hay rack	2	7484	0.0267
	Pull type forage harvester	5	3980	0.1256
	Self-propelled forage harvester	1	889	0.1124
	Forage wagon	1	4528	0.0220
			Harvest MD	0.4911

The time-transformed injury data were then distributed into production system-specific operations and categorized by the type of machine under each of the three operations. For example, self-propelled combines had an injury count of 13 and an exposure count of 8447. This means that of the 8447 people exposed to self-propelled combines, 13 were injured making a distribution percentage of .1539%. This number, 0.001539, was then summed with the other machine distribution values in the corn harvest category to determine a machine distribution value (MD). The machine distribution values for the operations were then multiplied by the time transformed data to arrive at a usable injury count for each of the operations. The injury count is finally used in the probability of injury calculation as seen in equation 2. The full calculation of arriving at the probability of injury values can be followed through in Table 7.

The probability of injury data table includes the injury values obtained for each Midwest state and each year from 1996 to 2011, with the time and machine type transformations included in the data set as seen in Table 7. Injury values were transformed to get an injury count for each of the production systems and their operations to fit equation 2. Table 7 consists of example probability of injury calculations that were completed for each system and operation in every state and year of the risk assessment. In this table each year each state's injury count (IC) is multiplied by the time distribution (TD), multiplied by the operation specific machine distribution (MD) and then divided by the number of people performing the operation (P) to calculate the probability of injury in each state, year, production system, and year as seen in equation 3.

Table 7. Condensed calculations of probability of injury values for corn establishment, management, and harvest

Year	State	BLS Injury Count (SIC)	Time Distribution (TD)	Machine Distribution (MD)	Distributed Injury Count	Number of People	P(i)
Establishment							
1996	IN	300	.8344	0.001468	0.367	37005	0.0000099
. . .							
2011	WI	200	.8344	0.001468	0.245	27505	0.0000089
Management							
1996	IN	300	.8344	0.000679	0.169	37005	0.0000046
. . .							
2011	WI	200	.8344	0.000679	0.113	27505	0.0000041
Harvest							
1996	IN	300	.8344	0.004644	1.162	37005	0.000031
. . .							
2011	WI	200	.8344	0.004644	0.774	27505	0.000028

$$TI = \frac{IC\ X\ \ TD\ X\ MD}{P} \tag{3}$$

Where TI = Transformed probability of injury, IC = State injury count, TD= Time Distribution, MD = Machine Distribution, P = Number of people performing an operation involving equipment from MD, and $IC\ X\ TD\ X\ MD$= Injury count in an operation based on machine type

2 – Build a spreadsheet model with appropriate risk algorithms

A spreadsheet was used to develop the model and implement the risk algorithms. Within the model, data were stratified by production system. Table 8 contains an example of the model components for year one of corn, which would also be duplicated for year one of biofuel switchgrass. For each operation, there was a probability of exposure value and a probability of injury value for each year in the life cycle. Each production system repeated this format for each of the ten years in the life cycle of this risk assessment. Spreadsheet formulas and calculations can be seen in APPENDIX A.

Table 8. Example of components in corn production system risk assessment

Corn, Year One

Operation	**Exposure**	**Injury**	**Risk**
Establishment	✓	✓	✓
Management	✓	✓	✓
Harvest	✓	✓	✓
Yearly Risk			✓

The model included probabilities of injury and exposure for establishment, management, and harvest. The worker injury risk value for a production system in each year was calculated by summing the risks of the operations. In the case of multiple years, the worker injury risk for each year was summed to calculate a risk value for the life cycle of each system being analyzed. Equation 4 is the summation of the difference in worker injury risk for each of the operations and years of the compared production systems during the ten year life cycle. Equation 4 was used to calculate the difference in worker injury risk between corn and biofuel switchgrass. This calculation used the various probability of injury and probability of exposure values for each production system and operation in the Monte Carlo simulation. For each iteration, a value was randomly sampled for each of the variables and output a single difference in worker injury risk value. This process continued until a difference in worker injury risk frequency distribution was formed.

$$\Delta Risk = \sum_{y=1}^{l} \sum_{i=1}^{m} \left\{ \left\{ \left\{ \mathbf{P}(\mathrm{e})_{System\ 1} \right\} \mathrm{X} \left\{ \mathbf{P}(\mathrm{i})_{System\ 1} \right\} - \left\{ \mathbf{P}(\mathrm{e})_{System\ 2} \right\} \mathrm{X} \left\{ \mathbf{P}(\mathrm{i})_{System\ 2} \right\} \right\}_i \right\}_y \quad (4)$$

Where $\mathbf{P}(\mathrm{e})$ = probability of exposure, $\mathbf{P}(\mathrm{i})$ = probability of Injury, l = number of years in the life cycle (10), and m = number of operations (3)

3 – Build pilot deterministic calculations to validate the model

A pilot deterministic calculation was conducted to determine if the model was functioning as intended. In this calculation numbers exceeding a probability of 1 would warrant an investigation that inspected the functionality of the model. The pilot deterministic calculation was a fixed estimate for each of the variables measuring the probability of exposure and injury. The probability of exposure and injury values were averaged and input into the risk algorithm. Each of the values in equation 4 had an averaged single point estimate from the data that was collected and transformed. The deterministic calculation also allows the input of single point estimates in cases where only a single measurement is available. The single point estimate was an average level of risk in the assessment, but provided no further knowledge on the likelihood of injury. Once the pilot deterministic calculation was completed and no errors were identified, a stochastic model was completed.

4 – Stochastic model and sensitivity analysis calculations

The stochastic model used a Monte Carlo simulation to generate an output frequency distribution of worker injury risk that allows a range of values to be interpreted. This distribution increases the chance of capturing the actual worker injury risk value by considering all possible values provided as inputs. The stochastic approach uses a range of input values for both exposure and injury probability variables in the model to predict the probability of injury and exposure values in each production system. Instead of using one value (a single point estimate) to calculate the difference in worker injury risk, a distribution of values for each input variable was used.

There are several types of probability distributions that have been used in human safety risk assessments. Johnson (1997) described the functionality of the beta and the triangle distributions commonly used in stochastic risk analysis. The beta and triangle distributions are often used in situations with limited data (Johnson, 1997). The beta and triangle distributions are similar in that they both require minimum, most likely and maximum values to define them. The primary difference between the beta and triangle distribution is in the shape, as triangle distributions have sharp transitions while the beta distribution have a rounded transition between minimum, most likely and maximum values.

