Evaluation of yield sensors for site-specific management

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Evaluation of yield sensors for site-specific management

by

Selcuk Arslan

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in partial fulfillment of the requirements for the degree of

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ABSTRACT

The performance of an impact-based yield monitor was investigated via field and laboratory experiments. In another study, X-ray techniques were used to examine the potential use of x-rays for yield measurements of harvested crops. Field and laboratory experiments showed that proper yield sensor calibration is the most important factor to keep the error less than ±4% when individual grain tank loads are considered. Field and laboratory tests provided evidence of decreasing error with increasing harvest area. In field tests, the accuracy of yield monitors increased consistently when yield measurements were averaged over 15, 30, and 60 m long segments, respectively. In laboratory experiments, the fluctuations observed in instantaneous yield data suggested that yield signals should be averaged over 4 to 10 seconds to attain the accuracy found for individual grain tank loads. Therefore, the accuracy determined at the end of harvest strips, using a weigh wagon as a comparison reference, should not be considered as true accuracy for small area applications. Grain yield variations can have an impact on accuracy. The smallest error occurred at constant flow rates whereas yield monitor error increased when step changes and transient flow rates were induced using the laboratory test stand. Another factor affecting the accuracy of the yield monitor was the combine ground speed. Changing the ground speed, depending on yield variations, also increased the yield monitor error. The accuracy of a yield monitor then would change across a field due to spatial yield variability and changing combine ground speed. The yield sensor's response to sudden flow rate changes was quite satisfactory. X-ray techniques provided high accuracy in corn flow rate measurements showing repeatable correlation coefficients of 0.99 between gray scale values and mass flow rate ranging from 2 to 6 kg/s. It is possible to increase the dynamic range of flow rates by making proper arrangements in the test setup and using different algorithms.
CHAPTER 1. GENERAL INTRODUCTION

Introduction

Motivation for precision farming

The driving forces behind the precision farming management philosophy have been well expressed in the literature. Soil and yield variability on fields have been shown through soil and yield maps (Colvin, 1993; Everett and Pierce, 1996; Pierce et al., 1996; Pringle et al., 1993; Searcy et al., 1989). As an alternative to field-based average agricultural practices, managing soils depending on locally determined requirements within a field is proposed. According to this proposition, using various forms of application technologies can optimize the inputs (application rates of seeds, fertilizers, and chemicals) and the output (yield) in known sections of a field. Input requirements for a specific location would be determined based on the crop, soil, yield, and weather history. Managing agronomic fields based on their locally determined requirements should bring two benefits in general:

1. Optimization of yield throughout farm fields

Conventional farming techniques have long treated fields as homogeneous entities by using preadjusted farm equipment (such as planters and fertilizers) in agronomic fields. Composition of soils, however, varies from point to point, which may introduce a large range of spatial variability in any field. It follows that it might be more reasonable to treat a field as a collection of small cells, each cell being managed as a separate unit. As a consequence of managing each cell based on its locally identified requirements, the yield in a field could be optimized overall. The new technological applications (Global Positioning Systems, Geographic Information Systems, sensor technologies, etc.), more information on soil properties and plant growth, and tools such as variable rate applicators are anticipated to allow farmers to manage their fields spatially. This management philosophy has been deemed promising by researchers as a tool to accomplish optimum farming.
2. Reducing environmental contamination

Field-based application rates of agrochemicals can result in excessive chemical application to certain locations in fields. One unfortunate outcome of chemical application has been ground water contamination through chemical leaching and surface pollution, which can threaten the environment and public health. Spatially variable farm management has the potential to reduce these threats by more accurate employment of the chemicals to meet the needs of specific locations.

Precision farming today is based on techniques such as positioning, soil sampling and yield monitoring, soil and yield mapping, and variable rate application. Generation of large data sets can give a detailed description of a field. Hardware and software, currently available in the market for the end users, can be used to obtain soil, yield, and application maps, though the dependability of these products is debatable at the current time. It has been noted that more advancement is needed in agronomic knowledge in order to relate the cause and effects in grain yield (Stafford, 1996).

Need for continuous yield monitoring

The key factors for precision farming to become reality are the knowledge and the technology to manage soils in smaller areas. Knowledge is necessary to relate cause and effects that determine the final product (yield) while some form of technology is required to obtain sufficient data for analyses, interpretation, and decision making. Yield monitoring is an essential element in generating the yield maps that display grain yield variability. Accurate determination of the yield in small cells would help identify the locations that need specific treatments. Yield maps do not explain why yield variation occurs, however they display where certain yield patterns take place. The ability to pinpoint locations in which yield can be improved and/or chemical inputs can be reduced would be one of the key factors in achieving optimum production farming.

In order to generate yield maps, fields are divided into small areas or management zones that are constructed depending on soil types. The amount of grain coming from each cell or zone needs to be
A grain flow sensor, usually mounted at the exit of the clean grain elevator of a combine, measures or estimates the mass flow rate of the crop continuously. Then the grain flow data are processed, usually with yield mapping software, and the grain yield is determined corresponding to data recorded previously. The yield is tagged with position information to determine the location of the measured yield in a field. One or more data points are used to determine the average grain yield in each cell. An accurate yield map is crucial as it provides valuable information on the determination of application rates for the following season(s) when the yield data are incorporated with the soil, crop, and weather data and factors such as topography and past management practices.

**Problem statement**

Several factors make accurate continuous flow rate measurements challenging: one of the most important issues is maintaining high accuracy over a large range of flow rates stemming from spatial yield variability. Achieving high accuracy over a wide range of flow rates requires current yield sensors to be calibrated at different yield levels or flow rates. Calibration is done using a range of flow rates that is likely to be encountered during the harvest and provides best accuracy levels for the anticipated flow range. Dependency on calibration makes the use of a yield monitor prone to errors (Doerge, 1997; Ambuel, 1995). Another consideration is the dependence of grain flow measurements on moisture content values. Varying moisture makes flow sensing susceptible to errors, too. When using volumetric flow meters, converting the volume flow rate to mass flow rate requires incorporation of the changes in crop density. This conversion introduces the error existing in moisture readings in mass flow rate values (Birrell et al., 1996). Kernel density changes have implications on impact based flow sensors as well: impact characteristics of grain are influenced by density changes. One other factor that affects the accuracy (of impact based flow sensors) is that the sensor may change its sensitivity to the force being applied due to coating caused by the accumulation of moisture, dust, and weed sap on the sensing element. The sensing surface of the flow sensor thus
needs to be cleaned occasionally to avoid coating. Strubbe et al. (1996) conducted a study regarding
the effect of grain flow profile characteristics on the accuracy of momentum-based sensors. They
demonstrated that the grain flow profile prior to impact, and hence mass flow readings, were
influenced by field slope variations and the properties and composition of grain.

Making accurate yield measurements has been a concern for yield monitor manufacturers,
researchers, and farmers. In early studies, attention had been directed towards large-scale accuracies of
continuous grain yield sensors. Usually, focus was largely on the overall accuracy of yield monitors over
the length of the harvest strips. Strong agreement between commercial yield monitors and electronic
scales or weigh wagons in terms of accumulated grain weight measured at the end of strips were
considered acceptable.

Advertised accuracies of yield sensors vary within the range of 0.5 to 4% (Mangold, 1996).
Research, however, suggested that reported accuracies were valid on a field basis or on long strips.
According to Missotten et al. (1996), error increases with decreasing harvested area. They found 5%
accuracy on 20x20 m² cells. When cutting width measurement errors and speed sensor errors were
incorporated, the overall error increased to 7.5% on those 400 m² grids. Lamb et al. (1994), using a
plot combine, found ± 25% accuracy over 15.2 m (~50 ft) sections. Doerge (1997) found ± 10%
accuracy for accumulated grain mass over 1800 kg and ± 25% accuracy for masses less than 1800 kg.
He also concluded that moisture measurements and yield estimations are not reliable for grain having
moisture content greater than 25%.

Reduction in the accuracy of a yield monitor over short distances may indicate that we are not
determining the correct amount of yield obtained from each block for yield mapping. This in turn
makes it difficult to determine the proper amount of inputs to be applied and output obtained from
each site. As of 1999, there was no commercially available yield monitor in the market whose
accuracy has been reported based on various grid sizes. The importance of making accurate yield
measurements needs to be recognized since there is a potential for misinterpretation of the cause and
effects of grain yield variability.

Consequently, for yield sensors to find routine implementation in site-specific farm
management, they should be capable of sustaining high accuracy regardless of yield, moisture content
and field slope variations even over relatively small areas without requiring operator interventions
such as calibration and sensor cleaning. This dissertation relates to the research projects undertaken
to explore the performance of yield sensors through field and laboratory experiments. It also presents
a novel x-ray technique for grain flow rate measurements.

Objectives

The goals of this dissertation are to present the findings of the field and laboratory
experiments designed to gain more understanding on accurate grain yield measurements for yield
mapping. Information was sought on the best use of a commercial yield monitor for spatially variable
farm management. The specific objectives of the laboratory and field tests were as follows:

Field experiments

- determine the accuracy of yield measurements as affected by cell sizes
- observe the response of a combine to instantaneous grain flow rate changes
- evaluate the effect of varying ground speed on yield measurements
- reach conclusions on yield mapping resolution

Laboratory tests

- find out the important parameters in the calibration procedure affecting accuracy
- determine the accuracy of a yield sensor on a test stand
- investigate the use of x-ray techniques for continuous grain flow rate measurements
Dissertation Organization

The entire dissertation contains six chapters. The general introduction contains a general literature review following the dissertation organization section. Continuous grain yield monitors, grain yield measurements, and mapping experiences are introduced in the literature review. Chapters 2 through 5 were written in the paper format as they were published or proposed for publication.

Chapter 2 was published as a technical note in the Journal of Applied Engineering in Agriculture. This chapter is devoted to the laboratory test stand that was built to test the performance of a commercial yield monitor. The operation of the test stand is explained and initial test results found following the completion of the test stand are presented.

Chapter 3 has been accepted for publication in the Journal of Applied Engineering in Agriculture. It addresses the results obtained from the laboratory test stand. The accuracy and the dynamic response of the yield monitor are compared to an electronic scale under various operating conditions. Effects of calibration on the yield monitor's accuracy are discussed.

Chapter 4 has been submitted for publication in the Journal of Precision Agriculture. This chapter presents the findings obtained from field studies conducted in the 1996 and 1997 harvest seasons. Field studies relate to the performance evaluation of the yield sensors as they were compared to electronic scales. The impact of varying ground speed and the effect of combine dynamics on the overall yield mapping accuracy have been evaluated.

Chapter 5 has been submitted for publication in the Computers and Electronics in Agriculture. This chapter presents the use of x-ray techniques for continuous grain yield monitoring. Flow rate measurements were done and the dependence of mass flow rate on grain moisture content was investigated.

Chapters 2 to 5 contain an abstract, introduction, materials and methods, results and discussion, and conclusion. At the end of each chapter are the references for the corresponding study. The final chapter summarizes and discusses the overall findings of the previous chapters.
Literature Review

Major research areas in precision farming

Precision farming operations can be considered a cycle (Stafford, 1996). According to this, there are three major phases in precision farming. These are data gathering, data processing, and application. Each stage is presented shortly below:

1. Data collection

Soil property and nutrient measurements, yield measurement, and position determination take place in this step. The necessary information for identifying the spatial soil properties and grain yield variation is acquired. Continuous yield monitoring (which is the emphasis of this dissertation) requires a yield sensor, a moisture sensor, and a positioning system (usually a Global Positioning System with a differential correction) for yield data collection.

2. Data processing (data analysis), interpretation and decision making

Knowledge is essential to translate information about specific locations to actions or choices. Decision support systems are used to determine the application rates that are to be varied as a function of location in a field. The ultimate goal of these steps are to make prescriptions for variable rate applications depending on the past and present status of the soil, yield, and weather. Geographic Information Systems (GIS) are powerful tools for gathering, storing, and processing the data as well as presenting the results in various formats such as tables and graphics (Holлист et al., 1996).

3. Variable rate application

Predetermined rates of inputs can be applied to specific locations with variable rate applicators. Planters, seeding machines, fertilizers, chemical applicators, and irrigation equipment are currently available in the market, which are capable of varying the application rates on-the-go.

It was stated that a farmer could start the precision agriculture applications at any stage of the precision farming cycle (Stafford, 1997). However, several years of data are needed to observe the yield trends in a particular field. The yield trends may give valuable information to predict grain yield.
The philosophy of precision agriculture is easy to comprehend; nonetheless, all three phases of precision farming have their own difficulties in practice. For instance, reliable on-the-go data collection for soil parameters has been a considerable problem rather than being a routine procedure to date. Intensive soil sampling is hard work and time consuming because of the lack of reliable equipment for continuous measurements. Except for yield sensing, the collected samples require laboratory analysis in most cases for successful implementation of site-specific management since automated collection of soil, crop, and pest data on a fine spatial resolution has not been accomplished (Sudduth et al., 1997). Some researchers expressed doubts on the dependability of continuous yield data for small area applications. Not only the yield sensors, but the combine itself is a major source of error in grain yield measurements if the yield is measured after the grain is processed through the combine. According to reported research results and talks with leading farmers, the value of prescription farming is evident, albeit the influence of many variables (soil structure and texture, nutrients, topography, pH, weed infestations, drainage, compaction, past management practices, and weather conditions) on yield under different conditions and farming practices has not yet been understood. Future experiences with spatial yield variability and its causes, and the advances in technological applications should make farmers better farm managers.

