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Agricultural Worker Injury Comparative Risk Assessment Methodology: Assessing Corn and Biofuel Switchgrass Production Systems

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Abstract

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Keywords

Agricultural production, Agricultural risk assessment, Agricultural safety, Biofuel production safety, Exposure distribution, Farm safety, Human safety risk assessment, Injury distribution, Monte Carlo, Regional risk assessment

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Comments

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ABSTRACT. *Keeping workers safe is a continuing challenge in agricultural production. Risk assessment methodologies have been used widely in other industries to better understand systems and enhance decision making, yet their use in production agriculture has been limited. This article describes the considerations and the approach taken to measure the difference in worker injury risks between two agricultural production systems. A model was developed specifically for the comparison of worker injury risk between corn and biofuel switchgrass production systems. The model is composed of injury and exposure values that were used in a Monte Carlo simulation. The output of this risk assessment shows that approximately 99% of the values from the Monte Carlo simulation rank corn production as a greater worker injury risk than biofuel switchgrass production. Furthermore, the greatest contributing factors for each production system were identified as harvest, and that finding aligns with current literature.*

Keywords. *Agricultural production, Agricultural risk assessment, Agricultural safety, Biofuel production safety, Exposure distribution, Farm safety, Human safety risk assessment, Injury distribution, Monte Carlo, Regional risk assessment.*

Production agriculture is ranked among the most dangerous industries by OSHA (2013), with a fatality rate of 24.9 per 100,000 workers as compared to the fatality rate of 3.5 per 100,000 workers for all occupations in 2011 (OSHA, 2013). The high rate of fatalities in agriculture has seen little change over the years. Between 1992 and 2012, the fatality rate ranged from 22.2 to 32.5 per 100,000 workers (BLS, 2012), much higher than fatality rates for all industries over the same period. Fatality rates do not include youth under the age of 16, so actual rates are likely much higher.

The hazardous nature of the industry is costly not only in terms of human injuries and fatalities but also from a financial perspective. According to the National Safety Council (NSC, 2013), the average approximate cost of an injury across all industries is $37,000, and the average cost of a fatality across all industries is approximately $1.4 million. Using an estimated non-fatal injury count of 120,000 and a fatal injury count of 543 from the National Safety Council (NSC, 2013), the estimated cost of agricultural injuries and fatalities is nearly $5.2 billion per year. Worker safety data already suggest that agricultural

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production is a dangerous industry, yet Leigh et al. (2014), in researching crop farm injuries, reported that up to 73% of injuries are not reported. This means that the rates of injuries and fatalities, as well as the potential savings in human lives and associated costs, could be much greater than reported. For these reasons, a better understanding of the safety risks in agricultural operations can have benefits from a worker safety perspective as well as a financial perspective.

Risk Assessment

Risk assessments help to better understand systems by quantifying the likelihood of an event occurring and describing the potential consequences of that event. Risk assessments are often used in complex systems to calculate probabilities of negative events, such as injuries, fatalities, and catastrophic environmental impacts, that are then used to assist in the development of mitigation methods that reduce the probability of these events (Clemons and Simmons, 1998). Risk assessment information also helps develop a complete understanding of the system to improve safety decisions (Mosher and Keren, 2011).

Risk assessment originated in system reliability studies in the aerospace industry in the 1950s. This method was eventually used to determine the safety of highly complex systems in which failure would have great consequences, such as intercontinental ballistic missile systems in the 1960s (EPA, 2017). Hansson and Aven (2014) described risk analysis as a research area popular in the 1970s to measure hazards and consequences in the natural environment. As the military continued updating its standards for system safety, the National Safety Council began to adopt risk analysis methodologies in 1994 to apply in teaching engineering graduates to design with regard to safety (EPA, 2017).

As risk assessment progressed with methodologies and frameworks, it was continually implemented in new industries. A recent example of this is from Hansson and Aven (2014), who described two major types of risk studies: those that focus on assessing hazards and risk in specific contexts and those that focus on developing new theories, models, and methods of assessing risk. This article focuses on the second approach, i.e., developing a new methodology and framework to assess and compare risk levels between two agricultural production systems.

Risk Assessments throughout Industry

Risk assessment models and frameworks have been used in many industries over the past couple of decades. Several industries have used risk assessment methodologies to formulate prevention efforts, with a goal of reducing worker injuries. Ghasemi et al. (2010) developed a method of assessing pillar recovery risk in coal mining operations. Controllable and uncontrollable parameters were considered to calculate an overall risk of pillar recovery on a scale of 1 to 100. Mitropoulos and Namboodiri (2011) studied how task demand, defined as how difficult it is to do the work safely, in construction operations affects safety risk. Mitropoulos and Namboodiri (2011) built on established risk assessment methods within the construction industry to determine risk related to task demand. Finally, Shyur (2008) researched safety risk due to human error in aviation based on accident and safety indicators.