A – Defining distributions

Before running the Monte Carlo simulation, probability distributions were fit to the probability of exposure and probability of injury data for the Monte Carlo simulation to sample. By fitting a distribution to the data, the Monte Carlo simulation sampled every possible data point falling under the distribution rather than sampling only the data collected (Vose, 2008). These distributions are defined by fitting them to the data and testing the goodness of fit. In total there were 7 unique variables used as inputs for the model. Each variable was a probability distribution formed around the input data. These included:

probability of injury for establishment, management, and harvest operations in both corn and switchgrass production and the probability of exposure for corn harvest. A duplicate distribution was used for the probability of exposure for corn management because of the assumption that harvested crops were also managed. The probability of exposure values for switchgrass were estimated as described above in the problem formulation.

Several options were available for fitting distributions to the data. To remove the subjective bias from the analyst, the auto select feature in Crystal Ball™ was used to determine the best fit distribution. BetaPERT, gamma, and lognormal were selected to be the best fit by the software using the Anderson-Darling test. Tables 9 and 10 display the distributions that were fit to the data with generated distribution parameters. The location parameter of the lognormal distribution helped to describe the shape of the distribution. When using the location parameter in the Gamma distribution, it provided a location of the distribution on the number line.

Table 9. Corn input distributions descriptions

Operation	Probability of:	Distribution Type	Distribution Parameters
Establishment	Injury	Lognormal	Location: 0.000001440 Mean: 0.000012799 Standard Deviation: 0.000012380
Management	Injury	Lognormal	Location: 0.000000665 Mean: 0.000005913 Standard Deviation: 0.000005720
Harvest	Injury	Lognormal	Location: 0.000004553 Mean: 0.000040466 Standard Deviation: 0.000039141
Management/ Harvest	Exposure	BetaPERT	Minimum: 0.612582745 Likeliest: 0.988636364 Maximum: 0.989725920

Table 10. Biofuel switchgrass input distributions descriptions

Operation	Probability of:	Distribution Type	Distribution Parameters
Establishment	Injury	Gamma	Location: 0.000003948 Scale: 0.000013781 Shape: 0.899812371
Management	Injury	Gamma	Location: 0.000001346 Scale: 0.000004577 Shape: 0.923469397
Harvest	Injury	Gamma	Location: 0.000009739 Scale: 0.000034223 Shape: 0.893819321

B – Monte Carlo simulation

This risk assessment model used a Monte Carlo simulation, which works by randomly sampling the probability input variable distributions to calculate many possible values that form a frequency distribution (Vose, 2008). Each "run" of the model is known as an iteration. In each iteration, a single data point was randomly selected from the probability of injury and the probability of exposure distributions. These values are then multiplied together to form a single worker injury risk data point for each operation of each production system that are subtracted from one another to calculate a difference in worker injury risk data point. This random sampling continues until the set number of iterations, 500,000 in this case, have been run and a frequency distribution has been formed. 500,000 iterations were run because the computing power was available and the number was a sufficient amount of iterations to result in a smooth output frequency distribution. Furthermore iterations were run starting at 10,000 then 100,000 and in increments of 100,000 where they were run until 500,000 was reached. 500,000 was the point in which there were no noticeable changes in the output distribution. The output is a description of the likelihood of the level of worker injury risk that would be present in every possible scenario under the given input conditions (Vose, 2008). In this case, the distribution describes the difference in worker injury risk between corn and switchgrass production systems.

C – Sensitivity analysis

To identify input variables that are most likely to influence the level of risk, a sensitivity analysis was performed (Vose, 2008). The sensitivity analysis was performed by changing input variables and measuring the effect of changes on the worker injury risk level. The sensitivity analysis is used to show how input variables affect the outcome (Vose, 2008). The importance of a sensitivity analysis is to help develop a more in-depth understanding of critical factors of risk and their relationship to the model (Vose, 2008). The critical factors in this case are the inputs of the model and the relationship is how much those inputs affect the output.

5 – Determination of the greatest contributing factor to worker injury risk

The second research question asked which factor in corn and biofuel switchgrass production systems in the Midwest has the greatest effect on worker injury risk. The data to answer this question were gathered by inspecting the components that make up the risk of each production system. Worker injury risk values were calculated for each induvial operation in each production system, using a Monte Carlo simulation to compare the operations to one another. Rather than summing the worker injury risk of each operation within each of the production systems, each operation had its own worker injury risk calculation over a ten-year life cycle. The simulation ran 500,000 iterations for each operation (establishment, management, and harvest) in each production system. This provided a frequency distribution of worker injury risk for each of the operations to be compared over a ten-year lifecycle.

CHAPTER 4. RESULTS

Monte Carlo Simulation

The Monte Carlo output frequency distribution of the difference in risk ranges from -0.0038 to 0.0006 as seen in Figure 2. The distribution shows that of the 500,000 iterations, approximately 82% of them in them are negative, meaning corn production systems will produce a higher likelihood of worker injury more often. Positive iterations, approximately 18%, reflect the cases in which biofuel switchgrass produced a higher worker injury risk. The output frequency distribution appears to be an approximately normal distribution skewed slightly left having a longer tail. The mean of the distribution is at -.000134 (134 injuries per 100,000 workers) with a median value of -.000127 (127 injuries per 100,000 workers). Zero is where worker injury risk between corn and biofuel switchgrass production systems is equal, while to the left of zero, the negative values, corn production systems have a higher likelihood of injury.