Global Positioning Systems (GPS)

Ambuel et al. (1991) described a satellite based positioning system for farm equipment. The system employed satellite signals in order to determine the location of the equipment on which a receiver is mounted. The system consisted of a fixed station and a mobile station. Both stations have a receiver, a modem, radio, and a computer. A data logger also was a part of the mobile part of the system to record the performance of the agricultural equipment in addition to position information. The goal of the system was to determine the equipment performance as a function of the position of the equipment in the field.
Both receivers tracked the same satellites at the same time. The distances between the satellites and the receivers are calculated by multiplying the time of arrival of the signal and the speed of light. The position calculated for the fixed receiver is compared to its known position and the difference, error, is sent to the moving receiver. The moving receiver uses this error to find its precise position.

Lange (1996) evaluated the accuracy of differential GPS for precision agriculture applications. Lange states that the accuracy of base stations can be in the one meter range. The base station should be within 50 km of the moving receiver in order to obtain centimeter level accuracy. For applications that require accuracy within a meter, high quality code based differential GPS receivers are needed. It was also noted that carrier phase differential GPS should be employed if better accuracy is needed (10 cm or better), for guidance of a spray vehicle, for instance.

O’Conner et al. (1996) developed a system to automatically guide a tractor using GPS. Using one additional sensor (a steering potentiometer) they accomplished guidance of a tractor along straight rows “very accurately”. They found less than 2.5 cm standard deviation for the lateral position in each of the 8 line tracking tests they conducted.

Saunders et al. (1996) suggested that 0.2 to 20 m resolution was required in all areas of the field for precision farming.

**Grain yield sensors**

Numerous principles have been employed in an attempt to measure grain yield continuously during harvest. Sensors that were developed include both mass flow rate and volumetric flow rate sensors. Volume-based measurements are done using paddle wheel sensors or infrared sensors, which were put on the market as commercial products prior to 1997. Light Emitting Diodes (LED), a piezo-film based sensor, and an ultrasonic sensor also have been used; but, these sensors have not been developed to the point of commercialization. Mass flow sensors available in the market include impact plates (strain-gages, change of momentum plates, and potentiometers), nuclear devices (gamma ray
sensor), and load cells on conveyor belts (for potatoes). Researchers also developed a capacitive sensor and a triangular elevator. Impact based sensors are most common in the US whereas in Europe, nuclear (gamma ray) sensors have also been used for several years. Description of each product is as follows:

**Nuclear Sensor (Gamma Ray):** The system consists of a gamma ray emitter, a detector, and a display unit. The grain flows through the measuring gap between the emitter and detector. Some of the exposed energy is absorbed and hence reduced by the grain as it flows through the sensing volume. Grain flow is related to unabsorbed energy and displayed as tons per hour and hectare. The accuracy of this device is reported to be ± 0.5% (Massey-Ferguson, 1993).

**Impact-based Sensors:** Strain-gage load cells, weigh pads (platform scales), and potentiometer load cells use the same principle in determining the mass flow rate of the products. These sensors measure the force of grain exerted on the sensing device. Accuracy may vary from 0.5 to 4% using impact-based yield sensors (Mangold, 1996).

**Change of Momentum Plate:** A curved plate is mounted at the exit of the clean grain elevator. Friction and impact forces change the direction of the grain on the curved plate. The momentum of grain changes as the direction of flowing material is forced to change. Difference in the average material speed is maintained constant between the inlet and outlet of the sensor. Then, it follows that the mass flow rate is directly proportional to the force measured by a force transducer attached to the curved plate (Vansichen and De Baerdemaeker, 1991).

**Capacitive Sensor:** Dielectric constant of air/material mixture increases with increasing material concentration in a transport tube. The concentration of the material is determined by using capacitor plates around the transport tube. This method is claimed to be non-intrusive and insensitive to transmitted vibration. Calibration depends on the material being measured and varies with material distribution within the sensor, Stafford et al. (1991).

**Triangular Elevator:** Howard et al. (1993) designed and installed a triangular elevator on a commercial combine. The triangular elevator receives the grain at the lower boot position and elevates
the grain. Moving around the top rear boot, the grain changes direction and travels horizontally towards the front discharge of the elevator. Weight measurement is done as the grain is moved horizontally across the top leg of the elevator. Grain is discharged at the front of the elevator into the standard bubble auger. Installation of the elevator into the grain tank reduced the grain tank capacity less than $0.5 \text{ m}^3$.

According to the authors, ± 0.5% accuracy was achieved for three crops.

**Paddle Wheel Sensor:** The sensor consists of six paddle wheels. Paddles rotate when the grain accumulates and reaches a certain height determined by a level sensor. When the level of the grain reaches the level sensor, a relay box is activated by a signal sent from the level sensor, and the relay box engages an electromagnetic clutch which rotates the paddles. In order to find the volumetric grain flow rate, the number of revolutions per unit time was multiplied by the volume of the paddle wheel. To convert volumetric flow rate to mass flow rate, volumetric flow rate is multiplied by the density of the grain, which is determined by the grain moisture sensor. The accuracy is claimed to be within ± 1%.

**Infrared Sensor:** The volume of grain on paddles of the clean grain elevator is measured using this technique. The amount of light that is detected is used as a measure of grain on paddles. This sensor is mounted on the clean grain elevator rather than at the exit of the elevator. The accuracy of this system is reported to be ± 2 to 3% (Mangold, 1996).

**Belt Conveyors:** Belt conveyors with load cells were tested primarily for potatoes and sugar beets. They could be used for onions, tomatoes, and others using conveyor belts in the harvesters. The accuracy is claimed to be ± 2% by using belt conveyors (Hollist et al., 1996).

**Ultrasonic Sensor:** An ultrasonic sensor was mounted above the combine bin (Klemme et al., 1992). The sensor determines the depth or the change of depth of grain in the grain tank. Change of depth is used to calculate the change of volume of grain over a traveled distance. The tests were done in 1991 and "acceptable accuracies" were claimed. In order to determine the topography of the grain surface in grain tank it was suggested that more extensive ultrasonic signals be used.
Piezo-film Based Impact Sensor: A sensor developed from piezo-film strips (high polar Poly-Vinylidene Film (PVDF)) was mounted under combine sieves. The impact of individual kernels is recorded as a measure of grain flow rate. The sensor sampled a portion of the grain from the sieve. Average accuracy was about 4.5% in lab. In field tests, relatively large measurement errors were found (Borgelt, 1993).

Permanenent Magnet Motor: A 12 VDC permanent magnet motor was used to drive a combine clean grain tank filling auger. The motor is equipped with a shunt in the power line. The current which drives the permanent magnet motor is related to the voltage across the shunt. Measured voltage was found to be linearly related to the quantity of grain in the clean grain elevator.

LEDs (Light Emitting Diodes): A strip of electronic sensors was mounted in the combine grain bin. As the grain level rises or falls, the sensors send signals to Light Emitting Diodes which show the height of the grain at each level. The volume of the grain is then estimated. This system is not developed specifically for yield monitoring. However, it could be used for this purpose, according to Borgelt (1993). The measuring system could be equipped with 1, 4, 8, or 16 sensors.

Feedrate Sensors: Combine feed rate sensors used the torque required to drive the feeder conveyor as an indicator for the material feed rate (Schueller et al., 1985). Engine speed, auger torque, clean grain auger torque, and air pressure in the cleaning area were also used in an attempt to determine the feed rate. However, these indicators were not successful as an indicator for feed rate.

Yield monitoring and yield mapping experiences

Ambuel (1995) suggested that the yield measurement equipment as they are used commercially pose disadvantages. According to Ambuel, “The combine represents an even larger constraint to implementation of a well designed prescription farming system than does the equipment for the application of fertilizers, seeds and chemicals.” Three major problems were mentioned with using a combine in the yield monitoring process:
1. The harvest of multiple rows of grain makes it either difficult or impossible to employ variable rate application as proposed in prescription farming.

2. The mixing or diffusion from field sections of higher grain yields to sections of lower grain yields smoothes out the peaks and valleys before grain enters the grain tank. The grain that has been mixed reduces the accuracy of the yield mapping.

3. Time delay introduces error, though not as significant as the first two problems, according to Ambuel. The author also suggested that the calibration process makes yield sensors susceptible to errors.

In a study conducted by Auernhammer et al. (1993), yield was measured on combine harvesters. The authors used two measuring systems available in 1993 in Germany. The measuring systems were based on volume measurements (YIELD-O-METER) and on gamma radiation (DATAVISION FLOWCONTROL). These devices were installed at the end of the grain elevator. They carried out a two-year experiment to determine the practical use of the yield monitors. The purpose of the study was to test the reliability and accuracy and to determine the causes of measurement errors.

The calibration of the yield monitors was done at the beginning of each working day and after each change of field. In the second year of the data acquisition they recalibrated the volume measurement based device after each loading. This was done to investigate the effects of the calibration on measurements.

Using two combine harvesters, 280 grain tank loads were harvested in two years. Neither device malfunctioned during the two years, according to the researchers. Functional reliability of the devices was found to be excellent by the authors. The accuracy for each system was almost identical. However, the yield-o-meter that was based on volumetric measurements required numerous calibrations. When using this system, grain density also had to be determined.

Birrell et al. (1996) conducted a study for a comparison of yield monitors and mapping techniques. The researchers assert that a model of grain flow is needed in order to relate the flowrate
measured at the grain bin to the flow of grain at the combine head. It was also mentioned that a first order system with a time lag would be sufficient since the accuracy of the sensors probably does not warrant the use of a higher order model even though the actual dynamics of the combine could be of a higher order.

Colvin (1990) designed a weighing system and added a grain moisture measurement device to a small commercial combine. Converting the combine to a plot combine did not require major modifications, according to Colvin. Two weigh bars, attached beneath the clean grain auger, support the weighing tank. A continuous flow moisture meter was installed in the weighing tank. A hydraulic circuit, fed by the combine steering system, opens and closes the door of the weighing tank. When the weighing tank is full, the operator in the cab reads grain weight and moisture. The moisture is recorded manually by the operator. After the read-outs are made, the door of the weighing tank is opened hydraulically and the sample is released to the main grain tank. Colvin states that the moisture meter worked well for both corn and soybeans, but other crops were not tested. Uneven ground was considered the only problem in the experiments. Even though side slopes required the operator to be careful, no major drawbacks were encountered which might affect the accuracy of the readings. The system dramatically reduced the useable volume of the combine's clean grain tank.

Colvin et al. (1995) conducted experiments to compare yield between commercial yield monitors and scales in small areas. They concluded that the stop-and-go method was very time consuming for harvesting transects across fields. They suggested that continuous yield monitoring should be applied to all parts of the field. According to Colvin et al. (1995), “Work by the authors to date has not shown a satisfactory method of taking the signal from at least one commercial yield monitor and turning it into a set of data points that correlate well with the samples taken with the stop-and-go method.” The researchers could not get a good correlation between the yields from a commercial yield monitor and the yields determined with the stop-and-go method. “The question of
data processing both for actual yield level and for trying the proper position to a yield remains unanswered."

Lamb et al. (1994) emphasized the difficulties of continuous grain yield monitoring as follows:

The idea of grain yield measurement sounds easy. Just hook a sensor to the combine, interface that with a computer and locating system and off you go. As with all good ideas there are some perils (problems, pearls) which need to be taken into account and dealt with to make the best use of this technology. (p. 87)

The most important issues were considered to be the resolution and time lags by Lamb et al. (1995). The experiments they carried out on 15 m (50 ft) segments using a combine equipped with a grain yield sensor showed that the yield sensor over-estimated the grain yield for the yields between 5.0 and 9.0 t/ha. They also found that the yield sensor underestimated the yields greater than 9.0 t/ha. The authors stated a need for an increase in accuracy and resolution.

Perez-Munoz and Colvin (1996) concluded that the instantaneous yield measured with the Yield Monitor 2000 exhibited good results for 100 m strips. The yield monitor was considered to be a proper device as a commercial product. However, the authors suggest that the signal obtained with the yield monitor required further conditioning for yield mapping applications. Ramp up and decay times in the beginning and end of the strips were attributed as problems to be resolved along with the time delay associated with combine dynamics. Tests on 20 m segments did not provide a good basis for determining the accuracy of the yield monitor because of the time delays.

Schueller et al. (1985) conducted experiments on grain combine feed rate sensors. They utilized the torque needed to drive the feeder conveyor as an indicator of the material feed rate. Variations in readings were encountered because of the changing crop conditions and the interactions between crop and machine. The correlation coefficient between the average feeder torque and the total feed rate was found as 0.789.
They also used engine speed as another means of indication for material feed rate. The correlation was 0.714 between the engine speed drop and feed rate, and was 0.794 between the engine speed and the feeder torque. Several other methods were also discussed for feed rate determination. Methods found to be unsuccessful included sensors for auger torque, clean grain auger torque, air pressure in the cleaning area, and the flow of grain into the tank.

Searcy et al. (1989) instrumented an Allis-Chalmers N6 combine with a grain flow meter and position determination equipment. They developed grain yield maps showing the variations in the field as a function of the position. In order to produce the maps, they smoothed the position and grain flow rate data and reconstructed the yield.

A grain flow meter was used on the discharge side of the grain tank filling auger for measurements. An arithmetic averaging based filtering was employed for smoothing the flow rate data. They gathered the grain flow rate data based on location information from a microwave location system. They interpolated the grain flow rate data and the location data that corresponded to 1.35 m interval along the field.

To construct the yield maps, 6.1x6.0 m blocks were used. The average of the values falling inside the area was represented as the average yield in each block. The authors noted that visual observations of grain yield in the field were close to those of the yield maps. Nevertheless, there were also differences between the measured yield and manually taken samples. The total grain yield measured was found to be 7.1% less than the yield suggested by manual sampling. According to the authors, the major cause for this was the errors in estimating the grain yield by the grain flow model. They assert that nonlinearities, dynamic effects and positioning errors might have contributed the errors.