Businesses in construction or manufacturing industries that are regulated by the Occupational Safety and Health Administration (OSHA) are required to conduct hazard assessments or risk assessments to protect their employees. For example, the OSHA standard on personal protective equipment (OSHA, 1974) requires a hazard assessment and protective equipment. To assist employers in common industries, OSHA provides software tools (OSHA, 2014). One example is a software-driven, interactive, and game-based training tool that employers can use to better understand processes and safety.

Environmental Protection Agency Risk Assessment

The U.S. Environmental Protection Agency (EPA) has been using risk assessment since 1975 and over time has advanced risk assessment methods. In the 1990s, the EPA began issuing guidelines for conducting human health risk assessments that were later adapted to assess ecological risks (EPA, 2017). The guidelines for developmental toxicity risk assessment were among the early risk assessment guidelines that aimed to assess the potential risk to humans due to environmental contaminants (EPA, 1991). The EPA currently has 98 human health risk assessment guidelines, developed from 1986 to 2015, ranging from pesticides to genomics.

The EPA uses two main categories of risk assessment frameworks: human health risk assessments and ecological risk assessments. The focus of human health risk assessments is to identify hazards, estimate the human exposure to the hazards, determine the health consequences to humans as a result of the hazards, and finally determine the human health risk (EPA, 2014). Modified from human health risk assessments, ecological risk assessments focus on protecting plants and animals by estimating exposure to the hazards and the consequence of that exposure in terms of plant or animal health. Risks are estimated and practices are implemented using these assessments (EPA, 1992).

Beyond the general frameworks for these risk assessments are more focused models, tools, and databases available from the EPA. There are models for guiding estimates of dietary exposure, air quality, radiation, and more. Databases from the EPA range from biomarkers to toxicity values to water resources. The models, tools, and databases are based on the human health or ecological risk assessment frameworks and conform to specific scenarios (EPA, 2006).

Agricultural Risk Assessment

Unlike the EPA and other industries, worker health risk assessments in production agriculture are limited (Kingman and Field, 2005). Risk assessment methods have not been widely used in production agriculture, beyond the use of pesticide-related risk assessments by the EPA (2009), relative to other industries since their development. The limitation of agricultural risk assessments related to safety or other issues can be attributed to variance from farm to farm within agricultural systems and similar variances across states or regions (Sperber, 2005). More specifically, there is a lack of risk assessment methodologies for assessing risk over a region. However, there are some areas in which researchers have used risk assessments to evaluate worker injury risks in production agriculture. Yuan et al. (2015) researched grain dust explosions using Bayesian networks to determine the likelihood of a grain dust explosion. It was also possible for the researchers to identify probable causes of explosions and use this information to prevent them. Kingman and Field (2005) researched grain engulfments using fault tree analysis (FTA) and showed how FTA can be used in agriculture to address the root causes of unsafe situations.

Challenges of Using Worker Injury Risk Assessments in Agriculture

There are several challenges in using risk assessments in production agriculture. The first challenge is the complexity of many safety scenarios in production agriculture. Two common tools, fault tree analysis (FTA) and event tree analysis (ETA), are used to analyze the factors that influence a single outcome and the outcomes from a single initiating event, respectively (Clemons and Simmons, 1998). These tools are an appropriate choice when the number of causal pathways to investigate is limited. Analyzing an entire agricultural production system from planting to harvest requires more detail than is feasible given the many causal pathways of each production system.

A second challenge of risk assessment in production agriculture is the lack of primary data. No regular surveillance is completed on injuries and fatalities specific to production tasks such as planting and harvesting (BLS, 1996-2011). The lack of injury and fatality data complicates the implementation of commonly used risk assessment methods. Weather conditions and unpredictable work schedules during busy production times present additional uncertainty in risk assessment model inputs (Ericson, 2005).

A third challenge is the diversity of agricultural operations and conditions, which increases uncertainty about the generalizability of the data and lowers the validity of traditional numerical measures of central tendency and variance, such as the mean and standard deviation. Due to the cumulative uncertainty of data inputs, the output of an entire production system may not yield an output that is useful or beneficial on a practical basis (Clemons and Simmons, 1998).

A fourth challenge is the lack of a robust and objective method for measuring worker injury risk in production agriculture, and this renders another commonly used risk assessment tool ineffective. The risk assessment matrix (RAM) facilitates a subjective risk assessment using the analyst's knowledge and data collected by system users (Clemons and Simmons, 1998; DOD, 2012). The RAM displays subjective categorical probabilities and severities to characterize risk levels (Cox, 2008). The risk output from the RAM is effective in prioritizing risks within a single system but is less effective at measuring cumulative risks from multiple components of a complex system. The subjectivity of the RAM limits the generalizability of the risk value across systems or even between analysts.