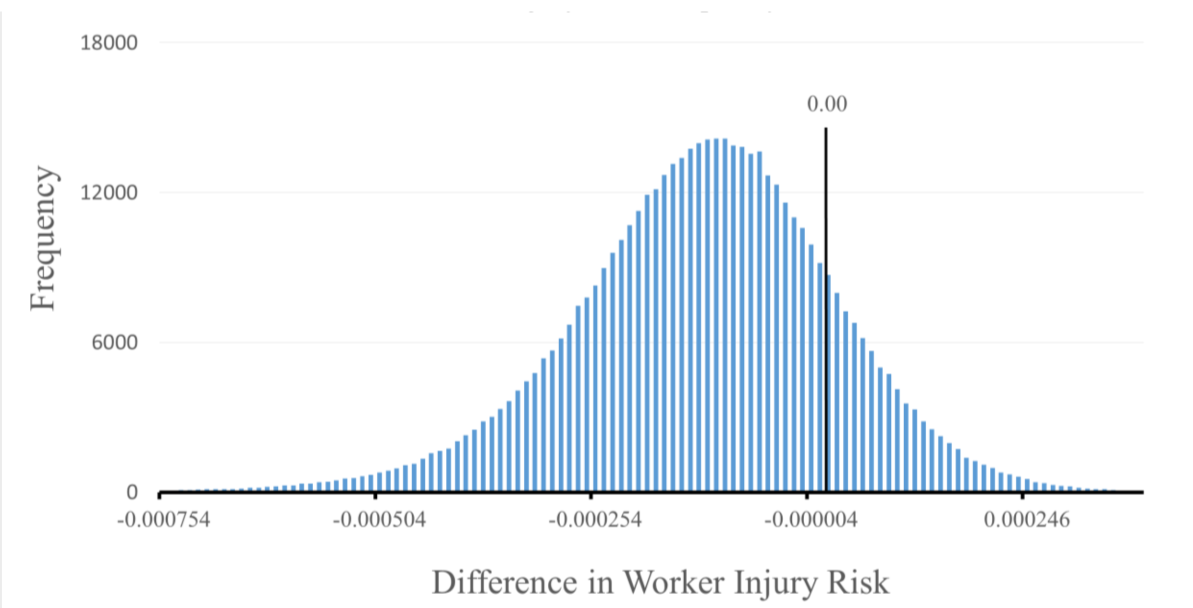

Figure 2. Difference in worker injury risk output frequency distribution

Sensitivity Analysis

A sensitivity analysis was completed for the model to determine which variables had the greatest effect on the variance of the output frequency distribution. The factors with the greatest contribution to variance were the harvest probability of injury values. The total contribution to variance due to the probability of injury for harvest operations of corn and biofuel switchgrass was 90.6%. Table 11 displays the contribution to variance of the various input variables of the model.

Table 11. Input variable contribution to variance in the output frequency distribution

Probability of	Operation	Contribution to Variance
Injury in Corn		
	Establishment	5.9%
	Management	1%
	Harvest	47.6%
Injury in Biofuel Switchgrass		
	Establishment	1.1%
	Management	1.0%
	Harvest	43.0%
Exposure in Corn		
	Management	<1%
	Harvest	<1%

Greatest Contributing Factor to Worker Injury Risk

To answer the second question of which operation is the greatest contributing factor to worker injury risk in the Midwest, a Monte Carlo simulation was completed for each operation in each production system to calculate worker injury risk of each operation. The mean value of each frequency distribution from the Monte Carlo Simulation for each operation was examined to determine the greatest contributing factor as seen in Table 12.

The operations that contributed the most to worker injury risk over a ten-year life cycle in the Midwest were harvest operations. Harvest operations were a magnitude greater than management operations and biofuel switchgrass establishment operations. Finally, the harvest operations were less than a magnitude greater than the mean corn establishments operation but the mean value of harvest operations were still three times greater.

Table 12. Operation contribution to worker injury risk

Production System	Operation	Mean Worker Injury Risk	Mean life cycle injuries per 100,000 workers
Corn			
	Establishment	.000128	128
	Management	.000055	55
	Harvest	.000375	375
Biofuel Switchgrass			
	Establishment	.000024	24
	Management	.000054	55
	Harvest	.000343	343

To visually represent what risk values each operation can hold, Figures 3 and 4 display the frequency distributions of worker injury risk for each production system's operations on the same worker injury risk number line. In Figure 3, the contribution to the total worker injury risk of corn production systems can be seen as described in Table 12 where harvest is the greatest contributing factor and management is the least contributing factor. Similarly, Figure 4 displays the biofuel switchgrass worker injury risk distributions that show the order of contribution to worker injury risk. Each of the six individual frequency distributions can be found in APPENDIX B with more detail.

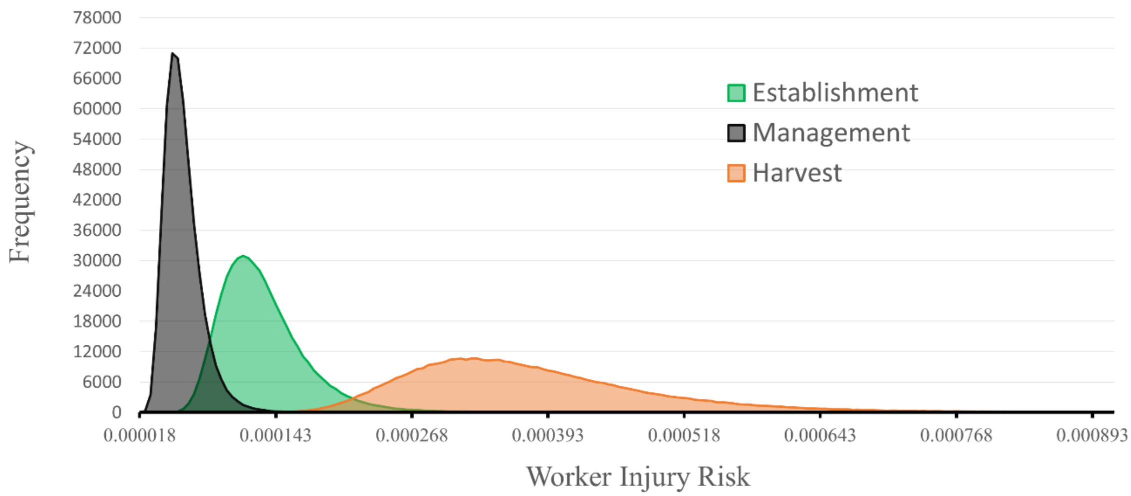

Figure 3. Worker injury risk frequency distributions for corn establishment, management, and harvest operations