Stafford et al. (1991) studied grain yield variation. They discussed flow sensors available in the market by 1991. According to the authors, mass flow sensors could be divided into two distinct types: true mass flow meters and inferential mass flow meters. True mass flow meters determine the mass flow of solids through the instrument while inferential mass flow meters measure both the instantaneous
concentration and the velocity of the flow and then determine the mass flow by combining these two parameters.

A nuclear sensor (gamma source and a detector) was used to determine the grain flow in a combine. Stafford et al. (1991) also used a capacitive sensor for the yield measurements and compared the two techniques. The capacitance technique depends on the dielectric constant of the air/material mixture in the tube which is used for transportation of the material. The dielectric constant changes due to the variations in the concentration of the material in the tube. This allows calculation of the amount of material passing through the transport system. However, the measurements are moisture dependent, according to the authors.

Stafford et al. (1991) used a PC-based GIS for the necessary manipulations of the yield data. The position of the combine across the field was determined by dead reckoning. The width of the blocks was taken as the actual measured cut widths of the combine. The length of the blocks varied depending on the fixed weight [295 N or 590 N (66 lbwt or 132 lbwt)] of grain which entered the holding tank.

The yield range was found to be about 1.0-7.2 t/ha with a mean yield of 5.03 t/ha in the second year of the measurements. Both nuclear and capacitive methods were found to be satisfactory. The nuclear sensor was reliable and calibration for this device was not dependent on the grain type. The capacitive sensor was also found to be reliable. However, calibration was needed for different types of grain. It was also sensitive to the cross-sectional distribution of grain in the sensing volume. Because of its simplicity, the authors claim that the capacitive sensor could be developed into a commercial sensor.

Stafford (1996) stated that the advance of precision agriculture was rapid and was due to easy access to positioning systems. According to Stafford, the technology side of precision agriculture leads the agronomic side. Yield variation has little significance on a distance less than 15-20 m. Stafford concluded that sections of 20 to 25 m were more realistic for resolution.

Strubbe et al. (1996) expressed that the best location for yield sensors seem to be the exit of the clean grain elevator. The authors determined, however, that there were problems with the
granular flow patterns at the exit of the clean grain elevator. It was suggested that crop condition, field conditions, grain yield, and straw yield may present considerable variability even in small grids. Thus, the influence of these factors needs to be determined in order to measure grain flow rate reliably on a combine, according to the authors.

Stott et al. (1993) used an instrumented combine for yield mapping. Objectives of the study were to develop a system to collect and analyze yield data and to develop yield maps. They used a combine harvester, a data acquisition system, a grain flow meter, a grain moisture monitor, and a position determination system in order to collect and analyze the data. The yield was found by using the following equation:

\[
Yield = \frac{\text{Grain Flow}}{(\text{Velocity} \times \text{Cutting Width})}
\]  

In the above equation, grain flow was determined from the yield monitor, velocity was determined from the positioning system, and the cut of width was taken as the width of eight rows of corn.

The accuracy of the yield monitor was found to be within ± 1%. The authors found that transport delay was independent of the averaging routine. A second-order critically damped system was determined to model the flow rate through the combine best. Fourth-order and 10 second moving averaging was the best for the yield maps for approximating the corn yield.

Vansichen and De Baerdemaeker (1991) measured wheat yield continuously on a combine. They calculated the flow rate by using the following expression:

\[
FR_{m}(t) = YI(x,y,t) \times AWI \times SP(t)
\]  

where \(FR_{m}(t)\) is grain flow rate at the combine head, \(YI(x,y)\) location dependent yield, \(AWI\) is the actual cutting width, and \(SP(t)\) is the ground speed of the combine. The authors state that the combine acts as a
dynamic system with respect to the grain flow. FR\textsubscript{out}, grain transported to the grain tank, is a function of FR\textsubscript{in}, flow rate at the head. This relationship was expressed as a function in the Laplace domain:

\[ L[FR_{out}(s)] = G(s) L[FR_{in}(s)] \]  

(3)

Using Equation 3, and by measuring yield at the grain tank, ground speed of the combine, actual cutting width, and the position of the combine as a function of time, yield as function of position in the field \( Y_l(x,y) \) can be found.

In this research, a flow rate sensor was used to measure yield which is based on the change of momentum when a change in direction is imposed on the material. The force imposed by the grain is used as a measure of the mass of grain at the time of measurement.

The researchers used an ultrasonic distance transducer to determine the actual cutting width. Travel speed was measured by using a microwave radar. They found that for a combine equipped with a 4.57 m header, the actual cutting width was generally about 4.23 m. Accuracy for the speed sensor was claimed to be about 2-2.5% when integrating over 4 m long distances. The authors warn that because of the errors of the sensors used for cutting width, speed, and yield measurements errors accumulate in the yield calculation. Time delay for grain to be transported from combine head to the grain tank was found to vary between 13.25 s and 14.25 s.

References


CHAPTER 2. LABORATORY TEST STAND FOR COMBINE GRAIN YIELD MONITORS

A technical note published in the Applied Engineering in Agriculture\textsuperscript{1}

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ABSTRACT

A laboratory test stand was constructed to compare the accuracy of a yield monitor to an electronic scale. The clean grain auger, clean grain elevator, and the grain bin filling auger from a combine were used to simulate the grain (corn) flow in the laboratory. Strong correlation was found between the yield monitor and the electronic scale with $R^2=0.99$ following the calibration of the yield monitor under laboratory conditions. Duration of each test run and the range of flow rates incorporated into the calibration procedure seemed to be significant factors in obtaining good accuracy for the yield monitor. Longer runs and high grain flow rates enhanced the agreement between the electronic scale and the yield monitor.

1. INTRODUCTION

Precision agriculture has received much attention in recent years. Accurate yield monitoring for yield mapping has also been the focus of many researchers. Much of the research has been directed to field experiments using commercially available yield monitors (Birrell et al., 1996; Auernhammer et al., 1993; Stafford et al., 1991; Vansichen et al., 1991). Experiments were also conducted to test the accuracy of the yield monitors (Missotten et al., 1996; Perez-Munoz and Colvin, 1996; Sanaei and Yule, 1996). In addition to the field and laboratory research conducted

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with commercially produced yield monitors, there is also much interest in developing yield monitors at universities, research centers, and in the agricultural industry.

2. MATERIALS AND METHODS

2.1. MATERIALS

2.1.1. Description of the test stand

A clean grain auger, clean grain elevator, and grain tank filling auger were used to simulate the clean grain flow from a combine. Parts from a John Deere 4420* (JD 4420) combine were used to construct the test unit (fig. 2.1). The clean grain elevator was extended by 0.85 m (2.8 ft) to create space under the filling auger for the scale. Grain flow data, combine ground speed, and elevator speed collected in field tests were used to create similar flow ranges on the laboratory test stand.

A grain feed-tank was used for feeding the grain to the clean grain auger. A grain weigh-tank (electronic scale) was mounted between the grain feed-tank and the filling auger in order to collect the exiting grain. The test stand included an AgLeader 2000 Yield Monitor and a Weigh-Tronix 1015 scale.

2.1.2. AgLeader 2000 Yield Monitor

The yield monitor employs four sensors for yield monitoring on the combine during harvest: grain flow sensor, ground speed sensor, clean grain elevator speed sensor, header height sensor. These sensors feed information to the yield monitor (main console) continuously. In addition to these sensors, a GPS (Global Positioning System) receiver is also connected to the yield monitor in order to

* Trade names are provided for the benefit of the reader and do not imply endorsement or preferential treatment of the products by Iowa State University or the USDA.
determine the real-time location of the combine. Grain moisture content can be measured by a sensor continuously or can be input manually as a variable.

In the laboratory setup, a function generator was used to simulate the combine ground speed; on and off position of the header was determined by using the count on/off switch on the yield monitor; and the moisture content of corn was measured with a portable moisture meter (Dickey-John Moisture Tester) and was input manually to the yield monitor. A “Low Grain Flow” chip (Version 3.03-L) was used. The moisture content of corn (Zea Maize) was 17% at the time of the initial laboratory tests. The yield monitor provides only the summary data (total weights in each run) if a positioning system is not interfaced with the yield monitor. Thus, a positioning system (DGPS), stationary but with access to GPS signals, was used for the laboratory tests to be able to record instantaneous yield data.

2.1.3. Weigh-Tronix - Model 1015 Indicator

Grain exiting the clean grain elevator was accumulated in a grain weigh-tank that was designed as an electronic scale. Four load cells each having 1112 N (250 lbf) loading capacity were used to suspend the scale. The measurements were recorded with a laptop computer and were also shown on the indicator’s display.

2.2. METHODS

2.2.1. Operation of the system

The test stand was driven by an electric motor. Grain was fed to the system by the grain feed-tank. The feed rate was adjusted by using the variable opening (slide mechanism) at the bottom of the grain tank. The grain tank opening and the elevator speed were adjusted so that typical mass flow rates encountered in field conditions could be used in the laboratory. The mass flow rate through the system could be varied from 0 kg/s to 4.5 kg/s (9.9 lb/s) and the elevator speed could be
varied from 310 to 370 rpm. The transmission ratio could be adjusted to achieve the desired elevator speeds.

Grain was accumulated in the grain weigh-tank, suspended by four load cells, to determine the cumulative amount of grain with time. The grain yield data were taken at a 1 Hz display rate with the yield monitor and at a 2 Hz display rate with the electronic scale. Ground speed was simulated at 4.82 km/hr (3 mph) using a function generator.

2.2.2. Calibration

Field calibration data were used in the yield monitor in preliminary laboratory tests. Initial tests showed that the yield monitor overestimated the total grain yield by 5-10% in most runs. Some trial runs resulted in about 20% difference in measured weight at reasonable flow rates. As the flow rate decreased the percent differences became too large to compare. Having observed the differences in weight measurements, it was decided to recalibrate the yield monitor. First, the calibration of the electronic scale was tested by using known weights in the appropriate loading range. The electronic scale proved to be accurate within ± 0.1% of applied load or ± 1 division (whichever is greater) as advertised in the user’s manual. Then tests were conducted to recalibrate the yield monitor by using the electronic scale as the reference. After the field calibration data were erased from the memory of the yield monitor, the accumulated weight values measured by the electronic scale were input as the actual weight values to the yield monitor and the yield monitor was recalibrated.

2.2.3. Data processing

Yield monitor

The yield data were stored in a 1 MB SRAM memory card. The yield data were first converted to a text file in “advanced format” by using the software “Precision Map 2000” by AgLeader. The time delays associated with data processing to compensate for combine dynamics
were all set to zero. This step eliminated the smoothing effects of the software on grain variation due to combine dynamics. It was intended to examine the yield data without compensating for the time delays to match the electronic scale.

*Electronic scale*

The weight of accumulating grain was displayed at a 2 Hz display rate using the electronic scale, and converted to one second cumulative data for comparison purposes.

The yield monitor and the electronic scale measured the grain in different ways. The yield monitor measured the instantaneous force exerted on the yield sensor by the flowing grain every second. This study used mass flow rate of corn in kilograms per second (kg/s), derived from the instantaneous force values recorded by the yield monitor. The electronic scale, on the other hand, monitored the weight of its content as the grain accumulated in the weigh-tank, thus providing cumulative weight information with time; these measurements were expressed in Newtons (N).

To compare the two measuring systems, two methods were used. First, the cumulative weight, in the case of yield monitor, was calculated from the mass flow data; this was done simply by adding up the amount of grain measured every second. Then cumulative weight for each system was plotted on the same graph. Second, the mass flow rate, in the case of the electronic scale, was derived from the change in measured weight every second. Then mass flow was plotted for each system on the same graph.

### 3. RESULTS AND DISCUSSION

The test stand functioned properly in laboratory conditions providing grain flow rates from 0 to 4.5 kg/s (9.9 lb/s) corresponding to 0 to 14,750 kg/ha (235 bu/Ac) at 4.82 km/h (3 mph) combine ground speed with 3 rows, 76 cm each. Clean grain elevator speed values could be varied from 310 to 370 rpm. Calibration of the yield monitor was done at elevator speeds from 340 to 360 rpm and
grain flow rates from 2 to 4 kg/s. The simulated flow rates and the elevator speeds are typical values encountered in field conditions using the JD 4420. Results presented here should be representative of these operating conditions. Tests at other elevator speeds at various flow rates may or may not suggest the need for recalibration of the yield monitor for those operating conditions. Detail on this aspect is not presented here.

Actual weight values used as the calibration data in the yield monitor were obtained from runs longer than 30 seconds. When several actual yield values measured in less than 20 seconds were also added to the calibration data, the correlation between the yield monitor and the electronic scale in terms of total weights was poor. Also, after several calibration trials for the yield monitor, it was observed that decreasing flow rate down to the threshold of the yield monitor, found to be about 1.5 kg/s [4900 kg/ha (78 bu/Ac)], was a significant factor in reducing the accuracy of the yield monitor. Therefore, performing longer tests, as much as possible, spanning a narrow flow rate region seemed to be the best way to achieve better accuracy.

Tests showed that $R^2$ was 0.99 suggesting a high correlation between the estimated total weight obtained from the yield monitor and the electronic scale (fig. 2.2). The largest percent difference was 9.17% while the smallest percent difference was 0.18% with an average percent difference of 2.11%. One of the tests showed that the total weights were 1063 N (239 lbf) and 1072 N (241 lbf) for the scale and the yield monitor, respectively (fig. 2.3). Other runs also displayed improved agreement of the total weights. The yield monitor showed more variation than the scale (fig. 2.4). Standard deviations were 0.57 N (0.127 lbf) and 1.314 N (0.29 lbf) for the electronic scale and the yield monitor, respectively. The difference in total weight estimation was 2.5% in this particular case.
4. CONCLUSIONS

The laboratory test unit performed satisfactorily within the actual range of grain flow rates that occur during harvest. A new calibration is necessary for the yield monitor under the laboratory conditions. The length of test runs and the range of grain flow rates seemed to have an impact on the accuracy of the yield monitor. Experiments at different elevator speeds with varying grain flow rates may require recalibration of the yield monitor for the best accuracy for those circumstances. A detailed examination of the yield monitor at different elevator speed values with various flow rates is necessary to draw conclusions regarding the performance of the yield monitor.