Agricultural Worker Risk Assessment Methodology

This article describes a methodology that was developed to measure the difference in worker injury risks between two agricultural production systems. Specifically, the approaches used to adapt conventional risk assessment tools for use in production agriculture are emphasized. Appropriate and available data sources, model inputs, and analysis tools are also discussed. This article concludes with implications for future agricultural risk assessments measuring worker injury risk.

This project was part of a larger project investigating the creation of sustainable Midwestern biofuel and bioproduct systems. The objective of the safety component of the project was to develop a risk assessment methodology to compare the worker injury risk between a conventional crop system (corn) and a biofuel crop system (biofuel switchgrass) in the Midwest region of the U.S. The Midwest region was defined by the U.S. Census Bureau (2013) and includes North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, and Ohio. The purpose of investigating biofuel switchgrass was to determine if the crop presents safety hazards specific to its production as its prevalence in agriculture increases. Switchgrass has been identified as a key biofuel crop of the future and has recently received renewed attention because of its ability to grow in many climates, its long growing duration, and its ability to produce harvestable yields as early as the second year of planting (Hadachek, 2017). Furthermore, Jacobs and Harlow (2015) also found that producers value the non-monetary benefits, including environmental and conservation advantages, associated with switchgrass production. It is important to understand if injury rates are predicted to be high before a crop is widely produced to prevent as many injuries and fatalities as possible. The risk assessment methodology was constructed specifically to:

- Allow a relative comparison of risk values between two production systems.
- Use available data to predict worker injury risk.
- Be scalable to allow more or less information to be added into the model as appropriate.

Risk Assessment Methodology

Five primary components of the risk assessment methodology are discussed: (1) risk assessment approaches, (2) probability of exposure and probability of injury, (3) sourcing input data, (4) constructing the risk assessment model, and (5) stochastic calculations.

1. Risk Assessment Approaches

Clemons and Simmons (1998) presented conventional approaches to calculate risk based on the product of the probability of an event and the severity of that event. The probability of an event is the likelihood that the event will occur. The severity is a measure of how negative or positive that event would be if it occurred. Risk is commonly used in monetary calculations in this manner. For example, if the probability of a fire occurring is 0.50 and the cost of a fire occurring is $10,000, then the monetary risk of a fire is $5,000.

Ryan (2016) developed a model that is based on the conventional approach but uses the probability of injury and the probability of exposure to calculate risk, as outlined in this research. The probability of injury was calculated using injury counts, and the probability of exposure was calculated using acre counts. The product of the probability of exposure and the probability of injury is a risk value that is the likelihood of injury given that exposure has occurred.

2. Probability of Exposure and Probability of Injury

To measure risk, an estimate of exposure is necessary. Exposure measures the contact that a subject has with the hazard in question. Exposure is measured in multiple ways, depending on the system characteristics and the data available to quantify the hazard. In toxicology studies, exposure is often measured with a dose value to quantify the amount of contact a human has with a hazard. With atrazine, exposure is measured in mg per kg per day (EPA, 2002). Measurements may represent acute or chronic exposure.

Ideal data to measure exposure for this research are in the form of time that farmers are exposed to specific types of machinery and the activities they perform. This level of detail enhances the risk assessment's reflection of reality, but time data are not currently available on a scale that covers the Midwest. In this research, exposure was measured as a probability of contact with a given operation, with acres as the measurement basis. Although acres are not the only possible unit of measurement or even the most ideal unit of measurement, acres were the most consistent and available data from the USDA for both cropping systems. For these reasons, the method of using acres as a measurement was chosen. The probability of exposure was calculated with equation 1 using a fractional relationship in which the numerator is the number of acres on which operations are performed and the denominator is the total amount of acres on which operations could be performed:

$$P(e) = \frac{\text{Number of acres on which an operation is performed}}{\text{Number of acres on which an operation could be performed}} \quad (1)$$

Probability of injury was the second term in calculating risk. Rather than a magnitude or various severity levels of injury, the probability of injury was used, in part because the available data did not include severity information. Injury data are measured in number of injuries on a regional basis and do not differentiate between injury types or injury severity. The probability of injury was calculated with equation 2 using a fractional relationship in which the numerator is the number of workers injured performing an operation and the denominator is the total amount of people performing that operation:

$$P(i) = \frac{\text{Number of people injured performing an operation}}{\text{Number of people performing an operation}} \quad (2)$$

3. Sourcing Input Data

Quantifying workers' risk of injury in agricultural production systems involves several sources of data. These data include injury and farmer data for calculation of the probability of injury and acre data for calculation of the probability of exposure. Injury data were separated by the type of agricultural production system, the operation in which the injury occurred, and the state in which injury the occurred. The exposure data were acre counts of each operation organized by state and the number of acres on which operations were performed for each agricultural production system.