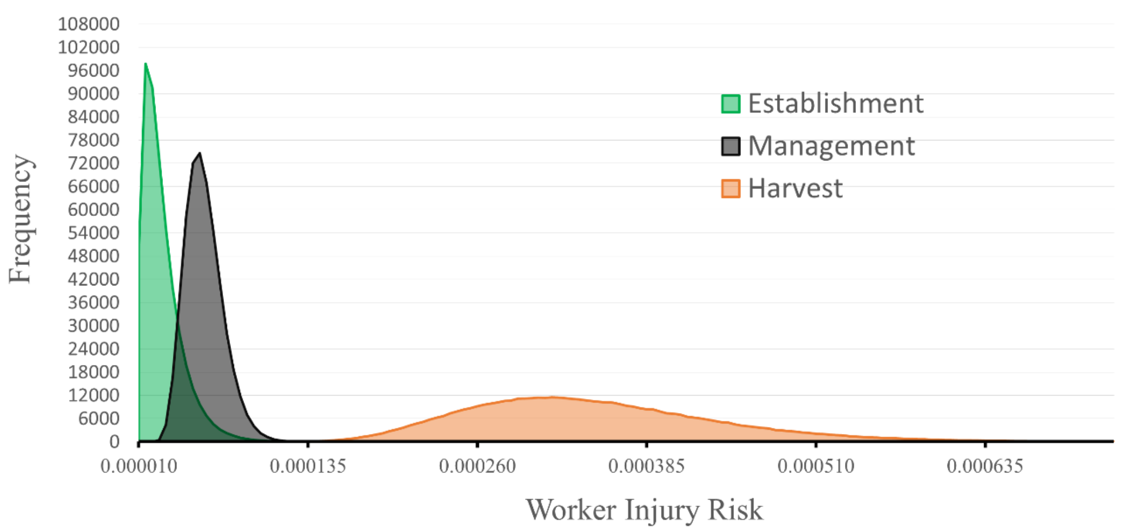

Figure 4. Worker injury risk frequency distributions for biofuel switchgrass establishment, management, and harvest operations

CHAPTER 5. SUMMARY, DISCUSSION, LIMITATIONS, AND FUTURE WORK

This research focused on answering the question of which production system - corn or biofuel switchgrass - has a higher worker injury risk. The model used the product of the probability of injury and the probability of exposure to calculate risk. The probability of exposure was calculated from the amount of acres an operation was performed on while the probability of injury was calculated from injury counts. The injury counts required transformation to distribute the injuries into the time frame and machine type for each production system. The data were fitted with probability distributions and were sampled in a Monte Carlo simulation to include all possible scenarios of risk. The output of the Monte Carlo simulation and the result of the research is a frequency distribution describing the difference in risk between the two production systems. The implementation of this comparative risk assessment model helps to build upon the body of knowledge in agricultural safety. This model can be used to help understand where efforts should be focused to reduce worker injury risks most efficiently and provides a baseline of risk assessment to further research in agricultural worker safety.

The novelty of this research is that while other agricultural safety research has focused on a smaller scale and post incident research this model focuses on a large region and includes a predictive element. The risk assessment model can forecast the worker injury risk of corn production systems relative to biofuel switchgrass production systems. Currently, this is the best estimate of what worker injury risk we could see with corn and biofuel switchgrass production on a regional scale.

Discussion

The risk assessment of worker injury between corn and biofuel switchgrass farming systems provides evidence that corn production systems have a higher likelihood of injury than switchgrass production systems. According to the model's frequency distribution, approximately 82% of the time corn will have a higher likelihood of worker injury. One important contributing factor to this finding is the reduced exposure to establishment activities in switchgrass production systems. After the second year, exposure to establishment is zero which in turns makes the operation worker injury risk, for those years, zero. While the establishment worker injury risk of switchgrass in years three to ten is zero, corn establishment risk is repeated and summed for each year. Though establishment is not the greatest contributing factor, the effect of reduced exposure to establishment in a single production system is what causes the greatest difference in worker injury risk. Harvest is the greatest contributing factor to worker injury risk but is nearly equal in both production systems which causes little change in the difference of worker injury risk. Exposure to establishment is greatly different between production systems over the ten-year life cycle. This implies that switchgrass has less worker injury risk due to the probability of exposure to establishment machinery and is reduced by 8 years when compared to corn, where the probability of exposure to establishment machinery is repeated in each of the ten years.

The sensitivity analysis shows that approximately 90% of the variance in the output is due to the probability of injury in harvest operations. It is well known that agricultural injury rates peak around harvest and these injuries may be the primary contributing factor to this conclusion (Hagek, Dosman, Rennie, Ingram, & Senthilselvan, 2004; Hanna & Schwab, 2013; Knapp, 1966;). This finding was replicated in corn and biofuel switchgrass harvest operations. Harvest activities play a large role in worker safety risk and future research on the probability of injury risk during harvest is warranted.

Risk assessments are used to make better decisions with the available information. From the results of this research, better decisions can be made on how to proceed with corn and biofuel switchgrass production from a safety standpoint. This can be done by focusing mitigation efforts on the greatest contributing factors. A high priority, should be to continue research on harvest operations of the corn production system due to the high contribution to variance and the higher likelihood of injury.

Limitations and Uncertainties

This model calculates an estimate of the difference in worker injury risk for corn and biofuel switchgrass production systems. Current available data provides enough information to calculate acute worker injury risk at the operational level (establishment, management, and harvest) but not at the individual worker activity level (e.g., fueling a tractor or stepping onto a raised platform). While individual worker activity level analysis would provide a more precise estimate, additional data must be located and collected to enter into the model. At some point, the acquisition of additional data may become more costly than the value of the risk assessment, making the collection of additional data both non-justifiable and non-feasible.

Effects on the output may also result from minor worker activities not included in the operations that are different between the systems but may still contribute to changing the output. The age of worker, safe practices used, and many variables can, when summed, greatly alter the total difference in risk between the production systems over ten years.

Exposure values for biofuel switchgrass were assumed to be one and these exaggerated the worker injury risk value of biofuel switchgrass. This means that the output of this model is not an exact calculation. If the actual biofuel switchgrass exposure values are less than one, the difference in worker injury risk will change making corn even more likely to have a greater worker injury risk. Furthermore, corn management exposure values were estimated to be equal to harvest exposure values. Though this is less conservative than the biofuel switchgrass estimates, it can still have an effect on the outcome.

The assumption that forage crops were a representative sample of biofuel switchgrass alters the results. The data used relating to forage crops was for the denominator in the calculation of the probability of injury, the number of farmers performing an operation. Because there are no counts of switchgrass farmers readily available at this time forage crop farmers was the best estimate. This estimate assumes that there are as many biofuel switchgrass farmers as there are forage crop farmers. This assumption was accepted based on the notion that forage crops are grown in a similar fashion and provide a representative sample of the prevalence of biofuel switchgrass farmers in the future.

