LARGE-SCALE FIELD STUDY OF IMPACT-BASED YIELD MONITOR PERFORMANCE

R. P. McNaull, M. J. Darr

ABSTRACT. *The grain yield monitor is the most common evaluation tool for determining the productivity of grain cropping systems. Most evaluations of grain yield monitors have focused on lab scale tests of the sensor performance and its ability to be calibrated in field trials. This study focused on the performance of the impact-based grain yield monitor during a full corn harvest season with observations and conclusions drawn on the load-to-load variation, field level, and full season accuracy from data collected over five seasons and encompassing over 2,000 evaluation loads. The load variance expectation of the impact-based yield monitor was characterized and the yield difference requirements for statistical significance were developed to aid in yield monitor based evaluations of agronomic strip trials. Following manufacturer recommended calibrations, a single cropping season calibration in corn produced field mean errors of ±5% and a season mean error of 1%. Results showed statistically significant shift in the yield monitor accuracy for grain moisture content greater than 22.5% and a load accuracy dependency on the mean mass flow rate during the full harvest season calibration evaluation.*

Keywords. *Combine harvesters, Mass flow, Precision agriculture, Real-time sensor, Yield map, Yield monitor.*

Yield is the common report card of grain production systems and allows comparison of decisions made during the production process. Comparing agronomic performance can be achieved through physically weighing harvested grain, however this requires a mobile scale system, reduces the spatial resolution as grain is aggregated to a transport vehicle, and in some cases benchmarking may be delayed until grain is marketed due to the availability of weighing mechanisms. The yield monitor's primary purpose on introduction was to serve as the source of information in the implementation of site-specific cropping practices, and as of 2015 there was over a 43% adoption rate of yield monitors in the Corn Belt (Erickson et al., 2017). The widespread adoption of yield monitoring technology has enabled producers to estimate harvested grain mass that otherwise could only be achieved through weighing grain. The accuracy of the yield monitor has been under investigation since its introduction and is typically compared against the traditional benchmark methods of large aggregated weights by producers. The aggregation typically is observed at the seasonal totals and at the field level when grain transport, sales, or storage methods allow.

A variety of technologies are available for commercial yield monitoring with the impact-based yield monitor being the most common in North America. The impact-based yield monitor is a system comprised of an impact plate mounted to a force transducer located at the discharge of the clean grain elevator and a controller or display that interprets information from the force transducer to estimate a grain mass flow rate (United States Patent No. 5,561,250; Myers, 1996). The conversion of the force transducer output to mass flow is based on an operator completed calibration process that is required to ensure yield monitor accuracy.

The accuracy of the impact-based yield monitor has been evaluated under a variety of conditions and formats. Determining the accuracy of the impact-based yield monitor defines the scope of which the resulting data can be used for agronomic and cropping practice decisions. In recent years, calibrated yield monitors have been utilized for a range of agronomic purposes, business decisions, and government yield reporting (USDA, 2016). Agronomic usage is better defined as hybrid test strips, split planter hybrid trials, and specific chemical or nutrient application evaluations.

Test stand evaluations were completed by Burks et al. (2003), evaluating mass flow variability and accumulated load weights, impact of varying flow rates (Burks et al., 2004), field terrain (Fulton et al., 2009), and crop property effects (Reinke et al., 2011). These studies focused on the impact-based yield monitor's ability to be calibrated to estimate mass flow and to compensate for other mechanical

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influences with the evaluation metric being average flow rate or accumulated mass. This helps define load weight accuracy in controlled environments, but does not characterize the performance of the yield monitor in normal field conditions that include moisture content variation and field dynamics.

Field test studies analyzing individual load errors, Grisso et al. (2002) reported field evaluations of load errors of 4% on a load basis and higher errors in loads less than 1,800 kg. Missotten et al. (1996) additionally reported larger load errors for small test plots. Krill (1996) reported load weight errors of less than 5% for corn and as high as 15% for soybeans for calibrated yield monitors. These studies observed smaller samples sizes of loads and did not observe complete field and season level yield monitor performance with yield monitor expectations for field and season accuracy primarily cited from manufacturer claims.

Characterizing the impact-based yield monitor performance across the full application spectrum will define the level of confidence yield data must be given when decision processes are driven by the yield monitor reported results. The objectives of this research was to characterize the performance of impact-based yield monitoring systems under consideration of different use cases for harvesting corn. The specific objectives were: 1) to determine grain tank load to load variability of the impact-based yield monitor, 2) to evaluate field level performance of the grain yield monitor, and 3) to evaluate field to field performance of a calibrated yield monitor.