To assist in determining where injuries occur within a production system, three exposure scenarios were identified as major operations for each production system: establishment (from March to May), management (from May to September), and harvest (from September to November). Although each operation is associated with specific work activities, to effectively measure the hazards, the operation level must be consistent between the production systems. The operations have differences in work tasks and worker actions between production systems. These differences were captured for each production system in most cases and served as the basis of exposure estimates for the two systems.

Data were obtained from the USDA Census of Agriculture and survey programs and the Bureau of Labor Statistics (BLS). The USDA Census of Agriculture and survey programs are a major source of acre counts to calculate exposures for different production systems as well as farmer counts to determine the denominator for the probability of injury calculation. Data from the USDA Census of Agriculture and survey programs were collected and categorized by groups and regions in the Midwest. The BLS Archived State Occupational Injuries, Illnesses, and Fatalities is a major consistent source for injury data by state and year that was used in the calculation of the probability of injury. Table 1 summarizes the collected data used in this risk assessment.

Switchgrass has recently received renewed interest in agricultural production but has yet to be widely produced. Therefore, the USDA had limited data on the acres of switchgrass grown and harvested. Corn production, on the other hand, had plentiful acre

Table 1. Summary of published data used in the model by type.

Type of Data	Source of Data	References
Acre counts	USDA survey programs	USDA, 1996-2011
Injury counts	BLS Archived State Occupational Injuries, Illnesses, and Fatalities	BLS, 1996-2011
Farmer counts	USDA Census of Agriculture	USDA, 1992, 1997, 2002, 2007

data for each state and year. Due to the limited data on switchgrass, similar grass-style crops, such as hay and alfalfa, were examined to estimate grass-style crop exposure. However, grass-style crops are typically planted once every few years and are harvested multiple times per year, which results in probability of exposure values greater than one. Specifically, the denominator (i.e., the number of acres on which an operation could be performed) was 3 to 8 times smaller than the numerator (i.e., the number of acres on which an operation was performed), resulting in a probability of >1. To compensate for this, a conservative estimate of 1 for the probability of exposure was assigned to biofuel switchgrass operations. Because a significant amount of replanting can be required for switchgrass crops in year 2 (Moser et al. (2004), the exposure estimate to establishment in year 2 was estimated at 0.5. For all following years in the life cycle of biofuel switchgrass establishment, exposure was estimated to be 0 to reflect that no replanting occurs after successful establishment. Vose (2008) described conservative assumptions as a tool to prevent unnecessary risks. In this case, a conservative assumption was made because methods to accurately estimate the probability of exposure for biofuel switchgrass were limited.

The final source of data required was the numerator for the probability of injury calculation. To determine this, a regional and yearly injury data source was required. The BLS provided agricultural-related injury data for each state and each year, but these data are not classified by specific production system and do not fit within the time period from March to November, which were critical needs for this research. For this reason, the BLS injury data were combined with data from another source (i.e., Gerberich, 1998) to more accurately estimate the probability of injury.

Gerberich (1998) studied when injuries occurred and the likelihood of injury by machine type in the Midwest. This was the most recent study available, and we assumed that the age of the research would have little effect on this risk assessment due to agricultural injury and fatality rates remaining relatively constant for many years. From Gerberich (1998), a percent of injury counts by month was used to determine the number of injuries that occurred from March to November for a single year. Gerberich (1998) reported that 83.44% of injuries occur in the months of March to November. From this, each year of BLS injury data was multiplied by 83.44% to calculate an injury count that fits within the scope of this research for each state and year for which data were collected.

Next, the percentages of injuries due to specific machines were calculated by relating machine types to relevant production systems. The percentages of injuries due to specific machines as reported by Gerberich (1998) were used to transform the BLS injury counts modified by time to reflect the same percentage of injuries in each machine category. The transformed BLS injury data were then placed into the operations (establishment, management, and harvest) where those machines were used. For example, combine and hay wagon injuries were assigned to harvest operations in corn and biofuel switchgrass, respectively. This allowed the BLS injury counts from across the Midwest to be split into different production systems and operations within each production system based on machine type. The final injury count resulted in non-fatal machine injuries from March to November. Although the method allowed injury data to be modeled by machine type, it likely overestimated the machine-related injury rates. We acknowledge this assumption.