Finally, the model is based on input distributions that were fit to the data and not sampled discretely. It was assumed that the actual probability of injury follows the probability distribution that is was fit to the limited input data. It is possible that the data in reality does not follow the probability distributions that were used. This could cause large changes if the limited data did not accurately describe the actual exposure and injury values. However, as with previous risk assessments, the distributions were assumed to accurately portray the data.

Future work

The research conducted in this project was an initial estimate of the difference in worker injury risk for agricultural workers in corn and biofuel switchgrass production systems. Future work that can build upon this research includes:

- Collection of more detailed data for exposure and injury inputs
- Validation of this model by assessing the risk of a well-known system to compare outputs
- Harvest-focused risk assessment and data collection

Furthermore, the model can be applied in many scenarios to compare different types of risks. For example, it is possible to compare the risk of different types of injures between multiple operations to determine which operation is most likely to have a higher worker injury risk for a specific injury. This model framework could also compare injury risks between soybean and corn production or corn and wheat production. The comparison between crops allows researchers to determine which production systems contribute the greatest amount to agricultural injury and fatality rates in the United States and helps predict rates for the future. This can help to narrow the focus for agricultural safety improvements that would make the greatest impact on reducing agricultural injuries and fatalities.

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APPENDIX A

MODEL ALGORITHM IN SPREADSHEET FORMAT AND DETERMINISTIC CALCULATIONS

This Appendix contains the calculations of the difference in worker injury risk in spreadsheet format. Each year of the ten year life cycle is shown with cell formulas as well as numerically. The numerical spreadsheet contains the single point estimates that were used for the deterministic calculations. For the Monte Carlo simulation, when the year risk difference column was summed over each of the ten years in the life cycle by the formula =SUM(L76,L68,L60,L52,L44,L36,L28,L20,L12,L4) a single iteration was completed. The single point estimate for the difference in worker injury risk was -0.000135059

Table A1. Year one calculation equations

	A	B	C	D	E	F	G	H	I	J	K	L
1	Biofuel switchgrass year 1				Corn year 1				**Operation Risk Difference**		**Year Risk Difference**	
2	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
3	**Establishment**				**Establishment**							
4		1	0	=B4*C4		1	0	=F4*G4	**1**	=D4-H4	**1**	=SUM(J4,J6,J8)
5	**Management**				**Management**							
6		1	0	=B6*C6		0	0	=F6*G6	**2**	=D6-H6		
7	**Harvest**				**Harvest**							
8		0	0	=B8*C8		0	0	=F8*G8	**3**	=D8-H8		

Table A2. Year one single point estimate calculation

	A	B	C	D	E	F	G	H	I	J	K	L
1	Biofuel switchgrass year 1				Corn year 1				**Operation Risk Difference**		**Year Risk Difference**	
2	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
3	**Establishment**				**Establishment**							
4		1	1.635E-05	1.634E-05		1	1.294E-05	1.294E-05	**1**	3.403E-06	**1**	-3.389E-05
5	**Management**				**Management**							
6		1	5.572E-06	5.57E-06		0.91	5.981E-06	5.465E-06	**2**	1.070E-07		
7	**Harvest**				**Harvest**							
8		0	4.033E-05	0		0.91	4.093E-05	3.740E-05	**3**	-3.740E-05		

Table A3. Year two calculation equations

	A	B	C	D	E	F	G	H	I	J	K	L
9	Biofuel switchgrass year 2				Corn year 2				**Operation Risk Difference**		**Year Risk Difference**	
10	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
11	**Establishment**				**Establishment**							
12		.5	0	=B12*C12		1	0	=F12*G12	**1**	=D12-H12	**2**	=SUM(J12,J14,J16)
13	**Management**				**Management**							
14		1	0	=B14*C14		0	0	=F14*G14	**2**	=D14-H14		
15	**Harvest**				**Harvest**							
16		.5	0	=B16*C16		0	0	=F16*G16	**3**	=D16-H16		

Table A4. Year two single point estimate calculation

	A	B	C	D	E	F	G	H	I	J	K	L
9	Biofuel switchgrass year 2				Corn year 2				**Operation Risk Difference**		**Year Risk Difference**	
10	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
11	**Establishment**				**Establishment**							
12		.5	1.635E-05	8.174E-06		1	1.294E-05	1.294E-05	**1**	-4.771E-06	**2**	-2.190E-05
13	**Management**				**Management**							
14		1	5.572E-06	5.572E-06		0.91	5.981E-06	5.465E-06	**2**	1.070E-07		
15	**Harvest**				**Harvest**							
16		.5	4.033E-05	2.016E-05		0.91	4.093E-05	3.740E-05	**3**	-1.723E-05		

Table A5. Year three calculation equations

	A	B	C	D	E	F	G	H	I	J	K	L
17	Biofuel switchgrass year 3				Corn year 3				Operation Risk Difference		Year Risk Difference	
18	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
19	**Establishment**				**Establishment**							
20		0	0	=B20*C20		1	0	=F20*G20	**1**	=D20-H20	**3**	=SUM(J20,J22,J24)
21	**Management**				**Management**							
22		1	0	=B22*C22		0	0	=F22*G22	**2**	=D22-H22		
23	**Harvest**				**Harvest**							
24		1	0	=B24*C24		0	0	=F24*G24	**3**	=D24-H24		

Table A6. Year three single point estimate calculation

	A	B	C	D	E	F	G	H	I	J	K	L
17	Biofuel switchgrass year 3				Corn year 3				Operation Risk Difference		Year Risk Difference	
18	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
19	**Establishment**				**Establishment**							
20		0	1.635E-05	0		1	1.294E-05	1.294E-05	**1**	-4.771E-06	**3**	-2.190E-05
21	**Management**				**Management**							
22		1	5.572E-06	5.572E-06		0.91	5.981E-06	5.465E-06	**2**	1.070E-07		
23	**Harvest**				**Harvest**							
24		1	4.033E-05	2.016E-05		0.91	4.093E-05	3.740E-05	**3**	-1.723E-05		

Table A7. Year four calculation equations

	A	B	C	D	E	F	G	H	I	J	K	L
25	Biofuel switchgrass year 4				Corn year 4				Operation Risk Difference		Year Risk Difference	
26	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
27	**Establishment**				**Establishment**							
28		0	0	=B28*C28		1	0	=F28*G28	**1**	=D28-H28	**4**	=SUM(J28,J30,J32)
29	**Management**				**Management**							
30		1	0	=B30*C30		0	0	=F30*G30	**2**	=D30-H30		
31	**Harvest**				**Harvest**							
32		1	0	=B32*C32		0	0	=F32*G32	**3**	=D32-H32		