MATERIALS AND METHODS

IMPACT-BASED YIELD MONITOR SYSTEM THEORY OF OPERATION

As previously described the impact-based yield measurement system consists of a plate instrumented with a load cell located at the top of the clean grain elevator and referred to commonly as the mass flow sensor. The mass flow sensor utilizes the discharge dynamics of the clean grain elevator by placement of the impact sensor in the path of grain as discharged from the paddles. The resulting force imparted on the impact plate by the grain is measured by the yield monitor system and a mathematical relationship of force to mass flow is used to estimate the grain mass flow rate. The mathematical relationship is developed from the calibration process and is designed to reduce the non-linear relationship of the measured force to measured mass (Myers, 1996).

The sensor system relies on the physics of grain discharging from the elevator to transfer the momentum of the grain to the impact plate. The resulting force and duration imparted by the grain onto the impact plate is equal to the product of the mass and change in velocity of the grain from before and after impacting the force sensor (Zhou and Liu, 2014). The change in velocity is only considered in the normal direction of the force sensor and is considered an ideal situation where the grain is assumed to act as a single particle. In actuality, specific particle velocity is a function of the elevator speed and grain particle position on the paddle with respect to the rotational point as the paddle rotates around the top of the elevator and adds to the complexity of mathematically modeling the grain impact process (Reinke et al., 2011).

Observing the process, two primary factors affect the impact plate-based system: the initial available energy of the grain as it leaves the elevator paddle and momentum transfer to the impact plate. The first factor is related to the mass of the grain and its exit velocity with the exit velocity being affected by several factors. The discharge velocity of the grain is influenced by the initial location of the grain particle on the paddle in reference to the pivot location and the frictional coefficient. The friction and initial position influences the generated tangential velocity of the grain as it is expelled from the paddle as a higher coefficient of friction slows the transition of the grain particle to the outer tip of the paddle, decreasing its final release position on the paddle and reducing the velocity. This creates a gradient of particle velocities based on the radial location of the grain particles on the paddles (Strubbe et al., 1996; Reinke et al., 2011). The grain pattern once expelled from the elevator varies with the paddle shape and paddle tip clearance with the shape of the discharge pattern affected by the volume of grain and paddle size (Strubbe et al., 1996). The shape of the paddles concentrate the grain flow towards the outer rotational radius of the paddle which are typically worn at the corners. The wear is best described by the permanent reduction in size of the paddle as the corners abrade from use and the permanent deformation of the paddle as the corners curl away from the direction of travel. The paddle tip clearance which is defined as the clearance from the outer tip of a paddle to the top of the elevator housing, influences the release point of the grain. As the tolerance gap increases, grain slips off of the paddle earlier in the ejection cycle as the paddle travels around the first 90° of the elevator top and changing the grain trajectory towards the impact plate. This reduces the velocity of the grain and modifies the impact angle of the grain to the force sensor. Additional wear to the top of the elevator and the deflector can modify the grain trajectory and interaction with the force sensor over time.

Momentum transfer is affected by grain density and coefficient of restitution (Reinke et al., 2011). The crop properties are an unknown factor to the force sensor when calibrated during normal harvest, requiring re-calibration to compensate for large changes. Previously demonstrated in a mathematical model applied to test stand data from the University of Kentucky Yield Monitor Test Stand, the surface frictional properties of grain increase with moisture content and momentum transfer decreases with the increasing moisture content (Reinke et al., 2011). This analysis used a regression approach to estimate the crop properties from simplified models, but indicates the type of change in force sensor response based on a modification of the crop properties. The study also indicated that if the crop properties could be estimated, a model may potentially be used to accurately estimate the grain mass flow across a wide range of crop variation. This emphasizes the need for calibrations when crop properties change to maintain accuracy and is typically recommended by yield monitor manufacturers to re-calibrate for large changes in moisture content and individual calibrations for each crop (i.e., corn, soybeans, wheat).

The yield monitor is calibrated to correct the mathematical relationship of force to mass flow accounting for the specific mechanical and crop specific variation of the harvester. The calibration process is completed by relating the accumulated measured force by the impact plate and the mass of grain harvested for the same time period. A single calibration point is created by initiating a calibration through a user interface to the yield monitoring system with an empty grain tank. The operator then harvests a set amount of grain, typically between 1,400 and 3,600 kg, at a consistent harvest speed. The consistent harvest speed attempts to produce a consistent mass flow rate. Once an acceptable mass of grain has been collected, the operator stops harvesting and completes the calibration process through the user interface. The grain is then offloaded onto a cart equipped with calibrated scales and the resulting weight is entered back into the yield monitor which updates the relationship between forces measured by the impact plate to grain mass. This process is ideally replicated at four or more different harvest speeds to produce a multi-point calibration that represents the operational flow range of the harvester for the specific crop.