4. Constructing the Risk Model

The first part of constructing a risk assessment model is to determine the life cycle. The life cycle for this risk assessment model was ten years. This period was based on the life cycle of biofuel switchgrass, which is the longer of the two production systems. Mitchell et al. (2013) described switchgrass stands lasting at least ten years without being replanted. By choosing the longest life cycle, 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 harvest are 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 10 years of continuous corn or 20 years of corn rotated with another crop.

For each operation, a probability of exposure and a probability of injury were calculated for every year in the life cycle for both production systems. The risk values for both production systems in each year were calculated by summing the risks of the three operations (establishment, management, and harvest). The risk values for each year were summed to calculate a risk value for the life cycle of each system. Table 2 is an example of the terms used for calculating risk for a single year in a single production system. This table also assists in the organization of the data and the process of risk assessment.

The comparison of corn and biofuel switchgrass productions systems was calculated as the difference in worker injury risk. The difference was used to compare the relative risk of a well-known farming production system with a newer production system. The framework allows assessors to determine if the lesser-known newer system will generate a greater worker risk than what is already accepted in the well-known system. Furthermore, by using the difference in risk, we assume that any underreporting of agricultural injuries will affect both systems equally and will not have an effect on the difference in risk. The exposure and injury estimates for each operation were calculated for each production system, and the difference between these two systems was calculated using equation 3. To calculate the difference in worker injury risk, the operational levels of risk in each production system are subtracted from one another for each year, and then the worker injury risk for each year is summed over the life cycle of the risk assessment:

$$\Delta Risk = \sum_{y=1}^{l}\sum_{i=1}^{m}\left\{\left\{P(e)_{system1}\times P(i)_{system1} - P(e)_{system2}\times P(i)_{system2}\right\}_i\right\}_y \qquad (3)$$

where $P(e)$ is the probability of exposure, $P(i)$ is the probability of injury, l is the number of years in the life cycle, and m is the number of operations.

5. Stochastic Calculations

A pilot deterministic calculation was run before the stochastic calculations to check for reasonable outputs from the model. This calculation was the change in worker injury risk between the production systems in which each variable was a fixed average value from the collected data. The model output resulted in a probability format between 1 and -1, as expected, which verified that the model was functioning properly.

Table 2. Production operations used in system risk assessment.

Operation	Exposure	Injury	Risk
Establishment	✓	✓	✓
Management	✓	✓	✓
Harvest	✓	✓	✓
Subtotal risk in a year			✓

The deterministic calculation provided a single value of worker injury risk for a given scenario. The stochastic approach used multiple input values for each variable to calculate multiple risk output values. When multiple output risk values are present, a frequency distribution is formed. The output risk frequency distribution provides more information than a single value because it shows a range and the likelihood of occurrence across that range (Vose, 2008).

Fitting Distributions to Input Data

For each state and each year, input variables hold different values, forming a large set of data to sample. There are usually gaps in the input data, and those gaps are filled by fitting a distribution to the input data. The stochastic approach randomly samples these input distributions, creates a single value to calculate a single output risk value, and then repeats the process for a set number of times. After many samples, a smooth output risk frequency distribution is formed that describes the possibilities the risk value can hold based on the input distributions.

Several types of distributions can be used in worker injury risk assessments. Johnson (1997) described the functionality of the beta and triangle distributions commonly used in stochastic risk analysis. The beta and triangle distributions are used in situations with limited data (Johnson, 1997), which is typically the case for agricultural data (Rautiainen and Reynolds, 2002). The beta distribution (betaPERT) is similar to the triangle distribution, but it weights values near the mode of the data set to occur more frequently, giving the distribution a more realistic shape than the triangle distribution (Vose, 2008).

The lognormal distribution is another commonly used distribution to model naturally occurring phenomena, starting at 0 and continuing to infinity. The lognormal distribution is easy to fit to data and easy to test if the fit is acceptable (Vose, 2008). In this research, the exposure and injury data are both naturally occurring, making the lognormal distribution a good candidate for use in the model. Another common distribution is the gamma distribution, which is commonly used in situations for determining time between events. More importantly for this research, it is also used in cases of random variability (Vose, 2008).

The best fit autoselect feature in Crystal Ball (Oracle, Redwood City, Cal.) was used to determine the distributions for each of the Monte Carlo simulation input variables to remove any bias from the analyst. BetaPERT, gamma, and lognormal were selected to be the best fit by the software using the Anderson-Darling test. The distributions and their parameters that were fit to the corn input data are shown in table 3, and the biofuel switchgrass input distributions are shown in table 4. The lognormal distributions in tables 3 and 4 require three values to determine their shape, location, mean, and standard deviation. Each of the lognormal distributions in tables 3 and 4 shows the values that were used to shape the distributions in each operation of each production system for the injury and exposure variables. Similarly, the BetaPERT values (minimum, likeliest, and maximum) in table 3 and the gamma values (location, scale, and shape) in table 4 are the values used to shape their respective types of distribution. None of the exposure distributions for biofuel switchgrass in table 4 had a distribution because exposure was conservatively estimated with a probability of 1, as described earlier. Similarly, the probability of exposure for corn establishment was conservatively estimated with a probability of 1 as well.