Table A8. Year four single point estimate calculation

	A	B	C	D	E	F	G	H	I	J	K	L
25	Biofuel switchgrass year 4				Corn year 4				Operation Risk Difference		Year Risk Difference	
26	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
27	**Establishment**				**Establishment**							
28		0	1.635E-05	0		1	1.294E-05	1.294E-05	**1**	-4.771E-06	**4**	-2.190E-05
29	**Management**				**Management**							
30		1	5.572E-06	5.572E-06		0.91	5.981E-06	5.465E-06	**2**	1.070E-07		
31	**Harvest**				**Harvest**							
32		1	4.033E-05	2.016E-05		0.91	4.093E-05	3.740E-05	**3**	-1.723E-05		

Table A9. Year five calculation equations

	A	B	C	D	E	F	G	H	I	J	K	L
33	Biofuel switchgrass year 5				Corn year 5				**Operation Risk Difference**		**Year Risk Difference**	
34	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
35	**Establishment**				**Establishment**							
36		0	0	=B36*C36		1	0	=F36*G36	**1**	=D36-H36	**5**	=SUM(J36,J38,J40)
37	**Management**				**Management**							
38		1	0	=B38*C38		0	0	=F38*G38	**2**	=D38-H38		
39	**Harvest**				**Harvest**							
40		1	0	=B40*C40		0	0	=F40*G40	**3**	=D40-H40		

Table A10. Year five single point estimate calculation

	A	B	C	D	E	F	G	H	I	J	K	L
33	Biofuel switchgrass year 5				Corn year 5				**Operation Risk Difference**		**Year Risk Difference**	
34	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
35	**Establishment**				**Establishment**							
36		0	1.635E-05	0		1	1.294E-05	1.294E-05	**1**	-4.771E-06	**5**	-2.190E-05
37	**Management**				**Management**							
38		1	5.572E-06	5.572E-06		0.91	5.981E-06	5.465E-06	**2**	1.070E-07		
39	**Harvest**				**Harvest**							
40		1	4.033E-05	2.016E-05		0.91	4.093E-05	3.740E-05	**3**	-1.723E-05		

Table A11. Year six calculation equations

	A	B	C	D	E	F	G	H	I	J	K	L
41	Biofuel switchgrass year 6				Corn year 6				Operation Risk Difference		Year Risk Difference	
42	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
43	**Establishment**				**Establishment**							
44		0	0	=B44*C44		1	0	=F44*G44	**1**	=D44-H44	**6**	=SUM(J44,J46,J48)
45	**Management**				**Management**							
46		1	0	=B46*C46		0	0	=F46*G46	**2**	=D46-H46		
47	**Harvest**				**Harvest**							
48		1	0	=B48*C48		0	0	=F48*G48	**3**	=D48-H48		

Table A12. Year six single point estimate calculation

	A	B	C	D	E	F	G	H	I	J	K	L
41	Biofuel switchgrass year 6				Corn year 6				Operation Risk Difference		Year Risk Difference	
42	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
43	**Establishment**				**Establishment**							
44		0	1.635E-05	0		1	1.294E-05	1.294E-05	**1**	-4.771E-06	**6**	-2.190E-05
45	**Management**				**Management**							
46		1	5.572E-06	5.572E-06		0.91	5.981E-06	5.465E-06	**2**	1.070E-07		
47	**Harvest**				**Harvest**							
48		1	4.033E-05	2.016E-05		0.91	4.093E-05	3.740E-05	**3**	-1.723E-05		

Table A13. Year seven calculation equations

	A	B	C	D	E	F	G	H	I	J	K	L
49	Biofuel switchgrass year 7				Corn year 7				**Operation Risk Difference**		**Year Risk Difference**	
50	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
51	**Establishment**				**Establishment**							
52		0	0	=B52*C52		1	0	=F52*G52	**1**	=D52-H52	**7**	=SUM(J52,J54,J56)
53	**Management**				**Management**							
54		1	0	=B54*C54		0	0	=F54*G54	**2**	=D54-H54		
55	**Harvest**				**Harvest**							
56		1	0	=B56*C56		0	0	=F56*G56	**3**	=D56-H56		

Table A14. Year seven single point estimate calculation

	A	B	C	D	E	F	G	H	I	J	K	L
49	Biofuel switchgrass year 7				Corn year 7				**Operation Risk Difference**		**Year Risk Difference**	
50	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
51	**Establishment**				**Establishment**							
52		0	1.635E-05	0		1	1.294E-05	1.294E-05	**1**	-4.771E-06	**7**	-2.190E-05
53	**Management**				**Management**							
54		1	5.572E-06	5.572E-06		0.91	5.981E-06	5.465E-06	**2**	1.070E-07		
55	**Harvest**				**Harvest**							
56		1	4.033E-05	2.016E-05		0.91	4.093E-05	3.740E-05	**3**	-1.723E-05		

Table A15. Year eight calculation equations

	A	B	C	D	E	F	G	H	I	J	K	L
57	Biofuel switchgrass year 8				Corn year 8				**Operation Risk Difference**		**Year Risk Difference**	
58	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
59	**Establishment**				**Establishment**							
60		0	0	=B60*C60		1	0	=F60*G60	**1**	=D60-H60	**8**	=SUM(J60,J62,J64)
61	**Management**				**Management**							
62		1	0	=B62*C62		0	0	=F62*G62	**2**	=D62-H62		
63	**Harvest**				**Harvest**							
64		1	0	=B64*C64		0	0	=F64*G64	**3**	=D64-H64		

Table A16. Year eight single point estimate calculation

	A	B	C	D	E	F	G	H	I	J	K	L
57	Biofuel switchgrass year 8				Corn year 8				**Operation Risk Difference**		**Year Risk Difference**	
58	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
59	**Establishment**				**Establishment**							
60		0	1.635E-05	0		1	1.294E-05	1.294E-05	**1**	-4.771E-06	**8**	-2.190E-05
61	**Management**				**Management**							
62		1	5.572E-06	5.572E-06		0.91	5.981E-06	5.465E-06	**2**	1.070E-07		
63	**Harvest**				**Harvest**							
64		1	4.033E-05	2.016E-05		0.91	4.093E-05	3.740E-05	**3**	-1.723E-05		