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References


Figure 2.1. Schematic of the laboratory test unit.
Figure 2.2. Linear fit for estimated total weights.
Figure 2.3. Accumulated weight.
Figure 2.4. Mass flow rate as determined from the yield monitor and electronic scale data.
CHAPTER 3. LABORATORY PERFORMANCE OF A YIELD MONITOR

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ABSTRACT

Response of a yield sensor to known grain flow variations was investigated under laboratory operating conditions through comparison with an electronic scale mounted on a test stand. The yield sensor had a quick response to sudden changes in corn flow. Based on total weight comparisons, the average percent error at constant flow rates was 2.1%. The error increased to 3.2% and 4.3% when step inputs and transients were applied, respectively. The overall accuracy was within the accuracy range (± 4%) reported by the manufacturer while the maximum error was more than 5%. The flow rate range used in the calibration was the most important factor in achieving high accuracy. Because of the fluctuations in estimated flow rate, a single data point did not correlate well with the actual grain flow rate. Averaging over 4 to 6 s usually resulted in an error less than 4%. When the flow rate varied more profoundly during steps and transients, approximately 10 second averaging was needed to maintain the accuracy in some of the tests. The effects of potential sources of errors (such as varying combine ground speed, changing crop conditions, and varying grain flow profile) also need to be considered to use the results of this study for field applications.

1. INTRODUCTION

The use of yield sensors is expanding rapidly; however, the accuracy of yield mapping over small areas has not been adequately addressed in the research literature. Current commercial

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practices assume that the advertised accuracies, < 4% (Mangold, 1996), apply to small areas as well. The accuracies of yield sensors have not been expressed by manufacturers based on specific cell sizes, for instance, on a 25x25 m² area. The importance of obtaining consistently high accuracy over small manageable areas needs to be emphasized in that variable rate application decisions will be based on the assumption that the yield mapping is done with the accuracy advertised for a specific yield sensor.

The accuracy of commercial yield sensors can be as good as ± 1% based on total weights obtained from harvest strips or from areas on the order of hectares (Auernhammer et al., 1993; Birrell et al., 1996; Murphy et al., 1995; Stafford et al., 1991; Stott et al., 1993; Vansichen and De Baerdemaeker, 1991). On the other hand, total weight comparisons of yield sensors to scales at the end of strips that result in excellent accuracy do not necessarily carry over to small cells or segments within the strip. The accuracy of continuous yield sensors decreases as the cell size decreases (Colvin et al., 1997; Doerge, 1997; Missotten et al., 1996). It was suggested that realistic cell lengths would be more than 20 m (Stafford, 1996). It still seems uncertain what level of accuracy can be expected with the current yield monitoring equipment installed on combines.

Combine harvesters themselves introduce significant errors in estimating spot yields due to the averaging and redistribution of grain inside a combine. This makes it challenging to estimate the yield coming from a certain location in the field since there are no adequate combine flow models suited for yield mapping. The material redistribution within the combine would make it difficult to determine the exact rate of crop harvesting at the combine header even if the yield sensors' accuracy were excellent.

The accuracy of a yield sensor at the field strip scale can be determined through field tests. The total amount of harvested grain is estimated by the yield sensor at the end of strips. The weight of grain is also measured by a scale and the percent error between the yield sensor and the scale is found. The calculated percent error is expressed as the accuracy of the yield sensor. The weigh-
wagon must be well-calibrated to be used as the standard for weight comparisons. Errors between yield sensors and the scales were reported to be greater than ± 10% using this technique when weights from individual grain loads were used (Missotten et al., 1996) and when loads less than 13,400 N (3000 lbwt) were considered (Doerge, 1997). Yield sensor accuracy was found to be 1% on a total area of 40 ha by Missotten et al. (1996).

Linear fits based on total weights have been used as another way of finding the goodness of fit between a yield sensor and a scale. For instance, Birrell et al. (1996) reported an $R^2=0.99$ to express the strong agreement of total estimated yields between yield sensors and scales. Perez-Munoz and Colvin (1996) conducted field tests to evaluate the performance of a yield sensor. Yield sensor performance in the field was good for 100 m strips. Twenty meter strips did not provide a fair basis for comparison due to the time delays at the beginning and the end of strips.

This current study was designed to make a comparison between the yield sensor and an electronic scale that were both mounted on the same test stand. The purpose was not only to compare total weights obtained at the end of test runs, but also to evaluate instantaneous yield measurement accuracy. No detailed reports have been published regarding instantaneous yield measurements. Incorporating the yield signals at the beginning and end of harvest strips into the grain yield mapping procedure for the full harvest strip is not suggested since these portions contain different information due to combine dynamics (Perez Munoz and Colvin, 1996; Murphy et al., 1995). Thus, it is desirable to determine the accuracy of continuous yield sensors using more unbiased approaches.

The thrust in this study was to gain more insight into the behavior of a yield sensor, independent of field conditions, using grain flows that are unaffected by combine dynamics due to field roughness or combine flow path geometry. Comparisons of yield sensors to scales might allow researchers to make more confident judgments on the accuracy and response speed of a particular yield sensor. Doing such tests on a laboratory test stand could eliminate unknown impacts on the accuracy caused by complex combine dynamics, changing ground speed, varying crop conditions and
grain flow profiles. In this research, a reference measurement system, an electronic scale whose accuracy has been experimentally proven to be better than the yield sensor, was used along with the yield sensor to measure grain flow rate on the same flow path to determine the performance of the yield sensor.

Objectives

The purpose of this study was to evaluate the performance of a grain yield sensor under laboratory conditions that are more predictable than field operating conditions. The specific objectives were to determine the important factors affecting the calibration accuracy, investigate the effects of changing flow patterns on accuracy, and observe the response characteristics of the yield sensor.

2. MATERIALS AND METHODS

2.1. System setup

A laboratory test stand constructed at the Agricultural Engineering Research Center, Iowa State University, by National Soil Tilth Laboratory personnel was used to conduct the experiments. The system was designed to sense grain flow continuously with both a yield sensor and an electronic scale (fig. 3.1). A yield sensor (AgLeader 2000*) was mounted at the exit of the clean grain elevator and collected instantaneous yield data every second. The electronic scale (Weigh-Tronix 1015) was located underneath the combine grain tank filling-auger and determined the weight of accumulated grain two times every second. The detailed description of the test stand is given elsewhere, including

* Trade names are provided for the benefit of the reader and do not imply endorsement or preferential treatment of the products by Iowa State University or the USDA.
the information on the yield monitor and the electronic scale, system operation, calibration of the yield sensor and the scale, and data processing (Arslan and Colvin, 1998).

Figure 3.2 shows the schematics of the data acquisition system. The function generator was used to simulate the combine ground speed (fig. 3.2a). On and off position of the header was determined by using the count on/off switch on the yield sensor console. The moisture content of corn was measured with a Dickey-John Moisture Tester and was input manually. If not interfaced with a positioning system the AgLeader 2000 yield monitor provides only summary data (total weights in each run). Therefore, a positioning system having access to GPS signals was used so that the yield monitor would record instantaneous yield data. The electronic scale had four load cells that sent the signals to the weight indicator (fig. 3.2b). The accumulated weight data were stored in a computer.

2.2. Experiments

Tests were conducted in four stages:

1. The smallest flow rate that could be measured accurately by the yield sensor (the threshold flow rate) was determined following calibration by gradually increasing the flow rate starting from very low flow values. Flow rate was increased stepwise in successive tests to check the agreement between yield sensor and the scale. The mass flow rate at which the yield sensor started to provide accurate flow rate estimations was considered to be the threshold flow rate of the yield sensor. This step was necessary to confirm that the electronic scale built for this study could be used as a reliable reference for the experiments to be conducted.

2. Percent error between the yield sensor and the scale was determined at various constant flow rates. Tests were done at flow rates from 0.5 to 5 kg/s following the calibration of the yield sensor.

3. Grain flow was interrupted during the experiments to apply step inputs at four different flow rates; these tests were repeated once at each flow rate.
4. Flow rates were varied during each run to observe the response of both systems to the transients. These tests included step increases from 2 kg/s to 4.5 kg/s; step decreases from 4.5 kg/s to 0 kg/s; sinusoidal inputs; step increases followed by step decreases in a single run; and random step changes in a single run.

The yield monitor error was found for step changes and transients by comparing the measured grain weight from both systems. The instantaneous data were used to average measured data points over 4, 6, and 10 s in order to investigate the influence of data averaging on yield monitor accuracy.

3. RESULTS AND DISCUSSION

The laboratory test stand was designed to simulate grain flow rates obtained from a plot combine (John Deere 4420) used in field experiments at Iowa State University. The yield monitor provided the instantaneous grain flow rate information, combine ground speed, and elevator speed (driving shaft rotational speed) for field experiments. Mass flow rates varied approximately from 2.7 kg/s (6 lbm/s) to 5 kg/s (11 lbm/s) at elevator speeds from 335 to 345 rpm with a ground speed of 4.8 km/h (3 mph) using a 3-row corn header on the JD 4420 during field experiments. In this study, the same range of flow rates was achieved at approximately the same elevator speeds so that comparable grain flow conditions could be created. The test stand had the ability to simulate mass flow rates up to 5 kg/s. Therefore, the flow rates investigated were limited by the test equipment used in this study. The elevator speeds were 325, 340, 345, and 360 rpm for flow rates of 4.5, 3.8, 2.5, and 1.6 kg/s, respectively, using the test stand. When the step inputs and transients were applied to the system the elevator speed decreased with increasing flow rates due to electric motor loading, and vice versa.

During the tests, flow rates could be varied easily using the adjustable opening at the bottom of the grain-feed tank. As the slide mechanism of the grain feed tank was opened, corn started to fall into the clean grain auger. Grain flow from the tank was constant for a fixed feed-tank opening. It
took time, however, for moving test stand components to be filled with grain until a steady flow was achieved at the yield sensor and the electronic scale. An average of 5 to 6 s (ramp-up time) elapsed until a steady flow was achieved at the electronic scale at about 3 kg/s. The minimum ramp up time was 4.5 s while 10 s was found to be the maximum to reach a steady flow through the system. Small ramp-up times occurred at high flow rates (> 4.0 kg/s) while large ramp-up times occurred at small flow rates (< 2.0 kg/s).

Test lengths influenced the accuracy obtainable from the yield sensor. Longer tests resulted in better agreement with estimated total weight values given by the scale. Calibration attempts that included total weights from tests taking less than 20 s were not satisfactory. When the tests taking less than 20 s were used in the calibration, the yield sensor error became very large. Short test runs were excluded to improve the accuracy of the yield sensor. Following calibration, the average error estimated by the yield sensor was less than 2% which was within the advertised accuracy range. It should be noted that the total weights used in each run were much less than the loads used for calibration under field conditions. It was possible to achieve 2% accuracy in the laboratory using loads less than 1,765 N (400 lbwt) by incorporating various flow rates into the calibration. It appeared that using various flow rates in the calibration was more important than maintaining a large amount of grain for each calibration load. Calibration load size seemed to be important only if the loads were too small, as resulted from short test runs. In field applications, yield sensors are sometimes recalibrated by adding the harvest loads to the previous calibration loads to improve the accuracy of the yield sensor. The loads obtained from short strips taking less than a half-minute to harvest may not guarantee higher accuracy or more consistent readings when incorporated into the calibration.
3.1 Threshold

Tests were conducted to confirm that the electronic scale had a smaller threshold flow rate and a higher resolution compared with the yield sensor. The tests started with a small flow rate and flow rate was increased gradually in each test until the yield sensor provided accurate flow rate estimations. Figures 3.3a and 3.3b show the responses found at about 0.45 kg/s and 1.7 kg/s, respectively (other tests not shown). The yield sensor did not measure the grain flow rates accurately when the flow rate was less than 1.7 kg/s (3.74 lbm/s). Instantaneous readings showed more variation in the yield sensor data than in electronic scale data. The electronic scale provided stable measurements for flow rates much smaller than 1.7 kg/s.