METHODOLOGY FOR DYNAMIC IN-FIELD YIELD MONITOR ERROR ANALYSIS

The natural operating state of a yield monitor can only be achieved through field testing. The exposure to natural field variation that induces flow rate changes, crop characteristics, and field dynamics cannot be achieved in a test stand. The largest variation associated with field testing are caused by crop characteristics. In-field testing utilizes freshly harvested grain that has not been damaged or degraded from handling. The process of yield monitor evaluation for this study varies from ASABE Standards S579.1 (2012) with the focus of this study limited to load and accumulated mass accuracy. This approach is based on how yield monitor accuracy is perceived in actual practice differing from the standard that puts emphasis on characterizing the response to flow rate changes and limits testing to consistent crop that is not representative of typical harvest conditions. Field testing additionally allows the performance of the yield monitor to be quantified from a similar perspective of the producer. Data was collected on a load basis where the yield monitor load total was zeroed and grain was then harvested until a minimum of 1,500 kg was accumulated in the grain tank. The grain was then unloaded into a calibrated scale cart and the resulting cart weight and yield monitor reported weight recorded. This process produced a yield monitor estimated load weight and ground truth load weight and is referred to as a load and represents a single replicate in this study. A culmination of loads (replicates) from the same combine harvester, same yield monitor calibration, and collected on the same day is defined as a data set. Data was grouped in this manner to produce a detailed analysis of the yield monitor accuracy. Three specific metrics were used to evaluate the season long and field level performance of a calibrated yield monitor during corn harvest: (1) the load to load variability under consistent crop conditions, (2) mean field error, and (3) the effects of load size on load variability (table 1).

Data for this study was collected beginning in the fall of 2010 and was completed in the fall of 2015 on a total of 36 combines equipped with impact-based grain yield monitors located in Central Iowa with fields slopes not exceeding 5%. Combines were tested independently using full header widths of crop for all tests. The yield monitors were calibrated using in-field scale carts and were evaluated on a load basis utilizing the same scale cart that was used to complete the calibration. Individual datasets observed corn moisture content (MC) of less than 25%. The moisture sensor accuracy for the season long calibration was monitored on a daily basis by comparing grain samples to the reported moisture of a Dickey-john GAC® 2500-UGMA and adjustments were made to the yield monitor moisture calibration if deviated greater than 2 moisture points. During the field level calibration yield monitor tests, a minimum of 12 replicates (loads) were collected per data set. Yield monitor error was calculated using the formula shown in equation 1.

$$YM\ Error(\%)=\frac{(YM\ Weight-Scale\,Cart\,Weight)}{Scale\,Cart\,Weight}\times 100 \quad (1)$$

where

YM Error = calculated error of the yield monitor estimated weight (%),

YM Weight = the load weight as reported by the yield monitor,

Scale Cart Weight = the corresponding load weight as reported by the calibrated scale cart.

During the field level calibration evaluation, the yield monitor was calibrated and the corresponding data set was collected in the same field. This method evaluated the field mean and load to load variability, providing an optimum scenario for yield monitor performance as the yield monitor is calibrated under the same crop conditions that the evaluation was completed. The analysis was focused on yield monitor error and did not investigate the cross data set differences of moisture content and test weight. These factors are excluded from the analysis because the yield monitor was calibrated in the specific conditions to appropriately compensate for the crop conditions.

The season calibration evaluation began by performing a multipoint yield monitor calibration at the start of the season in the first harvested field. The analysis was completed on all data collected after the calibration was performed. This approach provided observations of the yield monitor drift

Table 1. Data set description for specific evaluations.

Evaluation	Season	Data Sets	Machines	Replicates	Definition
Field calibration	2010-2015	38	22	1376	Load to load variability and mean error
Season calibration	2015	22	1	651	Mean field error
Load size	2014-2015	24	13	804	Effects of load size on variability

once calibrated and was evaluated with considerations for crop moisture change. Average flow rates ranged between 8 and 30 kg s^{-1} with a mean of 18 kg s^{-1} for the loads included in the data set with moisture content ranging from 13% to 25% with a mean of 18%. The yield monitor was calibrated on 22 September 2015, at 22% moisture content with a multipoint calibration completed at approximately 7, 10, 14, 20, and 24 kg s^{-1} with the final data set harvested 19 October 2015. The flow rates of the calibrations were confirmed post-harvest to appropriately represent the operational flow range (fig. 1).