Greatest Contributing Factor

To develop a better understanding of the difference in worker injury risk between the

Table 3. Corn input distributions descriptions.

Operation	Probability of:	Distribution Type	Distribution Parameters	
Establishment	Injury	Lognormal	Location	0.000001440
			Mean	0.000012799
			SD	0.000012380
	Exposure	No distribution	-	-
Management	Injury	Lognormal	Location	0.000000665
			Mean	0.000005913
			SD	0.000005720
	Exposure	BetaPERT	Minimum	0.612582745
			Likeliest	0.988636364
			Maximum	0.989725920
Harvest	Injury	Lognormal	Location	0.000001667
			Mean	0.000014818
			SD	0.000014332
	Exposure	BetaPERT	Minimum	0.612582745
			Likeliest	0.988636364
			Maximum	0.989725920

Table 4. Biofuel switchgrass input distributions descriptions.

Operation	Probability of:	Distribution Type	Distribution Parameters	
Establishment	Injury	Gamma	Location	0.000003948
			Scale	0.000013781
			Shape	0.899812371
	Exposure	No distribution	-	-
Management	Injury	Gamma	Location	0.000001346
			Scale	0.000004577
			Shape	0.923469397
	Exposure	No distribution	-	-
Harvest	Injury	Gamma	Location	0.000002883
			Scale	0.000009555
			Shape	0.947950826
	Exposure	No distribution	-	-

two production systems, the greatest contributing factors of each production system were determined. This consisted of a separate Monte Carlo simulation for each of the operations (establishment, management, and harvest) in each production system. Worker injury risk was calculated for each operation and summed over the ten-year life cycle. The simulation for each individual operation of each production system was run for 500,000 iterations. This resulted in establishment, management, and harvest worker injury risk distributions that were overlaid with one another to visualize the differences in worker injury risk between operations of a production system.

Results

The result of this research is a probabilistic risk assessment methodology that calculates the difference in worker injury risk between two agricultural production systems. Upon review of the risk output, risk analysts can judge the level of risk to be acceptable or unacceptable. In the case of unacceptable risk, interventions or preventative measures are targeted at the most impactful input variables. Figure 1 shows a conceptual model that illustrates the process of how raw data are transformed into input variables that can be used to estimate worker injury risk for an agricultural production system. This model was used to

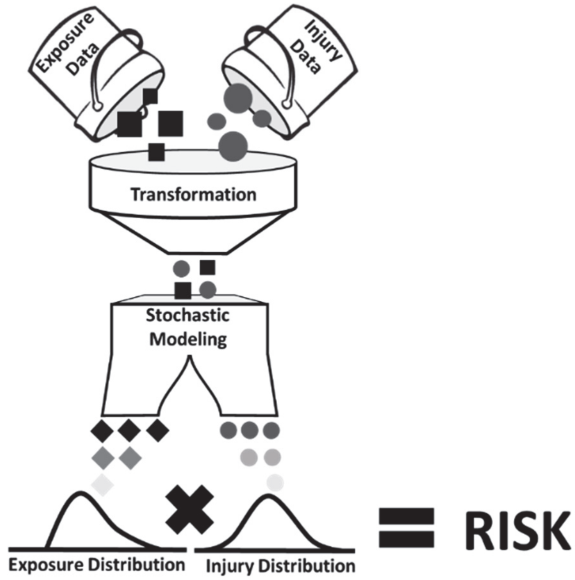

Figure 1. Risk model depicting the process in which risk is calculated for each production system.

determine the difference in worker injury risk between corn and biofuel switchgrass production.

Monte Carlo Simulation

The Monte Carlo simulation was run for 500,000 iterations and output a frequency distribution of the difference in worker injury risk between biofuel switchgrass and corn production, as shown in figure 2. To assist in viewing, the distribution in figure 2 was truncated to remove the long tails. The raw output distribution ranges from -0.00126 to 0.00016 and shows that approximately 99% of the 500,000 iterations resulted in corn production (negative values) having a higher worker injury risk. The negative values represent corn having