3.2. Constant flow

Table 3.1 shows total weight differences determined between the yield sensor and the electronic scale along with the associated mass flow rates. Each test lasted approximately 60 s. Error was smaller in the case of normal flow rates, that is tests from 1 through 8. At small flow rates the yield sensor did not estimate the total weights accurately, resulting in large percent errors (tests from 9 to 11). The system was overloaded by increasing the flow rate up to 7.0 kg/s in one test to simulate a grain flow out of the calibration range (test no. 12). The large error found in this particular case might be due to the sudden decrease in the clean grain elevator speed as the flow rate increased. The yield sensor’s response was satisfactory in terms of total weights. The average percent difference from Test 1 to Test 8 was 2.1%. Weights smaller than 540 N (120 lbwt) were not included in error calculation because they were obtained with flow rates below the threshold flow rate value. Two of the tests, Test 4 and Test 5, had relatively large errors compared to the other tests. Smaller errors were found for lower and slightly higher flow rates as shown in Table 3.1. The errors found in Tests 4 and 5 might suggest a consistency problem in making accurate flow rate measurements. The yield sensor’s error at constant flow rates was less than 4% in most of the tests based on total weights as
Table 3.1. Measured loads (N) at different constant flow rates.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Flow rate, kg/s</th>
<th>Electronic Scale</th>
<th>Yield Sensor</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.2</td>
<td>1234.8</td>
<td>1215.2</td>
<td>1.59</td>
</tr>
<tr>
<td>2</td>
<td>4.2</td>
<td>1362.2</td>
<td>1332.8</td>
<td>2.16</td>
</tr>
<tr>
<td>3</td>
<td>4.2</td>
<td>1372.0</td>
<td>1372.0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>4.1</td>
<td>1176.0</td>
<td>1127.0</td>
<td>4.17</td>
</tr>
<tr>
<td>5</td>
<td>4.0</td>
<td>1136.8</td>
<td>1087.8</td>
<td>4.31</td>
</tr>
<tr>
<td>6</td>
<td>2.3</td>
<td>784.0</td>
<td>764.4</td>
<td>2.5</td>
</tr>
<tr>
<td>7</td>
<td>2.3</td>
<td>784.0</td>
<td>774.2</td>
<td>1.25</td>
</tr>
<tr>
<td>8</td>
<td>2.0</td>
<td>725.2</td>
<td>715.4</td>
<td>1.35</td>
</tr>
<tr>
<td>9</td>
<td>1.0</td>
<td>519.4</td>
<td>323.4</td>
<td>37.73</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>215.6</td>
<td>0.0</td>
<td>100</td>
</tr>
<tr>
<td>11</td>
<td>0.5</td>
<td>196.0</td>
<td>0.0</td>
<td>100</td>
</tr>
<tr>
<td>12</td>
<td>7.0*</td>
<td>539.0</td>
<td>313.6</td>
<td>43.81</td>
</tr>
</tbody>
</table>

*The test stand was intentionally overloaded in this run

long as the yield sensor was used within the calibration range. This information might be translated into field applications in that it is necessary to calibrate the yield sensor over a range of flow rates in order to optimize the yield sensor's accuracy. The loads used in the laboratory showed that the yield sensor could be calibrated well without using large weights. Being able to calibrate the yield sensor with smaller loads would be helpful to obtain reasonable accuracy especially for short strip lengths. Ideally, the best accuracy can be obtained by calibrating the yield sensor over a narrow flow range that would increase the resolution of the yield sensor. This, however, would require the sensor to be used only in that particular dynamic flow rate range to maintain the accuracy. In field operations, due to spatial yield variability, the yield sensor must be calibrated so that all possible flow rates that can be encountered in actual harvest are incorporated into the calibration. This seems to be the reason for multiple calibrations suggested for field use of this particular sensor. The manufacturer suggests recalibrating the sensor by adding the actual weights of new loads as the strips are being harvested. By doing so, the calibration range can be broadened and/or the number of data points increased, which may enhance the accuracy or may provide more consistent flow measurements.
3.3. Step changes

Grain flow was stopped in the middle of the experiments to induce a step change in the flow rate. After approximately five seconds, the grain feed-tank was opened again introducing another step change to the laboratory test system. Due to the grain accumulation in augers and elevators, the resulting grain flow at the sensor and on the scale was not an ideal step input.

The step changes were imposed at four different grain flow rates: 1.7 kg/s, 2.5 kg/s, 3.8 kg/s, and 4.8 kg/s. The response of each system to the step changes was similar in all cases evaluated. Figures 3.4a and 3.4b show the mass flow rates determined by both systems for flow rates of 3.8 and 4.8 kg/s. The yield sensor showed more variation compared to the scale in both cases. In the segment between the 43rd and 63rd seconds in fig. 3.4a, a 4% difference was found between the scale and the yield sensor, which was less than the average difference of 5.8% obtained over the whole 70 s. When the segment from the 46th second to the 54th second was used for comparison, however, the difference increased to 6.5%. The yield sensor estimated the average grain yield more accurately when the signal is integrated over a longer segment. Figure 3.4b had an average of 3.3% error while the error was 2.5% for the section between 43rd and 53rd seconds. It is interesting that there is better agreement on a segment of the plot that would suggest lesser agreement based on visual inspection.

The yield sensor showed a quick response (slightly faster than the scale) to the changes in flow rate. No delays in response were observed following the step inputs. Based on these observations, increasing and decreasing yields estimated by the yield sensors on yield maps in the beginning and at the end of harvest strips can be attributed solely to the combine dynamics.

3.4. Transients

Two examples are given for the response of the yield sensor to transients (fig. 3.5a and 3.5b). Grain flow rate was increased and decreased randomly during the first experiment. Both measurement systems showed similar variations in grain flow rate throughout most of the test;
however, there was a relatively large disagreement in flow rate estimations on a segment between the 20th and 35th seconds (fig. 3.5a). There was an 11% difference for this segment, while the error for the whole test was 5.5%. Figure 3.5b showed a relatively large fluctuation in yield sensor output for the section between the 25th and 32nd seconds. The percent error in this particular case increased from 6.9% for the whole test to 13.8% for the segment between the 25th and 32nd seconds. The variation seen at the end of the fig. 3.5b has been ignored since the flow rate in this part is less than the threshold of the yield sensor.

Impulses of grain hitting the impact plate and the signal aliasing due to the dynamics of the chain and seven-tooth sprocket could be potential sources for noise in the measurements. At a 350 rpm elevator speed, the chain link frequency would be about 41 Hz (350 rpm x 7 / 60) while paddle frequency is approximately 10 Hz. The AgLeader yield sensors are capable of collecting the flow signals at 500 Hz. The average of measurements is recorded by a data card at a 1 Hz frequency. Thus, the sampling rate of the yield sensor is high enough to compensate for the potential noise. The segment between 25th and 35th seconds in Figure 3.5b suggests that there was a relatively large disagreement in measurement of the grain flow. Similar behavior in other figures raise concerns in that this type of unexpected disagreement could be due to noise included in the measurements. Signal aliasing, however, does not seem to be a factor contributing to such disagreements because of the adequate sampling rate of 500 Hz. The disagreements may not be due to poor yield data collection but may be due to data processing within the yield sensor.

The calculated errors for the three cases (constant flow, step inputs, and transients) are summarized in Table 3.2. An increase in the average percent error was noticeable from constant flow to step changes, and from step changes to transients. The maximum error of 9.1% found in the case of constant flow tests possibly occurred because of a small total weight [402 N (90 lbwt)] used in one test. The average errors in Table 3.2 are the average of all tests done for constant flow, step inputs, and transients, respectively. The overall average of the errors is 3.2%, which is within the advertised
Table 3.2. Summary of the calculated percent errors (%).

<table>
<thead>
<tr>
<th></th>
<th>Whole test</th>
<th>Instantaneous</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Maximum</td>
<td>Extreme</td>
</tr>
<tr>
<td>Constant flow</td>
<td>2.1</td>
<td>9.1*</td>
<td>-</td>
</tr>
<tr>
<td>Step inputs</td>
<td>3.2</td>
<td>5.8</td>
<td>6.5</td>
</tr>
<tr>
<td>Transients</td>
<td>4.3</td>
<td>6.9</td>
<td>13.8</td>
</tr>
</tbody>
</table>

* Total weight of 402 N (~90 lbwt)

accuracy of the yield sensor. There were cases, however, where the errors were larger than 5% as shown in the middle column of Table 3.2. The maximum error refers to the largest error found amongst the test runs for each type of experiment. The extreme cases refer to the error calculated for the portions that had relatively large disagreements in instantaneous data, resulting in approximately two times more error compared to the error for the whole test runs. Extreme cases did not exist for constant flows since there were not steps or transients that would destabilize the yield estimations.

Table 3.2 shows that as the grain flow becomes unsteady, the accuracy in grain yield estimation decreases. This observation would also suggest information about field operations where grain flow fluctuates during harvest rather than being steady. It should be noted that the extreme cases where large disagreements occurred in instantaneous flow rate estimations seemed to occur randomly. These incidents had varying levels of severity in different tests and large differences in readings did not consistently occur at a specific flow rate range. The percent error based on individual data points was found to be 13.8% between the 25th and 32nd seconds (fig. 3.5b) whereas the error decreased to 5.5% when the data were averaged over 10 s (24th to 33rd seconds). In another case (not shown), the error decreased by 40% if the data were averaged over a 20 s interval instead of an 8 s interval. These examples were given here because the differences were profound in these particular examples both quantitatively and visually.
The effect of averaging on accuracy was investigated by averaging instantaneous data over 4, 6, and 10 s. Table 3.3 shows the results obtained from a total of four step inputs and five transients including a sinusoidal input. The data points measured in the middle part of step changes were excluded when averaging. Similarly, the data were not used for averaging when flow rates were below threshold flow rate (such as the beginning and end of the tests and low flow rates induced during sinusoidal inputs and transients). Doing so, 6 to 11, 4 to 9, and 3 to 5 segments were obtained in each test for 4, 6, and 10 s averaging, respectively (Table 3.3). For each of these segments, the error was found and then the average of the errors was calculated for each test run for each averaging routine. The range in Table 3.3 refers to the minimum and maximum errors found in each averaging. For instance, for 4 s averaging 2.2% error was found in one of the tests while another test resulted in 6.1% error as the average of all 4 s segments in that particular test. The other test runs resulted in errors between 2.2 and 6.1%.

While the average error was less than <4% in each row in Table 3, errors larger than 4% were found in some segments in each test. Error in a segment was affected by the amount of variation in measured grain flow. Smoother segments in measured flow rates resulted in errors as low as 0.1% while errors as high as 11% were found for some segments. This was true for each averaging. Four second averaging resulted in an average error of 3.7%. Table 3.3 shows that error decreases as the number of data points increases from 4s averaging to 6 s averaging. Averaging more data points did not necessarily enhance the accuracy in some tests. Ten second averaging reduced relatively large errors found in four or six second averaging procedures if the measured data did not include one or more sudden changes in flow rate. When instantaneous data were averaged for transient inputs, 10 s averaging usually included at least one abrupt change. In those cases, the error found for 10 s averaging did not result in an error much different from 6 s averaging. When less variation was present in flow rate such as the steady parts of step inputs, averaging over longer segments usually
Table 3.3. Yield monitor error (%) for 4, 6, and 10 s averaging.

<table>
<thead>
<tr>
<th></th>
<th>Average error</th>
<th>Range</th>
<th>Number of segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 s</td>
<td>3.7</td>
<td>2.2 ... 6.1</td>
<td>6 to 11</td>
</tr>
<tr>
<td>6 s</td>
<td>3.3</td>
<td>1.6 ... 5.9</td>
<td>4 to 9</td>
</tr>
<tr>
<td>10 s</td>
<td>3.3</td>
<td>1.4 ... 5.9</td>
<td>3 to 5</td>
</tr>
</tbody>
</table>

reduced the error. In case of constant flow rate tests, the error decreased consistently from 4 s to 6 s averaging, and 6 s to 10 s averaging with errors ranging from 2.7 to 1.7%.

As a result, averaging over 4 s intervals kept the accuracy of the yield monitor within advertised accuracy (> 4%) for constant flow rates. For varying flow rates 6 s averaging would provide better accuracy compared to 4 s averaging while 10 s averaging may not necessarily improve the accuracy further. However, 10 s averaging was useful to improve accuracy in long segments where there were large differences between the yield monitor and the scale. A single data point did not necessarily accurately reflect grain flow rate since the yield monitor data had considerable fluctuations compared to scale data. The test results implied that the degree of yield variability and the number of data points used for averaging would determine accuracy in yield mapping. A reasonable approach for a trade-off between cell size and accuracy would be to start with examining the degree of yield variability in a particular field. Relatively higher accuracies can be obtained in small areas by averaging 4 to 6 data points if the yield is relatively uniform. Considering the presence of variations in yield monitor data and some of the large differences in grain flow estimations shown as extreme cases in Table 2, 10 s averaging might maintain the accuracy in field operations within the estimated calibration accuracy. Ten second averaging would result in a distance of 14 m (45 ft) at 4.82 km/h (3 mph) and approximately 22.5 m (75 ft) at 8 km/h (5 mph) combine ground speed.

The laboratory test stand did not completely simulate field operating conditions. The test stand eliminated the effects of combine dynamics, varying combine ground speed, changing crop
conditions, and ground slope variations on grain yield measurements. Impacts of these effects on yield sensor response remain unanswered. Vibration generated by the laboratory test stand could also be ignored: while the test stand was running idle, neither the scale nor the yield sensor reported any values.

The calibration procedure and the tests conducted in this study provide understanding about the basics of achieving good accuracy and the uncertainties introduced by fluctuations in grain flow rate. The manufacturer (AgLeader Technology) produces two types of chips, low-flow chips and high-flow chips, to be installed in the yield sensors. Each type of chip is designed such that better resolution and accuracy could be obtained depending on the dynamic range of flow rates being measured. The same low-flow chip that was used in field experiments was used in the laboratory tests to obtain better results because of the low flow rate ranges used in this study. Doing such tests with larger flow rates and using a high-flow chip would probably duplicate the results found in this study. The principles of obtaining good calibration accuracy would not change. However, it would be necessary to use a wider dynamic range for good calibration results because of the larger scale of flow rates. The yield sensor might provide more consistent yield estimations at high flows during and after step changes and transients if a larger test stand were used in laboratory experiments.

4. CONCLUSIONS

1. The most important factor in achieving good accuracy was the range of flow rates incorporated into the calibration. Better accuracy levels can be obtained after careful calibration in field operations as well by targeting realistic flow rates that can be encountered during harvest.

2. The yield sensor was calibrated with loads [from 8,180 to 13,475 N (from 190 to 310 lbwt)] much smaller than suggested values for field operations [17,800 N (4000 lbwt)]. Despite the small loads used in the calibration it was possible to calibrate the yield sensor with an estimated average error less than 2% for constant flow rates.
3. The average error was 2.1% for constant flow conditions. Varying the flow rate by applying step and transient changes increased the average error to 3.2% and 4.3%, respectively.