An analysis on load size to measured error variability was completed based on the assumption that increasing load size would decrease the load to load variability error as the effect of random error associated with the impact-based yield monitor would be reduced. The process for evaluating the variation across multiple data sets required that individual data sets be adjusted for the mean error of the data set referred to as calibration bias. Each data set had the calibration bias removed by subtracting the data set mean error from all load weight errors of the data set to produce a mean error of zero. The variability within a data set was not changed through this process so that all loads are comparable across data sets. Load weights ranged from 2 to 8 Mg and the maximum load size was limited by harvester storage capacity. Load weights were binned by 1 Mg increments and evaluations completed on the distribution of error.

SCALE CART CALIBRATION AND ACCURACY VALIDATION

Scale carts used for yield monitor calibration and performance evaluation were calibrated before the harvest season and verified for accuracy post the harvest season following the same process as the pre-season calibration. The scale cart calibrations were completed following the manufacturers recommended procedure using a certified truck scale to produce the ground truth weights. Validation of the scale cart calibrations were completed by starting from empty and filling the cart in 2,200 kg increments to at least 90% of the cart's capacity, recording the reported weight and the truck scale weight. Loads collected during yield monitor testing were typically captured in 2,200 to 4,000 kg increments with the step loads producing an adequate characterization of the scale cart accuracy in measuring the small step changes. The overall cart error is observed along with the error of the step changes (fig. 2). The step weight change error is determined for example by calculating the error of the increase in weight of a partially filled cart and the resulting change measured by the truck scale.

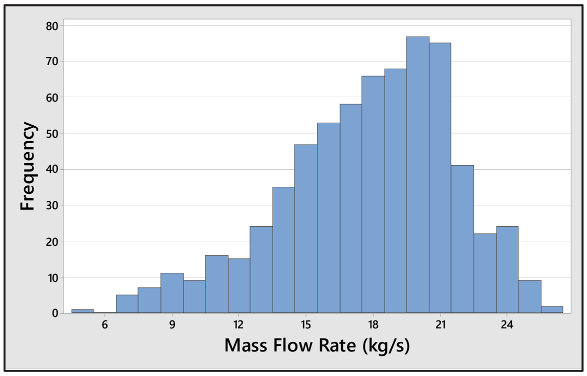

Figure 1. Mean mass flow rate for individual replicates for the season long single multipoint calibration study.

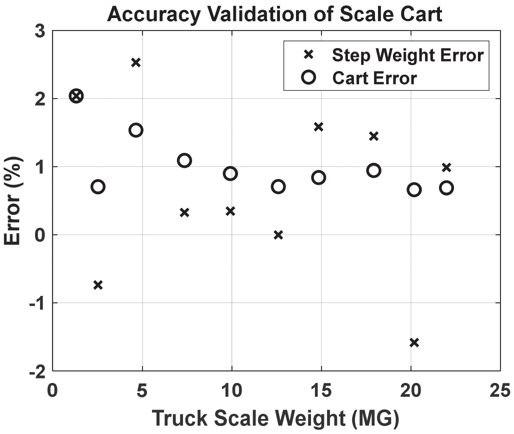

Figure 2. Scale cart accuracy for step increases in weight and total weight for pre-season validation.

RESULTS AND DISCUSSION

FIELD LEVEL YIELD MONITOR CALIBRATION PERFORMANCE

A calibrated yield monitor is expected to produce a normal distribution of error on a load basis with ideally a mean error of zero and any deviation of the mean from zero, being considered a bias in the calibration. The analysis was completed in two parts by first evaluating the mean error of individual yield monitors, and the second evaluating the load to load variability of a calibrated yield monitor.

Field level calibrations ideally compensate for the specific crop conditions and operational flow rates that induce error bias. Evaluating individual calibrations can help draw conclusions about expected accuracy when a specific calibration is completed. A total of 38 individual calibrations, each represented by a data set, were completed in this study with resulting field means ranging from -7% to 4.4%, combined mean of -0.5%, and a standard deviation of 2.1% for field means. Previous studies reported expected yield monitor mean absolute error of 0 to 4% (Missotten et al., 1996; Grisso et al., 2002). The variation in mean accuracy of the calibration indicates that regardless of the calibration there is an expected range for mean error of the yield monitor.