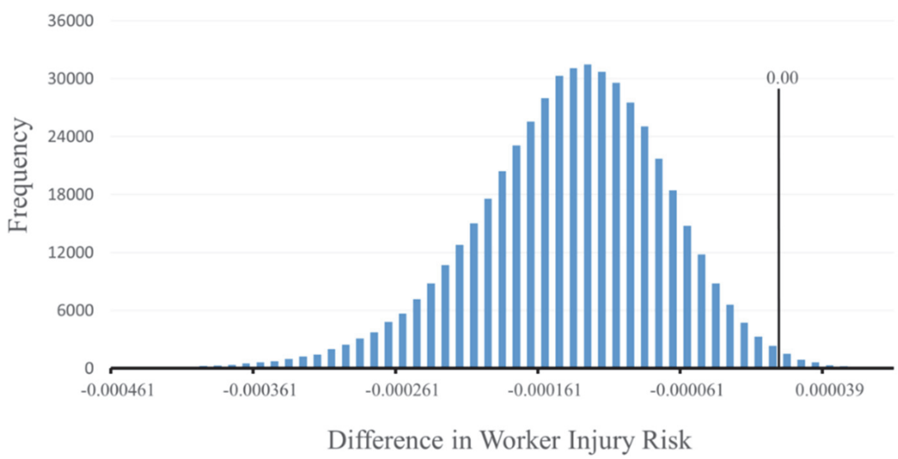

Figure 2. Difference in life cycle worker injury risk frequency for corn versus switchgrass.

a higher risk because corn worker injury risk was subtracted from switchgrass worker injury risk in this research. Approximately 1% of the iterations are positive values, where biofuel switchgrass production has a higher worker injury risk. The mean of the difference in worker injury risk distribution is -0.000138 (14 more life cycle injuries per 100,000 workers for corn than for biofuel switchgrass), and the median is -0.000133 (13 more life cycle injuries per 100,000 workers for corn than for biofuel switchgrass).

Greatest Contributing Factor

The worker injury risks for establishment, management, and harvest in each production system were determined over a ten-year life cycle and are summarized in table 5. The summary provides an overview of the mean, median, and mean life cycle injuries per 100,000 workers for each of the probability distributions of worker injury risk for each operation. The mean and median for each operation show little difference, indicating that these distributions are approximately normal. The mean values also show the mean life cycle injuries that occur in each operation for each production system to provide a comparison value between operations and production systems. The mean life cycle injuries per 100,000 workers show that harvest has the greatest mean life cycle injury rate in both production systems, making it the greatest contributing factor to worker injury risk in each production system. Furthermore, harvest is also a greater contributing factor in corn when compared to biofuel switchgrass, making corn harvest the greatest contributing factor in this risk assessment. Figures 3 and 4 show worker injury risk graphically for each operation in each production system over a ten-year life cycle. Figure 3 shows the worker injury risk distributions for corn production, and figure 4 shows the worker injury risk distributions for biofuel switchgrass.

Table 5. Operation contribution to life cycle worker injury risk.

Production System	Operation	Mean Worker Injury Risk	Median Worker Injury Risk	Mean Life Cycle Injuries per 100,000 Workers
Corn	Establishment	0.000128	0.000121	13
	Management	0.000055	0.000052	6
	Harvest	0.000137	0.000130	14
Biofuel switchgrass	Establishment	0.000025	0.000021	3
	Management	0.000056	0.000054	6
	Harvest	0.000101	0.000098	10

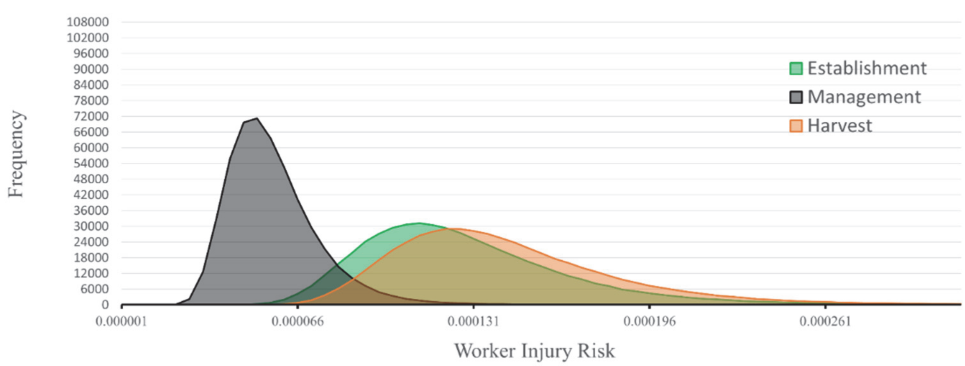

Figure 3. Greatest contributing factor to life cycle worker injury risk in corn production operations.

Figure 4. Greatest contributing factor to life cycle worker injury risk in biofuel switchgrass operations.

Discussion

The primary purpose of this research was to create a methodology to estimate worker injury risk and to calculate the difference in estimated worker injury risk between corn and biofuel switchgrass production systems in the Midwestern U.S. By calculating the difference in risk levels, the methodology facilitates a relative comparison of risk between the two production systems. The model was intended to use available data and to be scalable to allow the use of more or less data in various scenarios.