4. Due to large fluctuations in instantaneous flow measurements, a single flow reading did not accurately indicate the grain flow rate. Data averaging over 4 to 6 s generally maintained the accuracy. Ten-second data averaging eliminated the possibility for reduction of accuracy when disagreements occurred over long segments.

5. If the minimum and maximum number of data points found for averaging in the laboratory were to be considered valid for field applications, the cell lengths would approximately be 9 m (30 ft) and 22.5 m (75 ft) for a combine speed of 8 km/h (5 mph).

6. The yield sensor’s dynamic response was quite satisfactory. Yield signals that have increasing and decreasing segments in the entry and exit of harvest strips seem to be the result of complex combine threshing and separating behavior.

The laboratory test stand did not completely simulate field conditions. It would be reasonable to be conservative regarding the number of data points for averaging considering the sources for potential errors in the field such as combine dynamics, changing grain flow profiles due to vibration and field slope variations, changing crop conditions, and varying combine ground speed.

ACKNOWLEDGEMENTS

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References


Figure 3.1. Laboratory test stand.
Figure 3.2. Schematics of the data acquisition system for the yield monitor and the electronic scale.
Figure 3.3a. Threshold flow rate determination for the yield sensor - flow rate at 0.45 kg/s.
Figure 3.3b. Threshold flow rate determination for the yield sensor - flow rate at 1.7 kg/s.
Figure 3.4a. Response of yield sensor and scale to step changes at 3.8 kg/s flow rate.
Figure 3.4b. Response of yield sensor and scale to step changes at 4.8 kg/s flow rate.
Figure 3.5a. Response to randomly introduced transient.
Figure 3.5b. Response to step decreases in flow rate.
CHAPTER 4. AN EVALUATION OF THE RESPONSE OF YIELD MONITORS AND COMBINES TO VARYING YIELDS

A paper submitted to the Journal of Precision Agriculture

Selcuk Arslan 1,2 and Thomas S. Colvin 1,3

ABSTRACT

Various field experiments were conducted to determine the response of a yield sensor and a combine harvester. Grain yield measurement comparisons were made between an impact based yield sensor and an electronic scale in adjacent harvest strips. Yield measurements were more prone to errors as the segment lengths decreased. Grain yield difference between the yield sensor and scale ranged from 5 to 14%, 4 to 13%, 3 to 12%, and 2 to 11% for 15, 30, 60, and 300 m long segments. The yield differences between neighboring segments might have been caused by yield variability to a degree; however, consistent decrease in yield differences with increasing segment lengths implied that better accuracies could be obtained in longer management areas. The combine's response to grain yield changes was evaluated by creating certain yield patterns in harvest strips. Grain diffusion within the combine was more obvious when abrupt yield changes were introduced at known locations. Grain mixing and redistribution inside the combine may dictate the selection of segment sizes in the site-specific decision making process. Grain flow rate values were more stable at a constant ground speed compared to varying ground speed. The average error was 3.4% and 5.2% at constant ground speed and varying speed, respectively. Careful calibration and constant combine speed were important to achieve better accuracy with the grain yield monitors.

1 Graduate student and Professor, respectively
2 Primary researcher and author
3 Corresponding author
1. INTRODUCTION

The advertised accuracies of continuous yield monitors vary from 0.5 to 4% if the monitors are installed and used as directed (Mangold, 1996). These accuracies have also been experimentally confirmed by researchers and farmers (Auernhammer et al., 1993; Birrell et al., 1996; Missotten et al., 1996; Vansichen and Baerdemaeker, 1991). It was also noted, however, that claimed accuracies were valid on a field basis or on long strips. According to Missotten et al. (1996), error in continuous yield measurements increased with decreasing harvested area. They found 5% error on 20x20 m areas using a change-of-momentum based yield sensor. When cutting width measurement errors and speed sensor errors were incorporated, overall error increased to 7.5% on 400 m² segments. Lamb et al. (1994) found ± 25% accuracy over 15.2 m sections. Doerge (1997) compared yield monitors to weigh wagons and reported 2 to 4% differences for loads above 17,800 N (4000 lbwt) and more than ± 10% differences for loads of less than 17,800 N.

The accuracy needed to relate yields to variable applications probably is within ± 5 to 10%, according to Howard et al. (1993). Nevertheless, for the purpose of buying and selling grain, the accuracy would need to be within ± 0.2% (Iowa Agriculture and Land Stewardship Department, oral communications). Stafford (1996) suggested 10 m position resolution for yield mapping. “The instantaneous accuracy of flow sensors has not been reported”, according to Stafford (1996). Lark as cited by Stafford (1996), investigated the response of a combine to abrupt changes in grain flow rate. The yield changes in the beginning and at the end of harvest strips were considered. They concluded that yield sensors could not resolve yield variation over intervals less than 15 m. It was suggested that a more realistic scale of resolution might be 20 to 25 m. Using colored bands of grain, Whelan and McBratney (1997) investigated the delivery time distribution of the colored grain. After entering the colored band, 20% of the total grain (middle section in the band) arrived in 7 s whereas the total distribution of the grain in the band took approximately 25 s. They observed relatively smooth distribution of the colored band with some irregularities. Correct time delay adjustment is necessary.
through a deconvolution process if small cell applications are aimed, but may not be necessary for determining only the yield trends in fields, according to Whelan and McBratney. These findings show that lumped parameter combine grain flow models (Searcy et al., 1989) have inherent errors associated with grain distribution along the combine flow path.

One of the pitfalls of field experiments for determining the performance of yield monitors for site-specific applications is the in-field yield variability itself. Several approaches can be taken to determine the reliability of yield monitors for small segments. First, a thorough visual observation would give information on the spatial yield variability in a field. Then the yield map of this field could be used to verify areas having certain yield patterns that have been observed visually. Second, satellite images could be compared to yield maps to evaluate the level of agreement on yield variability. The first approach will not give a quantitative measure to identify yield variability while satellite imaging may not be accessible at all times for all farmers, even if not costly. Within-field management zones can be formed using aerial digital videography (Anderson and Yang, 1996). It was stated that, in the medium term, high resolution satellite data would provide a spatial resolution at scales of 5 to 10 m or less (Steven and Millar, 1997). Third, a comparison can be made between a yield monitor and a scale in adjacent harvest strips. This comparison can be based on whole strips or each strip can be divided into small segments (Colvin et al., 1995; Missotten et al., 1996; Doerge, 1997). The most preferred method to determine accuracy would probably be to compare continuous yield monitor data with a reference flow rate measurement system that would make flow rate measurements on the same grain flow path. Mounting a scale inside the grain tank could do this.

Smoothing/averaging effects of combines are well known (Searcy et al., 1989; Whelan and McBratney, 1997). The yield measured at the top of or on the clean grain elevator does not accurately indicate the yield at the combine head even though a time shift may be used to tag the measured yield to a specific location. In addition, the time delay is not a constant, but changes with the load (Howard et al, 1993). According to Ambuel (1995), “The combine represents an even larger
constraint to implementation of a well designed prescription farming system than does the equipment for the application of fertilizers, seeds and chemicals". Following these statements, the dynamics of a combine seems as important as, if not more important than, the accuracy of a yield monitor to determine the amount of grain associated with a certain area in the field, given that yield measurement takes place after the grain has gone through the cleaning process inside the combine.

**Objectives**

The goal of this study was to gain more understanding of the behavior of the combines and the yield monitors through field experiments. The specific objectives of these tests were to

- determine the accuracy of yield monitors on a field scale,
- investigate how accuracy is affected by harvested segment areas,
- evaluate the effect of varying ground speed on grain flow measurements,
- observe the response of a combine to instantaneous changes in grain flow rate.

The first two objectives were fulfilled by comparing the measured yield with yield monitors and electronic scales. In one test, yield comparisons were done between yield monitors and electronic scales in adjacent strips. Side-by-side comparisons in neighboring strips were used to determine the effect of varying segment areas on the yield measurement accuracy. In a second test, the yield was measured on the same grain flow by mounting a scale in the combine grain tank.

To achieve the last two objectives, certain yield patterns were created in harvest strips to introduce predictable yield differences during combining. Known locations of yield changes in harvest strips helped determine how the combine altered the anticipated shape of the grain flow rate profile. In these tests, an electronic scale mounted inside the clean grain tank measured the same grain flow as the yield monitor.
2. MATERIALS AND METHODS

Test 1: Scale and yield monitor comparison in adjacent strips

In this test, yield comparisons between a yield monitor and electronic scales were done by harvesting and measuring yield in adjacent strips of a corn field near Perry, Iowa. The field was divided into seven strips running East-West as shown in fig. 4.1. Each strip was about 365 m long and consisted of eight rows. Three strips labeled as 2, 4, and 6 in fig. 4.1 were divided into two four-row strips (North-N and South-S).

A John Deere 4420* combine was equipped with an AgLeader 2000 yield monitor and an electronic scale mounted inside the clean grain tank of the combine. The JD 4420 was used to harvest

<table>
<thead>
<tr>
<th>Number of rows</th>
<th>Strip No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>2x4</td>
<td>2(N,S)</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>2x4</td>
<td>4(N,S)</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>2x4</td>
<td>6(N,S)</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 4.1. Corn rows harvested in 4- and 8-rows.

*Trade names are provided for the benefit of the reader and do not imply endorsement or preferential treatment of the products by Iowa State University or the USDA.
Strips 2, 4, and 6 using four rows of a five-row head. Four-row strips in the upper sections of Strips 2, 4, and 6 were harvested using the electronic scale. The adjacent 4-row strips (2S, 4S, and 6S) were harvested continuously using the yield monitor. A Case IH 2188 with an 8-row head harvested Strips 1, 3, 5, and 7 continuously using another AgLeader 2000 yield monitor prior to harvest with the JD 4420.

Data collection using the electronic scale was based on a stop-and-go method (Colvin, 1990). The weight of grain and moisture content were recorded for 15 m segments. In this paper, the term "segment" will refer to each block generated in harvest strips, which can be 15, 30, 60 m, or longer depending on the length considered for comparisons with the corresponding width of the combine head used in the experiments. The yield monitors on the JD 4420 and Case IH 2188 collected yield data continuously without stopping over the entire strips. The yield monitor on the JD 4420 collected data every two seconds. The continuous yield data from the JD 4420 were integrated to generate 15 m long segments along strips to match the scale data. The yield data obtained from the Case IH 2188 had a different output format: the yield was recorded every 9 s as the combine harvested continuously. Measured yield corresponded to 15 m segments along the Strips 1, 3, 5, and 7 with a constant speed of approximately 5.5 km/h.

Yield comparisons were made between scale strips and neighboring yield monitor strips. The strip pairs evaluated were 1-2N, 2N-2S, 3-4N, 4N-4S, 5-6N, and 6N-6S. Yield data from both devices resulted in 24 segments of 15 m length along the strips. The adjacent scale and yield monitor segments were considered two samples that are paired by location. The null hypothesis was that the mean difference (kg/ha) between the adjacent segments was zero. It was assumed that the yield would be the same between close areas. Then 15 m segments were combined into 30 and 60 m segments and the same hypothesis was tested for the same strip pairs. There were 12 and 6 segments for 30 and 60 m segments along the strips, respectively (fig. 4.2).
Figure 4.2. Illustration of 30 and 60 m segments in any of the strip pairs, constructed by combining successive 15 m segments.

**Test 2: Stepped increasing and decreasing grain flow**

Simultaneous measurements of corn flow in one combine were made by a yield monitor and combine mounted electronic scale in Ankeny, Iowa. Grain flow measurements were made on fields that had been preharvested so that step increases or decreases in grain flow could be produced. The yield monitor in a Case-IH 2166 AFS combine with a six-row corn head collected the yield data. Corn flow rate was measured with the yield monitor and the grain was accumulated on an electronic scale of 4,440 N (1000 lbwt) capacity that was mounted inside the grain tank. Loads for the strips ranged from 2,670 N to 3,565 N (600 to 800 lbwt). The electronic scale had an accuracy of ± 0.1% of
the applied load. The weight of grain added to the scale per second was used to determine the grain flow rate to match yield monitor data for comparison.

Figure 4.3 shows the schematic for the experiments. Dashed areas show areas preharvested in the six-row strips to create increasing (fig. 4.3a) and decreasing (fig. 4.3b) yield patterns. The number of rows to be harvested was increased or decreased by one row every 23 m (70 ft) to induce abrupt changes in grain flow through the combine. The first segment in each strip was kept longer [30 m (100 ft)] to achieve steady grain flow through the combine.

The experiments consisted of three steps. First, harvesting was done in the direction of step increases in grain flow (fig. 4.3a). Comparisons between yield monitor and scale were made by plotting the measured grain flow rates from both devices. The total measured weights from both systems were compared on a strip basis. In the second step, tests were done in the direction of step decreases in grain flow (fig. 4.3b). Tests in these two steps were repeated three times at a constant

Figure 4.3. Harvest strips to create predictable grain flow through the combine. a) Starting with 1 row up to 6 rows. b) Starting with 6 rows down to 1 row.
ground speed of 8 km/h. The third step included tests with varying ground speeds from 6 to 1 row and then 1 to 6 rows from 8 to 11 km/h. The combine speed was varied depending on the yield variation in the field in order to keep the combine full of grain during the operation. These runs were repeated once. Consequently, a total of six strips were harvested at constant ground speed and four strips at varying ground speed.

Dynamic range

To investigate the flow rate range that could be measured with the yield monitor, one row of corn was harvested at 8 km/h. This test was repeated four times and the measured total weights were compared with the scale. The harvesting was done without stopping over the strips. The total weights of the loads were about 735 N (165 lbwt).