Considering that individual loads are part of a larger distribution of error with a mean and standard deviation, the calibration is made up of four loads that are drawn from the distribution when the calibration is created. This is considering the effects of random error associated with the impact-based mass flow sensor. Testing the hypothesis that a larger standard deviation indicates the probability of a larger bias, a regression analysis of mean error predicted by standard deviation was found to have no statistical significance on mean field error or absolute mean field error (table 2). This indicates that mean error at the field level is independent of the mass flow sensor variability.

Table 2. ANOVA results for mean calibration error by standard deviation.

Source	SS	DF	MS	F-Value	P-Value
Data set	0.00035	1	0.00035	0.72	0.401
Error	0.01726	36	0.00048	1.00	0.5

Observing the yield monitor error as a cumulative density function (fig. 3), nearly 70% of the data sets with unique calibrations resided within ±2.5% mean error. Considering each data set was subject to its own calibration, less than 5% of data set mean error resided outside of ±5% accuracy. This performance generally agrees with many manufacturer claims of accuracy, but was also evaluated under ideal conditions with the yield monitor accuracy tested under the same conditions as the calibration.

Individual load errors have been described in the range of 2% to 4% (Doerge, 1996), less than 5% (Krill, 1996), and greater than 10% for smaller loads (<1,800 kg). An investigation into the load-to-load error variability of a yield monitor was of interest for comparing the estimated yield of two individual loads for specific agronomic treatment evaluation. Knowing that load to load error variability exists, characterizing the variability can be used to create evaluation guidelines for individual load weights produced by a yield monitor. Variability of the yield monitor was best described by the standard deviation of load error distribution. The aggregated standard deviations were normally distributed with a mean of 3.3% and standard deviation of 1.2% (fig. 4). This describes the average expected variation within the 38 data sets and 1,376 loads reported within this study.

The resulting distribution of data set standard deviations by calibration was used to develop recommendations for comparing independent loads. Assuming that error was normally distributed for a single data set and mean error of the data set was considered negligible as comparison of two samples harvested by the same machine and yield monitor calibration would be subject to the same bias, a general recommendation was developed. Observing a single load, consider that the load is a sample from the population with a mean of $\bar{x}_1$ and standard deviation σ_1. The load error is a sample from a population, $\bar{x}_1 \pm 2 \cdot \sigma_1$ (95%), and the actual standard deviation of the specific yield monitor calibration is generally unknown to producers as this type of analysis is not completed by producers. Application of a prediction interval to the distribution of standard deviations produced in this study was used with the upper prediction interval tail to estimate the maximum expected standard deviation for yield monitors outside of this study. Application of a chi squared distribution properties to the predicted standard deviation for a single load produced an estimated yield difference requirement to determine if samples are statistically different. A range of confidence levels when applied to the highest yielding sample based on the chi squared distribution and utilizing the maximum level of the standard deviation prediction interval for the specified confidence level, produces a required yield difference to determine statistical difference between two independent yield samples (table 3). For example, to determine statistical difference between two separate loads or replicates at the 95% confidence level with the highest yielding sample at 12.5 Mg ha^{-1} (200 bu ac^{-1}) would require a difference of 1.95 Mg ha^{-1} (31 bu ac^{-1}).

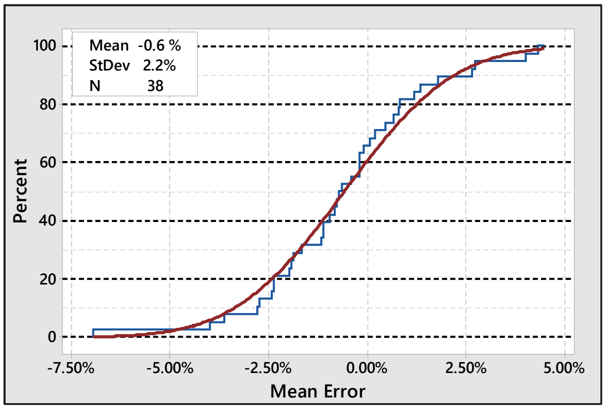

Figure 3. Cumulative density function for calibrated yield monitor error from individual combines.

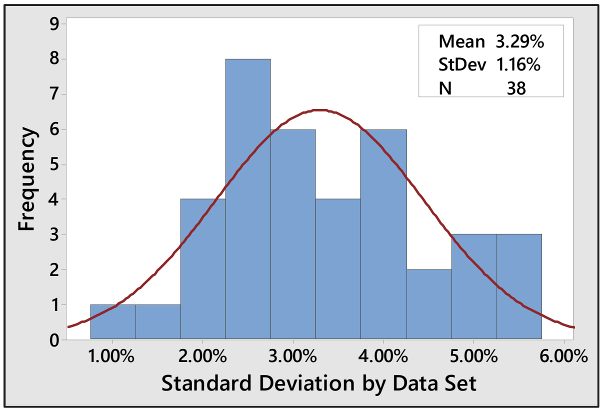

Figure 4. Distribution of standard deviation of yield monitor error for individual data sets.