The methodology was designed to be fairly broad in scope. This gives analysts the option to modify the details of the assessment by changing the operations used in the calculation and the level of detail for each operation. Variables, operations, and sub-operations can be added or removed from the model for different scenarios. In addition, the model can be used to evaluate worker risk in other agricultural production systems.

Due to its ability to be broad in scope, this model also comes with limitations. This model uses Monte Carlo simulation, which has its own inherent limitations. One of these limitations is the difficultly in determining the difference between uncertainty and variability in the data, which could have a significant effect on the output. There is also model uncertainty due to the inclusion and exclusion of variables and data within the model, which is generally handled by the analyst providing evidence of why the model was built the way it was. Another common limitation of Monte Carlo simulation is the fluctuation of the values in the tails, reflecting rare events (Vose, 2008). However, this was of minimal concern in this study because the events in the tails are rare and the purpose of this research was to gather an understanding of how different the two production systems are, not how different they could be in a rare scenario. The main limitation that should be noted is that the Monte Carlo simulation used distributions that were fit to the data distribution pattern and not the actual data. This was done to fill gaps and assumed that the areas where there are no data conform to the distribution.

In the case of corn and biofuel switchgrass, the model shows that corn production systems will have a greater worker injury risk 99% of the time. Although this may seem obvious because corn is more prevalent in the Midwest, that is not the case for this model because probabilities were used in the calculation. The number of corn farmers relative to the number of biofuel switchgrass farmers is irrelevant because they are normalized by using probabilities. A more intriguing point is that switchgrass exposure values were overestimated at a probability of 1, but switchgrass is still less likely to have more injuries than corn 99% of the time.

The key difference between corn and biofuel switchgrass that makes corn so much more likely to have higher worker injury risk is exposure. For biofuel switchgrass, establishment is completed in the first two years, with no more establishment operations in the following eight years. Therefore, while corn workers are exposed to hazards in establishment for ten years, biofuel switchgrass workers are exposed to these hazards for only two years. Over a ten-year life cycle, this can make a large difference in the overall worker injury risk, which helps explain the large difference in injury risk between corn and biofuel switchgrass. If more data were available, the exposures could provide more information by including different conservation methods or worker behavior that could occur in the production of either crop. However, the purpose of this model was to give an overview of the change in risk in the Midwest, rather than specific practices between farms. While different practices or suboperations within each operation (establishment, management, and harvest) in each production system could be included in the information and data used in this risk assessment, they were not the focus of this research.

The fact that establishment is a major factor in the difference between corn and biofuel switchgrass worker injury risk is reflected in the greatest contributing factor to worker injury risk. While establishment has the smallest contribution to worker injury risk in biofuel switchgrass because of the limited worker exposure to this operation, the greatest contributing factor to worker injury risk in both production systems is harvest. This agrees with the literature in that harvest can be the most dangerous operation in agricultural production because injury rates are elevated during harvest (Hagel et al., 2004; Hanna and Schwab, 2013; Knapp, 1966), which further validates the functionality of this model.

The mean life cycle worker injury values in table 5 summarize the mean number of injuries per 100,000 workers in the life cycle. The mean worker injury risk value was used to summarize the differences between operations and production systems to determine which operations involve the greatest worker injury risk. As previously mentioned, the harvest operations in each production system have the greatest mean life cycle injuries per 100,000 workers of all operations. The management operation is similar in both production systems, and this is likely due to the management equipment being similar in the two production systems. Finally, establishment showed the greatest difference between the two production systems in mean life cycle injuries per 100,000 workers. Establishment was shown to have such a great difference because it only occurs in the beginning of the life cycle for biofuel switchgrass, while it occurs each year in the life cycle for corn.

However, as figures 3 and 4 show, the worker injury risk distributions of the operations overlap with one another. When looking at the distributions as a whole and not just the means, it is possible for establishment or management in corn or biofuel switchgrass to have the greatest worker injury risk. However, the overlaps of the distributions are relatively small, meaning that the chance of this occurring is small. In corn operations, the establishment and harvest distributions overlap greatly, indicating that there is a larger chance that establishment could be the greatest contributing factor in corn operations when compared to biofuel switchgrass production.

Finally, this study has shown that risk can be modeled and the model can produce logical results with limited agricultural data. These results are in the form of relative risk values showing that corn production will have greater worker injury risk than biofuel switchgrass over a ten-year life cycle. This study has also shown that conservative assumptions can be made in the case of missing exposure data, and the model can still provide useful results until actual data are available. This model serves as a contribution to risk assessment in agriculture and can be used for many other production systems.

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