Test 3: Response of combine and yield monitor to abrupt yield changes

The response of the combine and the yield monitor to sudden grain yield changes were investigated by measuring the same grain flow by both devices. The combine, yield monitor, and electronic scale in Test 2 were used in Test 3. Border strips were cut across the rows to introduce sudden changes in grain flow during actual harvest (fig. 4.4). Empty segment lengths of 4.5 m (15 ft) and 9 m (30 ft) were created in the strips 30 m (100 ft) apart (fig. 4.4a). Strips having empty segments of 14 and 18 m (45 and 60 ft) were also prepared (fig. 4.4b). Harvest was done in both directions at a constant speed of 8 km/h. A total of sixteen strips were harvested. Five rows of the head were used to match the capacity of scale. The combine's response to known grain flow changes was determined by plotting mass flow rates measured by the yield monitor and the scale on the same graph. The yield monitor and the scale were also compared in terms of agreement on total weight measurements.
Figure 4.4. Schematic showing segments of 4.5, 9, 14, and 18 m removed from harvest strips.

Error estimation and calibration

The yields were measured by the scales and the yield monitors in adjacent strip comparisons. In the remaining experiments, each comparison was made on the same flow stream. Throughout this paper the term "error" refers to the percent difference of the measured quantities between a yield monitor and a scale. According to this, percent yield difference equals 100*(scale weight - yield monitor weight)/(scale weight). In all experiments, the scale measurements were considered true values.
Test 1:

The scale on the JD 4420 was a weigh bin, mounted inside the grain tank, that was used to collect accumulated grain weight at the end of each 15 m segment. Calibration of the scale was done by using known weights. The scale was calibrated using known weights and had an accuracy within $\pm 0.1\%$ of the applied load over the capacity of 4,450 N (1000 lbwt).

The yield monitor on the JD 4420 used a low-flow chip because of the flow rate range of the combine. Five loads were used for the calibration of the yield monitor ranging from 1,670 N (375 lbwt) to 4,680 N (1050 lbwt) using four rows of the five-row head. The field was flat with small undulations and harvest was done in different directions in different strips. The yield comparisons were made in East-West directions for all strip pairs.

Test 2 and Test 3:

The electronic scale (Weigh-Tronix 1015) on the Case IH 2188 had a main console that displayed the accumulated grain weight two times every second. The data were also stored in a laptop computer simultaneously. The amount of grain added to scale was used to derive mass flow rate of grain (kg/s).

The yield monitor on the Case IH 2188 had a high flow chip and was calibrated using five rows of the six row head. A total of 16 loads were used, each having a weight of about 2,670 N (600 lbwt). The topography in these fields was even with a small slope from north to south. Harvest was done in both directions during these experiments also.

In general, the calibrations of the yield monitors were done using less amounts of grain than suggested by the manufacturer. The yield sensors reported estimated average errors within 2 to 3% following the calibrations, despite the small loads used for calibrations of the yield monitors used in this study.
3. RESULTS AND DISCUSSIONS

Test 1: Scale and yield monitor comparison in adjacent strips

*Yield plots*

Yield monitor strips were divided into 15 m segments to match neighboring stop-and-go segments. Plots displayed disagreements on measured yield between adjacent areas. Two cases, Strips 2N-2S and 4N-4S, are shown in figs 4.5a and 4.5b, respectively. Increases and decreases in grain yield occurred at a different rate in most segments. No strong visual agreement was observed on grain yield values in neighboring strips. The largest correlation coefficient was found to be 0.4 in six pairs evaluated. A moving average improved the correlation coefficient to 0.53. Some of the discrepancies in the plots might find their explanation in the effects of time delay and combine dynamics as far as continuous data are concerned. The scale used in the experiments was known to be a reliable reference to determine segment yields. The time delay or other combine dynamics did not affect batch weighing in stop-and-go measurements. Another factor reducing the agreement on yield comparisons was probably the spatial yield variability in adjacent strips. There was about 10 to 15% yield variability within the field. The degree of grain yield variability in adjacent segments was not known exactly, but was anticipated to be relatively small because of the likelihood of spatial dependence of closely spaced sample locations. None of the strip pairs presented a correlation coefficient sufficient to draw reliable conclusions about the accuracy of the yield monitor. A better way to test the performance of yield monitors seems to be using an electronic scale as a reference measuring device on the same flow stream within one combine.

*Average yield and load summaries*

Calculated grain yield values are given in Table 4.1. Scale Strips 2N, 4N, and 6N are shown between yield monitor strips as in the field harvest sequence. Scale data had lower yield estimates
Table 4.1. Average yields for 4-row strips and 8-row strips, kg/ha.

<table>
<thead>
<tr>
<th>Strip no.</th>
<th>Case 2188 (Yield monitor)</th>
<th>JD 4420 (Yield monitor)</th>
<th>JD 4420 (Scale)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10043</td>
<td>9792</td>
<td>8976</td>
</tr>
<tr>
<td>2N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2S</td>
<td>9792</td>
<td>10106</td>
<td>9792</td>
</tr>
<tr>
<td>3</td>
<td>9980</td>
<td>10106</td>
<td></td>
</tr>
<tr>
<td>4S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4N</td>
<td>9792</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>9918</td>
<td>9164</td>
<td>9353</td>
</tr>
<tr>
<td>6S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6N</td>
<td>9164</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>9776</td>
<td>9687</td>
<td>9374</td>
</tr>
</tbody>
</table>

(North strips) compared to yield monitors (South strips) in all pairs except for Strip 6N-6S. Average of all strips in Table 1 was 9680 kg/ha (154 bu/Ac at 15.5% moisture content). Case IH 2188 (yield monitor) strips had an average of 9776 kg/ha (156 bu/Ac) while JD 4420 strips had an average of 9687 kg/ha (154 bu/Ac). Continuous strips altogether had an average of 9731 kg/ha (155 bu/Ac) while scale strips (JD 4420) had 9374 kg/ha (149 bu/Ac) which was the smallest average yield calculated amongst all. In general, the yield monitors had a tendency of measuring higher yield than the scales.

Paired strips 1-2N, 2N-2S, 4N-4S, and 5-6N suggested that the mean differences between the scale segments and the continuous segments were statistically significant at the 95% confidence level. Thus, two thirds of the six pairs suggested that the mean yield estimates of the scale and yield monitor were not the same. Moving averages did not improve the results (not shown): five out of six cases were significantly different. The degree of freedom in spatial data analysis is less than that of simple statistics. That is, the correlation for a spatial data analysis is always less than simple statistics. Spatial data analysis was not sought since a strong correlation did not exist as a result of simple data analysis.

Table 4.2 displays the average differences in grain yield as determined by weighing and associated standard deviations as a function of segment lengths. The shortest segments caused the largest average percent differences. As the length of the section increased from 15 m to 30 m and
Table 4.2. Percent difference in grain yield (kg/ha) as determined by weight as a function of various segment lengths.

<table>
<thead>
<tr>
<th>Strip No.</th>
<th>Length of section, m</th>
<th>Average % difference</th>
<th>Standard deviation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2N</td>
<td>15</td>
<td>14.35</td>
<td>11.25</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>13.44</td>
<td>6.10</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>11.00</td>
<td>7.17</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>10.62</td>
<td>–</td>
</tr>
<tr>
<td>2N-2S</td>
<td>15</td>
<td>10.15</td>
<td>8.01</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>9.61</td>
<td>6.88</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>9.47</td>
<td>5.14</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>8.33</td>
<td>–</td>
</tr>
<tr>
<td>3-4N</td>
<td>15</td>
<td>8.91</td>
<td>13.12</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>8.22</td>
<td>9.31</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>7.41</td>
<td>4.57</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>1.88</td>
<td>–</td>
</tr>
<tr>
<td>4N-4S</td>
<td>15</td>
<td>5.31</td>
<td>4.53</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>4.59</td>
<td>3.95</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>3.31</td>
<td>2.96</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>3.10</td>
<td>–</td>
</tr>
<tr>
<td>5-6N</td>
<td>15</td>
<td>11.38</td>
<td>8.26</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>11.28</td>
<td>3.76</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>10.11</td>
<td>5.36</td>
</tr>
<tr>
<td></td>
<td>full</td>
<td>6.04</td>
<td>–</td>
</tr>
<tr>
<td>6N-6S</td>
<td>15</td>
<td>6.41</td>
<td>5.67</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>5.02</td>
<td>3.25</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>4.09</td>
<td>3.71</td>
</tr>
<tr>
<td></td>
<td>full</td>
<td>2.01</td>
<td>–</td>
</tr>
</tbody>
</table>

Yield from Strips 1, 3, 5 were determined with the Case-IH yield monitor
Yield from Strips 2N, 4N, 6N were determined with the electronic scale
Yield from Strips 2S, 4S, 6S were determined with the AgLeader yield monitor

then to 60 m, the average percent differences decreased and the smallest percent differences were obtained from full strip lengths. The change in segment lengths had no apparent influence on the variation of standard deviations.

Decreasing percent difference with increasing segment sizes suggested that the accuracy of the estimated yield was decreasing with smaller segments. Having observed the weakening accuracy
as the grain yield is integrated over shorter distances, it seems more correct to express the accuracy of a yield monitor in terms of certain distances or segment sizes. Suggested loads for the calibration of the yield monitor are above 8,900 N (2000 lbwt), which corresponds to approximately 150 m (492 ft) length for an average yield of 10,000 kg/ha (160 bu/Ac) harvested with an 8-row corn head. These lengths are usually too large for yield mapping applications.

Considering the paired strips in Table 4.2, the average difference (error) between the yield monitors and the scale was the largest in 15 m segments while the error decreased as longer segment lengths were increased. The smallest percent difference between the yield monitor and the scale was found in the case of full strip lengths for each pair of strips. The grain mixing in the combine does not allow an exact determination of the amount of grain in a segment. The smaller the segment size, the more the overall yield diffusion from one segment to another.

Decreasing the segment sizes thus makes measurements more prone to errors due to the combine dynamics. Although the numeric values found from side-by-side comparisons may not indicate the actual accuracy of yield measurements, consistent decrease in yield differences with increasing segment lengths, as shown in Table 4.2, implied that better accuracies could be obtained in longer segments.

Test 2: Stepped increasing and decreasing grain flow

Constant ground speed

Mass flow rates obtained from the yield monitor and the scale data are shown in fig. 4.6a. The number of harvest rows increased from one row to six rows at a ground speed of 8 km/h (5 mph). Figure 4.6b was obtained in the same harvest direction where the harvest started with six rows and decreased every 23 m (70 ft) after the 30 m (100 ft) section in the beginning. At a constant ground speed, the change in grain flow rate was obvious except for the last two segments (fig. 4.6a). There was about 80 to 100% increase in grain flow through the combine from the first segment to the
second segment in the beginning of the strip. Flow rate increased at a decreasing rate as the number of rows increased. The yield varied up to 20% within the field. The yield variability may be the reason some of the one row increments did not result in prominent step increases in some of the sections. The same observation seemed valid for fig. 4.6b since there was no apparent decrease in measured flow rate where the transition occurred from 6 rows to 5 rows, for instance. The degree of yield variability seemed to determine the slopes to step increases and decreases.

A total of six strips were harvested at constant ground speed, three of which ran in the South-North and the remaining three in the North-South direction. The average difference of the total weight estimation between the yield monitor and the scale was 3.4%. The capacity of the scale was 4,450 N (1000 lbwt) and total weight of the grain accumulated in the scale was usually near or below 3,565 N (800 lbwt).

Large fluctuations seen in scale data occurred on the field road after the combine head was raised, and were due to excessive vibration (fig. 4.6a). The yield monitor kept collecting yield data for about 12 s after the head was raised to measure the grain present in the combine. The electronic scale collected the accumulated weight of grain until the yield monitor terminated the data collection except for the last part of the fig. 4.6b. During this time, the combine moved on to the side road resulting in more vibration compared to field conditions because of rough ground. This resulted in unstable readings in scale data because the electronic scale did not employ additional signal conditioning for excessive vibration. A third degree moving average was used to smooth the scale data. Also, the time axis was adjusted to account for the 12 s delay in the combine in fig. 4.6.

Figures 4.6a and 4.6b depict that low and high yielding areas in a field can be determined with the yield monitor. The yield monitor was able to read small force values applied to the monitor as well as higher forces, implying that wide flow rate ranges can be measured accurately at the exit of the clean grain elevator.
The changes in the measured force values indicated by the yield monitor and the scale were not step changes (fig. 4.6a) for either increasing or decreasing rows. The gradual variations at the transitions from one section to another were attributed to the diffusion of grain inside the combine, especially in fig. 4.6a. In-field variability can be seen in fig. 4.6b since there were large fluctuations within 23 m segments. This suggests that the observed changes in grain flow were not step changes due to the culmination of grain diffusion inside the combine and the spatial yield variability in the field.

**Varying ground speed**

Varying the combine ground speed from 8 to 11 km/h (5 to 7 mph) resulted in less agreement on flow rate measurements than the constant ground speed (fig. 4.7a and 4.7b). The speed was increased with decreasing flow rates as the number of rows decreased and vice versa in order to keep the combine full of grain. Figure 4.7a displays better agreement than fig. 4.7b; however, the grain flow change from one section to another was not as profound as in fig. 4.6a. No clear pattern was observed in the case of decreasing flow rates (fig. 4.7b). The graphs suggested somewhat gradual changes in flow rate. The yield monitor measurements had more fluctuations at high flow rates compared to the cases in constant ground speed. At high flow rates the yield monitor had higher flow rate estimations than the scale. The average error, consequently, increased from 3.4% in the case of constant speed [8 km/h (5 mph)] to 5.2% at varying speed [8 to 11 km/h (5 to 7 mph)]. The magnitude of the fluctuations in the scale data were less at the end of the strip compared to fig. 4.6, which might be due to smoother ground conditions.