The required differences appear large when considering higher yielding crops. A reduction in the required yield difference can be achieved by increasing the number of treatment replicates or loads to reduce the effects of the yield monitor load to load variability. Increasing the number of replicates to at least three would allow for the application of statistical tests when comparing the yield between hybrids and supports the recommendations of previous studies that suggest multiple replications for on farm agronomic studies to raise confidence in the use of yield monitor technologies in evaluating smaller yield differences (Nelson et al., 2015).

FIELD-TO-FIELD ACCURACY FROM FULL SEASON CORN HARVEST

The season-long study began with the calibration of the yield monitor with a multipoint calibration and was not re-

Table 3. Required yield difference between yield samples to determine from statistically different populations.

Confidence Level	Std. Dev. Upper Tail	Required Yield Difference
50%	4.0%	3.9%
68%	4.4%	6.2%
90%	5.2%	12.1%
95%	5.6%	15.5%
99%	6.4%	23.3%

calibrated for the remainder of the season. The total harvest observed 3,900 Mg (186,000 bu) with six specific fields harvested. The overall season error for the yield monitor based on total grain mass was 0.6% versus the calibrated scale cart. Daily performance of the yield monitor varied early in the season as moisture conditions ranged from 19.5% to 26.5% and became more consistent later in the season when operating below 22% moisture content and ranges observed within a field were reduced (table 4). Field A on 25 September 2015, observed a large increase in error due to a rain event while harvesting. This caused a change in moisture content of the grain and additionally applied a large amount of surface moisture to the grain that had adverse effects on the impact-based mass flow sensor. Field B produced statistically different mean error for the two dates associated with the field. Inspection of the flow ranges indicated that 28 September operated with a mean of 16 kg s^{-1}, 29 September operated with a mean flow rate of 10 kg s^{-1}. This was at the lower end of the manual calibration flow range and was reflected with a 5% shift in mean error for the day. The reduction in the grain mass flow rate was due to down corn from high winds produced overnight between the two harvest days causing the operators to reduce harvest speed to accommodate for the crop conditions.

Considering the results of the Field B data set error when analyzed by flow rate, an evaluation of load errors versus the mean mass flow rate for individual loads as reported by the yield monitor was conducted (fig. 5). Load weight error was observed to be dependent on mass flow rate with a large increase in error for loads with flow rates less than 10 kg s^{-1}. Recall that low flow calibration points were produced at approximately 7 and 10 kg s^{-1} to provide calibration coverage in the lower flow rate ranges. This behavior of accuracy at the fringes of the calibration ranges can be expected and has been observed by Burks et al. (2003).

Observations were made in relation to the calibration point flow rates and the accuracy of the specific flow ranges. The application of the calibration was unknown for a multipoint calibration, but focusing on specific regions, there was a distinct shift in mean load error when binning the loads by mean mass flow rate. Evaluating the mean load error by range (table 5), it was observed that the ranges had statistically different mean error by mass flow rate. No conclusions could be drawn if the error by flow range was influenced by the yield monitor calibration points specifically because of the unknown application method of the calibration, but it was distinctly observable that the flow rate ranges produced statistically different mean error.

Observing field mean errors for the entire harvest season, figure 6, there was a large difference from Field A to the remainder of the harvest. When considering the overall field mean error was 0.4%, Field A biased the overall average high for the remainder of the season and produced a statistically different mean error than the remaining fields. The final five fields produced an average load error of -2.5% with limited variation. The average moisture content of Field B through F were less than 20.5%, where Field A ranged from 19.5% to 25% moisture content. The overall performance of the yield monitor for the season was better than expected considering the calibration was completed in Field A and no adjustment to the calibration was made throughout the season as crop moisture changed.