Table A17. Year nine calculation equations

	A	B	C	D	E	F	G	H	I	J	K	L
65	Biofuel switchgrass year 9				Corn year 9				**Operation Risk Difference**		**Year Risk Difference**	
66	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
67	**Establishment**				**Establishment**							
68		0	0	=B68*C68		1	0	=F68*G68	**1**	=D68-H68	**9**	=SUM(J68,J70,J72)
69	**Management**				**Management**							
70		1	0	=B70*C70		0	0	=F70*G70	**2**	=D70-H70		
71	**Harvest**				**Harvest**							
72		1	0	=B72*C72		0	0	=F72*G72	**3**	=D72-H72		

Table A18. Year nine single point estimate calculation

	A	B	C	D	E	F	G	H	I	J	K	L
65	Biofuel switchgrass year 9				Corn year 9				**Operation Risk Difference**		**Year Risk Difference**	
66	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
67	**Establishment**				**Establishment**							
68		0	1.635E-05	0		1	1.294E-05	1.294E-05	**1**	-4.771E-06	**9**	-2.190E-05
69	**Management**				**Management**							
70		1	5.572E-06	5.572E-06		0.91	5.981E-06	5.465E-06	**2**	1.070E-07		
71	**Harvest**				**Harvest**							
72		1	4.033E-05	2.016E-05		0.91	4.093E-05	3.740E-05	**3**	-1.723E-05		

Table A19. Year ten calculation equations

	A	B	C	D	E	F	G	H	I	J	K	L
73	Biofuel switchgrass year 10				Corn year 10				**Operation Risk Difference**		**Year Risk Difference**	
74	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
75	**Establishment**				**Establishment**							
76		0	0	=B76*C76		1	0	=F76*G68	**1**	=D76-H76	**10**	=SUM(J76,J78,J80)
77	**Management**				**Management**							
78		1	0	=B78*C78		0	0	=F78*G78	**2**	=D78-H78		
79	**Harvest**				**Harvest**							
80		1	0	=B80*C80		0	0	=F80*G80	**3**	=D80-H80		

Table A20. Year ten single point estimate calculation

	A	B	C	D	E	F	G	H	I	J	K	L
73	Biofuel switchgrass year 10				Corn year 10				**Operation Risk Difference**		**Year Risk Difference**	
74	**Operation**	**P(e)**	**P(i)**	**Risk**	**Operation**	**P(e)**	**P(i)**	**Risk**				
75	**Establishment**				**Establishment**							
76		0	1.635E-05	0		1	1.294E-05	1.294E-05	**1**	-4.771E-06	**10**	-2.190E-05
77	**Management**				**Management**							
78		1	5.572E-06	5.572E-06		0.91	5.981E-06	5.465E-06	**2**	1.070E-07		
79	**Harvest**				**Harvest**							
80		1	4.033E-05	2.016E-05		0.91	4.093E-05	3.740E-05	**3**	-1.723E-05		

APPENDIX B

INDIVIDUAL FREQUENCY DISTRIBUTIONS USED TO DETERMINE THE GREATEST CONTRIBUTING FACTOR TO WORKER INJURY RISK IN THE MODEL

This appendix contains the output distributions of worker injury risk for each operation - establishment, management, and harvest - in each production system - corn and biofuel switchgrass. The worker injury risk values were summed over the ten year lifecycle of the production systems. These distributions were used to determine the greatest contributing factor to worker injury risk in corn and biofuel switchgrass. Due to long tails on the frequency distributions the distributions in this appendix have been truncated by removing frequency categories with less than 50 counts.