Considering the large shift in field error from Field A to Field B, the relationship between load weight error and moisture content were observed (fig. 7). This was an expected variation due to the changes in crop properties induced by moisture content. Also note that the error greater than 10% observed in the evaluation of error by mass flow rate (fig. 5) was associated with high moisture content observed in figure 7. Below 20% moisture content, the

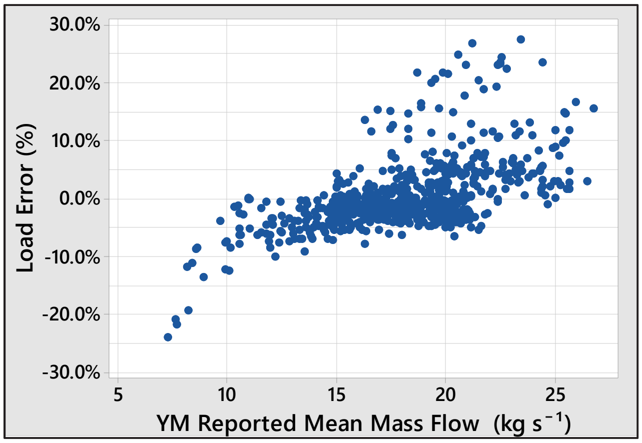

Figure 5. Load weight error versus average mass flow as reported by the yield monitor for the load period for seasonal evaluation.

Table 4. Daily performance of calibrated yield monitor.

Date	Field	Mean Error	Std. Dev. Error	Mean MC%	Loads	Grain Harvested (MT)
9/22/2015	A	2.5%	2.8%	21.1%	14	43.2
9/23/2015	A	5.4%	3.5%	19.5%	13	68.7
9/24/2015	A	6.1%	6.1%	21.3%	35	186.0
9/25/2015	A	17.6%	7.2%	25.1%	32	178.6
9/28/2015	A	9.3%	6.7%	24.9%	9	54.3
9/28/2015	B	-0.7%	1.7%	20.5%	53	325.0
9/29/2015	B	-5.9%	5.1%	19.5%	24	122.3
10/1/2015	A	2.9%	3.1%	22.3%	59	356.6
10/2/2015	A	2.9%	6.0%	22.6%	89	491.4
10/5/2015	C	-3.7%	1.7%	17.2%	23	134.6
10/5/2015	D	-4.8%	3.2%	18.5%	19	106.7
10/6/2015	D	-1.6%	1.5%	18.7%	70	447.7
10/7/2015	D	-3.2%	2.7%	18.3%	18	115.4
10/8/2015	D	-3.3%	6.9%	17.5%	19	113.8
10/9/2015	D	-3.8%	1.8%	17.1%	37	225.8
10/12/2015	E	-2.4%	1.8%	19.1%	27	171.1
10/13/2015	E	-1.7%	1.7%	18.9%	48	299.0
10/16/2015	E	-3.9%	5.9%	18.9%	9	55.6
10/16/2015	F	-4.7%	1.4%	16.8%	4	19.8
10/17/2015	F	-3.2%	1.5%	18.7%	65	265.8
10/19/2015	F	-2.4%	1.7%	15.6%	34	186.4

Table 5. Mean yield monitor error binned by mean flow rate ranges of corresponding loads.

Flow Range (kg s^{-1})	N	Mean Error	Group (95% CI)
<10	13	-13.1%	A
10-15	106	-3.7%	B
20-25	191	3.7%	C
25-20	375	-0.1%	D
>25	15	8.0%	E

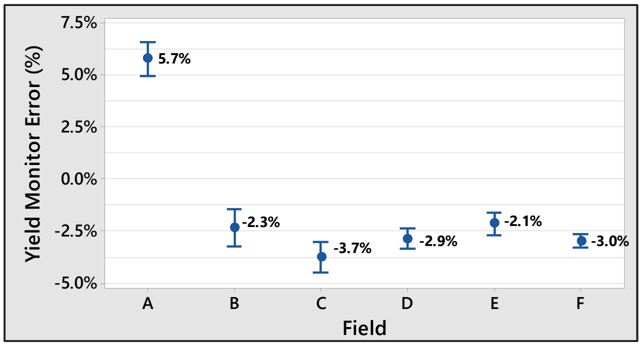

Figure 6. Confidence intervals (95%) on a field basis.

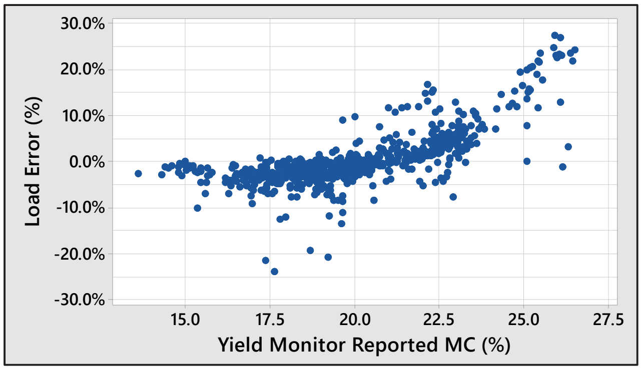

Figure 7. Load weight error vs. yield monitor reported grain moisture for seasonal evaluation.

influence of grain moisture on yield monitor accuracy per load was limited.

Differentiating the loads by moisture content ranges, loads with greater than 22.5% moisture produced a mean error greater than 8% (table 6) and were statistically different than the lower moisture ranges. Loads with average moisture content less than 20% had no statistical difference in load weight error and the 20% to 22.5% range showed to be statistically different than the 15% to 20% range. This indicated that the mass flow sensor adversely responded to moisture content greater than 20% and overestimated the accumulated grain mass. Average error of the yield monitor for loads less than 22.5% moisture content was -1.6% and was 8.0% for loads with a moisture content greater than 22.5%.

Table 6. Mean yield monitor error binned by moisture content (%).

Moisture Range (%)	N	Mean Error	Grouping		
<15	11	-1.5%	A	B	
15-17.5	87	-3.6%		B	
17.5-20	307	-2.7%		B	
20-22.5	160	2.0%	A		
>22.5	133	8.1%			C

The season performance of the yield monitor for a one time calibration performed within expectations for an impact-based yield monitor. The influence of mass flow rate on performance was larger than expected due to the range of flow rates encompassed by the calibration points. The effects of grain moisture agree with previous studies on the influence of crop properties and their interaction with the impact-based mass flow sensor

LOAD SIZE EFFECTS ON LOAD VARIATION

The hypothesis that larger load weights reduce the error variability of yield monitor reported load weights, assumed longer sustained flow rates reduce the influence of transitional flow rates that contribute to yield monitor error. These transitional flow rates were typically induced by entering and exiting crop and natural field variation. Larger loads also reduce the random error associated with the impact-based mass flow sensor and yield estimations.

Evaluating the variance by load size, a test for equal variances was completed to compare variances for load ranges binned in 2 Mg increments (table 7). Variances were found to be unequal between the 1-2 Mg versus 2-3 Mg and the 2-3 Mg versus 5-6 Mg load size ranges. Standard deviations ranged from 2.6% to 3.6% with no statistically significant decrease in variance for the larger load sizes. No reduction in variance was found for the data set observed by increasing load size. Previous studies indicated a reduction in the maximum errors for increased load size or harvested area from 5% to 3% harvesting wheat (Missotten et al., 1996).

CONCLUSIONS

Variability in the accuracy of the impact-based mass flow sensor was characterized on a load basis. The impact-based yield monitor produced a 3.3% mean standard deviation for load weights by data set. The daily standard deviation of load weight error for full season evaluation was 3.5% in comparison to the individual field calibrations. The similarities in the variation indicate that an appropriate characterization for the impact-based yield monitor was completed in this study.

Yield monitor mean error on a field level for accurately calibrated yield monitors can be expected to vary between ±5% error and ±2.5% error for 70% of calibrations based on results of this study. Recommendations for production agriculture-sized test plots were developed to define required yield differences for statistical confidence levels

Table 7. Resulting p-values for equal variance test for load weight error by load size ranges (P < 0.05 reject H_o of equal means).

Load Size Range	Load Size Range (Mg)						Std. Dev.	Load
(Mg)	2-3	3-4	4-5	5-6	6-7	7-8	Error	Count
1 - 2	0.01	0.70	0.31	0.18	0.41	0.53	3.1%	176
2 - 3	-	0.01	0.73	0.00	0.41	0.78	2.6%	356
3 - 4	-	-	0.23	0.34	0.29	0.44	3.2%	102
4 - 5	-	-	-	0.07	0.78	0.96	2.7%	41
5 - 6	-	-	-	-	0.08	0.21	3.6%	52
6 - 7	-	-	-	-	-	0.88	2.8%	59
7 - 8	-	-	-	-	-	-	2.7%	17

and it is recommended to use replicates if attempting to discern between smaller yield differences.

The full season evaluation of the yield monitor calibration confirmed that crop variation affects the impact-based yield monitor accuracy. Yield monitor accuracy did stabilize for grain moisture less than 20% in this study. The accuracy of the calibration was mass flow rate dependent, but no conclusions can be drawn about the quality of the calibration as its actual application to convert force measurement at the impact plate to mass flow is unknown. Operating in flow ranges at the fringe of the calibration ranges can be expected to reduce load weight accuracy as seen in this study where accuracy shifted by 4.8% in field B due to a 6 kg s^{-1} shift in average mass flow rate from 28 to 29 September. This study encompassed data sets of several magnitudes larger than previously reported in any yield monitor study and provides the most complete analysis of full season performance of a yield monitor.

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