Figure A1. Worker injury risk of corn establishment

Figure A2. Worker injury risk of corn management

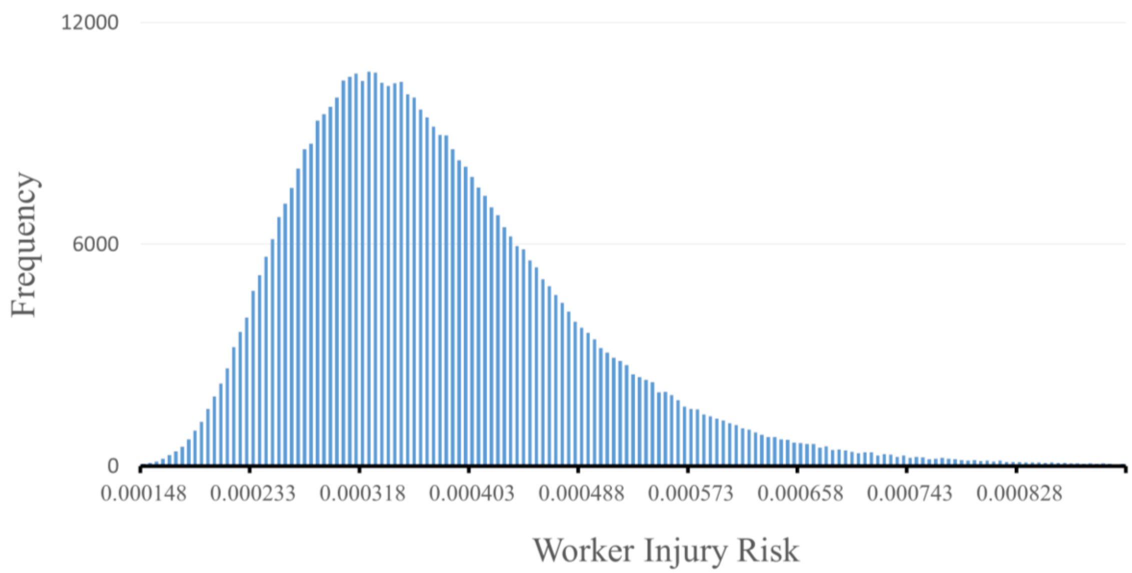

Figure A3. Worker injury risk of corn harvest

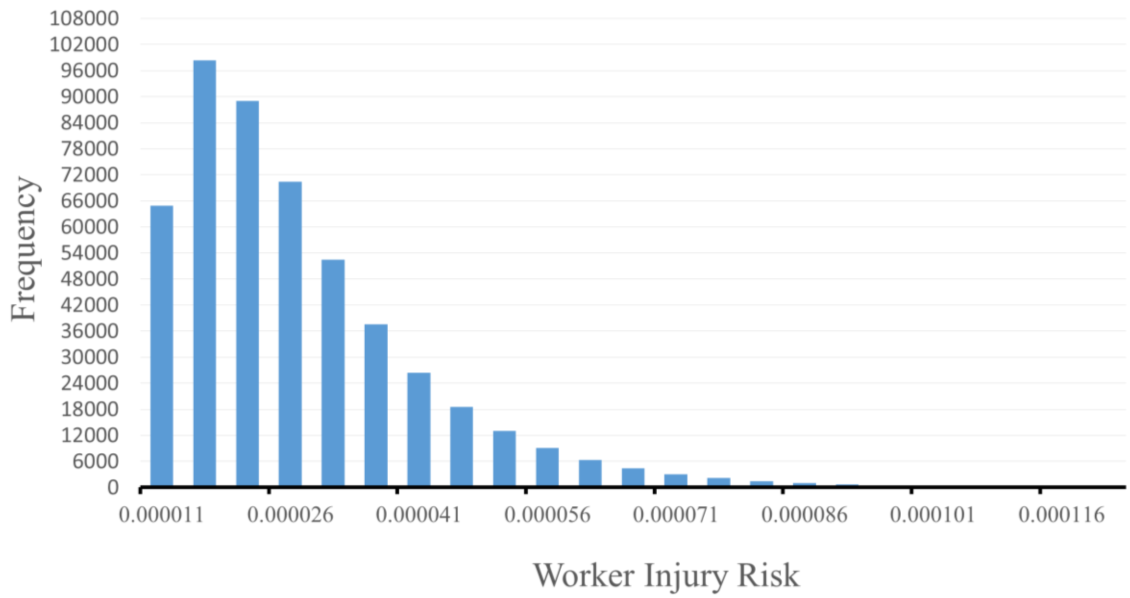

Figure A4. Worker injury risk of biofuel switchgrass establishment

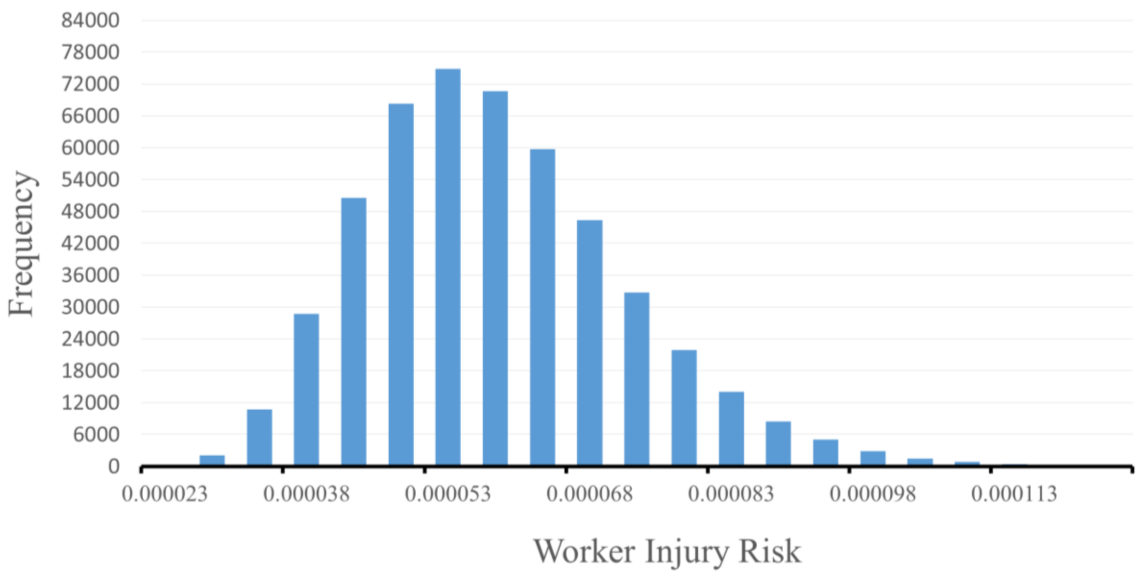

Figure A5. Worker injury risk of biofuel switchgrass management

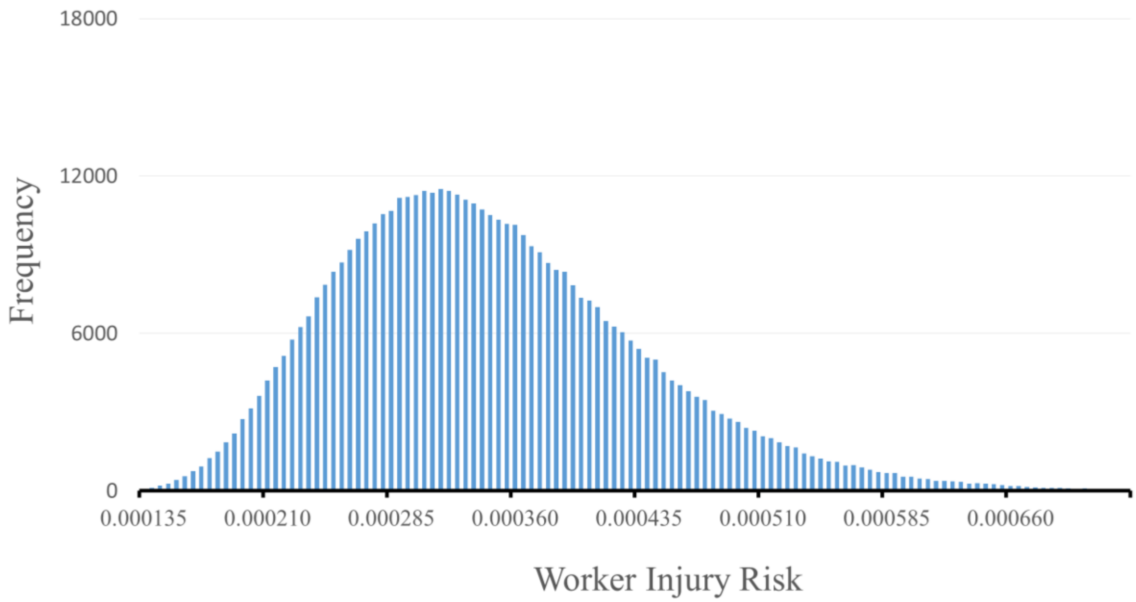

Figure A6. Worker injury risk of biofuel switchgrass harvest