**One row strips**

The total weight of grain was measured at the end of strips with the scale as well as the yield monitor. The percent weight difference in four repetitions ranged from 0 to 2.45% between
the scale and the yield monitor. Although the flow rate was kept substantially small compared to the average yield in this particular field, the yield monitor was able to estimate the total grain yield accurately. It was concluded that a wide range of flow rates could be measured with the yield monitor if it is properly calibrated. It was possible to calibrate the monitor using loads ranging from 4,450 to 6,680 N (1000 to 1500 lbwt). When calibrating, it is imperative to include the range of grain flow rates that are likely to be encountered in the field.

The average yield monitor errors found for both constant ground speed (3.45%) and varying ground speed (5.2%) were larger than the error allowed for scales. Thus, for buying and selling grain, the weight of grain may still need to be determined with a well calibrated weigh-wagon. According to Howard et al. (1993), accuracy of only 5 to 10% would be needed to relate yields to variable applications. When this criterion is considered, the yield monitors used in this study provided sufficient accuracy levels for making site-specific decisions.

Test 3: Response of combine and yield monitor to abrupt yield changes

Transients

Segments of 4.5, 9, 14, and 18 m were removed from the harvest strips to induce sudden grain flow changes during the test runs (figs 4.8a and 4.8b). Abrupt changes like these (shown as the ideal traces in figs 4.8a and 4.8b) would not occur in real field conditions. The information from these plots, however, may be useful to observe the combine’s response to transients due to in-field variability.

Ideal traces are shown in figs 4.8a and 4.8b for blank sections of the strips. These empty portions in strips did not appear accurately on the graphs. The diffusion of grain inside the combine resulted in a grain flow rate variation, which was different from the ideal trace. Only when the empty segments were longer than 9 m, did the flow rate through the combine actually approach zero. The grain mixing and smoothing was obvious in measured flow rates at the yield monitor.
Ideal traces were drawn from the distance information provided by the yield monitor. The combine diffusion filtered the yield variation resulting in reduced accuracy for sharply varying yield; however, the location of the peaks and valleys seem to be accurately placed. As a result, the smooth transitions from one segment to another in Test 1 and Test 2, and the distortion from the ideal traces in Test 3 clearly suggest that each dot on a yield map is not an accurate measure of grain yield to be tagged to a specific location in the field even if measured grain flow at the exit of the clean grain elevator may be excellent.

4. CONCLUSIONS

The objectives of this study were achieved through various field experiments. The following conclusions were drawn:

1. Average yields in adjacent segments were significantly different at the 95% confidence level. To which degree the yield variability affected yield differences in adjacent segments was unknown.

2. Decreasing the segment size for site-specific crop management would make yield estimations more prone to errors due to combine dynamics. The indicated yield differences between neighboring segments ranged approximately from 5 to 14%, 5 to 13%, 3 to 11%, and 2 to 11% for 15, 30, 60, and 300 m segments, respectively.

3. Combine ground speed affected the yield monitor's accuracy. Based on total weight comparisons, the average error of the yield monitor was 3.4% at a constant ground speed (8 km/h) whereas the average error was 5.2% at varying combine speed (8 to 11 km/h).

4. Yield monitors provided accuracy levels sufficient to determine yield trends for site-specific decision making.
5. An individual dot on a yield map representing the yield value at a specific location reflects spatial variability to a degree; however, combine diffusion filters out the variability reducing accuracy of the measurement of yield entering combine head.

6. The yield monitor measures the total amount of grain more accurately if properly calibrated and operated at a constant combine ground speed. It may measure grain flow rate accurately at the exit of the clean grain elevator, but fails to show exact grain yield variation within the field due to grain diffusion inside the combine.

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References


Figure 4.5a. Calculated yield by 15 m segments, Strip 2 (2N-2S).
Figure 4.5b. Calculated yield by 15 m segments, Strip 4 (4N-4S).
Figure 4.6a. Response to increasing flow rate at constant ground speed.
Figure 4.6b. Response to decreasing flow rate at constant ground speed.
Figure 4.7a. Response to increasing yield at a varying ground speed.
Figure 4.7b. Response to decreasing yield at a varying ground speed.
Figure 4.8a. Response of combine to abrupt yield changes - 4.5 and 9 m borders.
Figure 4.8b. Response of combine to abrupt yield changes - 18 and 14.5 m borders.
CHAPTER 5. GRAIN FLOW MEASUREMENTS WITH X-RAY TECHNIQUES

A paper submitted to the Journal of Computers and Electronics in Agriculture

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ABSTRACT

The use of low energy bremsstrahlung x-ray, 30 keV. densitometry is demonstrated for grain flow rate measurements. Constant mass flow rates for corn are related to measured x-ray intensity in gray scale values with a 0.99 correlation coefficient for flow rates ranging from 2 kg/s to 6 kg/s. Higher flow rate values can be measured by using slightly more energetic x-rays or a higher tube current. Measurements were done in real time at a 30 Hz sampling rate. Flow rate measurements are independent of grain moisture (due to a negligible change in the x-ray attenuation coefficient at typical moisture content values from 15% to 25%). Grain flow profile changes do not affect measurement accuracy. X-rays easily capture variations in the corn stream. Due to the low energy of the x-ray photons, biological shielding can easily be accomplished with 2 to 3 mm thick lead foil.

1. INTRODUCTION

Accurate, continuous yield monitoring is one of the key elements for success in precision farming. Several factors make accurate, continuous flow rate measurements challenging. One of the most important issues is maintaining high accuracy over the expected large range of flow rates, which result from spatial yield variability. The limited dynamic range of the current yield sensors at a specified accuracy requires multiple calibrations depending on the yield levels. Calibration is done
for a range of anticipated flow rates in a particular field and provides best accuracy levels only for this expected range. For calibration to be adequate, the operator needs to correctly anticipate the proper flow rate range for a given field. "Calibration of the mass flow sensor is probably the greatest potential source of error in yield monitors", according to Doerge (1997) since "anything that affects the way the grain flows through the combine or interacts with the impact sensor plate will affect the yield determination". Sanaei and Yule (1996) conducted extensive experiments using a volumetric flow meter (infrared sensor). They indicated that it is important to check crop density frequently to maintain accurate measurements. Calibration data required fine tuning during harvest for each grain type and variety (Sanaei and Yule, 1996).

Another important factor is the dependence of flow measurements on grain moisture content. Moisture content must be measured to obtain accurate yields since both volume and mass of grain are affected by grain moisture (Pierce et al., 1997). Corn moisture content varied as much as 10 percentage points within a field in the same day, according to Pierce et al. (1997) whereas the grain moisture content variations ranged from 12% to 30% in conditions typical to UK (Sanaei and Yule, 1996). It was stated that for soybeans and small grains spatial grain moisture data may not be as important since the moisture content of these grains relate to atmospheric conditions rather than physiological influences (Pierce et al., 1997). Varying moisture makes flow sensing more susceptible to errors. When using volumetric flow meters, converting the volume flow rate to mass flow rate requires incorporation of the changes in crop density. This conversion introduces the error existing in moisture readings to mass flow rate measurements (Birrell et al., 1996). The change in mass due to moisture has implications on impact based flow sensors as well. A change in the impulse of the impact has an effect on accuracy. This is influenced by the hardness of the kernel and by the coating on the impact plate. The sensor loses its sensitivity to the force being applied due to the coating caused by the accumulation of moisture, dust, and weed sap on the sensing element. The sensing surface of the flow sensor needs to be cleaned
occasionally to avoid coating. When handling high moisture grain, free moisture on the kernel surface changes impact characteristics (Doerge, 1997).

Strubbe et al. (1996) investigated another important aspect regarding the effect of grain flow profile characteristics on the accuracy of momentum based sensors. They conducted a study demonstrating that the grain flow profile prior to impact and hence mass flow readings were influenced by field slope variations and properties and composition of grain. Grain shifting on a volumetric (ultrasonic) yield sensor due to vibration and changes in field topography caused a serious problem in obtaining accurate grain flow estimations (Klemme et al., 1992).

Accuracies of yield sensors have been measured to be about 1.0% for field sizes on the order of hectares (Auernhammer et al., 1993; Birrell et al., 1996; Missotten et al., 1996; Vansichen and Baerdemaeker, 1991). Studies also reported that the actual accuracy of the commercial yield monitors were significantly lower on small areas. Missotten et al. (1996) found 7.5% errors on 400 m² areas including the cutting width and combine ground speed errors whereas ± 25% error was found on 15 m long sections within harvest strips. The accuracy of yield maps showing yield variability depends on how yield data are acquired. A spatial resolution of 15 m long cells was investigated (Missotten et al., 1996) while 10x10 m cells have been used in recent years in Europe (Stafford, 1996).

A number of approaches, both commercial and research prototypes, have been proposed for continuous yield sensing. Commercial yield monitors (both mass flow meters and volumetric flow meters) have been available to farmers for a half decade and are based on a wide variety of measurement methods including a momentum plate (Strubbe et al., 1996), a gamma ray sensor (Massey Ferguson, 1993), a paddle wheeled volume flow sensor (Birrell et al., 1996), strain gage based impact sensors (Borgelt, 1993), and an infrared sensor (Reitz and Kutzbach, 1996). Other sensors reported in the research literature include a capacitive sensor (Stafford et al., 1991), piezo-film strips (Pang and Zoerb, 1990), an elevator based flow sensor (Howard et al., 1993), and an
ultrasonic sensor (Klemme et al., 1992). Research has also been done on measuring the yield of cotton (Taylor and Ferguson, 1996), tomatoes, potatoes (Hollist et al., 1996), sugar beets, root and forage (Godwin and Wheeler, 1997; Wild and Auernhammer, 1997), and peanuts (Boydell et al., 1996).

For yield sensors to find routine implementation in precision farming practices, they should be capable of sustaining high accuracy regardless of yield, moisture content and field slope variations even over relatively small cell sizes without requiring operator interventions such as recalibration and cleaning.

X-ray techniques can form a strong alternative in flow rate measurements and would be favored over a number of other techniques for several reasons: first, x-ray techniques provide high accuracy levels in mass flow rates of grains. Second, the flowing materials would not physically interact with the measuring device, thus eliminating the coating problem at the sensing surface of a sensor (in the case of impact based sensors). Third, a large dynamic range can be achieved, thus avoiding frequent calibrations and operator intervention. Fourth, x-ray measurements are moisture independent making flow rate measurements less prone to errors due to varying moisture content. In addition, grain flow profile variations, a problem with some types of sensors, can be accounted for easily.

The objective of this study was to use x-ray techniques to measure mass flow rates of grain. Two types of experiments were performed in this study: flow rate measurements and moisture measurements. Mass flow rates of corn are determined by using transmitted beam intensity in terms of gray scale values. Conventional thickness measurements and energy dispersive methods are used to determine whether varying moisture content has an influence on the attenuation coefficients of corn.
2. MATERIALS AND METHODS

X-ray attenuation is widely used in material thickness gauging in industry. The interaction of x-rays with homogeneous material is expressed as follows:

\[ I(E) = I_o(E) e^{-\mu(E)x} \]  

(1)

where \( I_o(E) \): incident beam intensity

\( I(E) \): transmitted beam intensity

\( \mu(E) \): linear attenuation coefficient of the material

\( x \): distance x-rays traverse in the material

\( E \): x-ray energy

Transmitted beam intensity decreases exponentially with an increase in material thickness. Given the linear attenuation coefficient of the material, by measuring the incident beam intensity \( I_o(E) \) and the transmitted beam intensity \( I(E) \) material thickness can be calculated. The amount of a material in a sensing volume (instantaneous yield at the exit of the clean grain tank filling auger of a combine, for instance) can also be determined via x-ray thickness measurements. The approach here would be to correlate transmitted beam intensity in terms of gray scale values to the amount of material present between the x-ray generator and the detector. These values can easily be converted to mass flow rate.

Ruwe et al. (1966) investigated the influence of moisture variations in gamma ray measurements of attenuation coefficients of grains including corn, soybeans and forages by using a Co-60 source. The change in mass of corn and soybeans due to addition of water was 2% over a moisture range of 0 to 40%. They did not observe a significant difference in attenuation coefficients as the moisture content varied over the specified range. Although results found by Ruwe et al. do not directly translate to the operating regime used in the x-ray tests (40 kV), they do provide some insight into grain moisture content dependency. Co-60 radioisotope emits gamma rays at about 1.1 and 1.3
and 1.3 MeV energy levels where attenuation coefficients are very low. Hence, sufficient resolution would not be achieved to differentiate between grains with small changes in moisture content values. Therefore, the effect of moisture on x-ray measurements needs to be studied at low energy levels where the attenuation coefficients of light materials differ from each other more profoundly.

2.1. Flow rate measurements

System setup

Configuration for the x-ray measurement system is shown in fig. 5.1. Grain present between the x-ray generator and the image intensifier absorbed some of the incident energy. X-ray tube voltage and current settings used in the experiments were 30 kV and 3.0 mA, respectively. The transmitted x-ray photons were converted to visible light by the image intensifier. The output of the image intensifier varies from black to white as x-ray intensity goes from zero to saturation level. The resulting image is captured by a CCD (Charged Coupled Device) camera and transmitted to the data acquisition computer and then to a monitor for visual inspection. The CCD camera and frame grabber card digitize the visible image into 640x480 pixels in 256 gray scales where white is 255 and black is 0. The data acquisition computer stores these digitized values for future analysis. One of the 480 horizontal lines representing the grain flow projection is used for analysis. The system can acquire data with a 30 Hz sampling rate. Gray scale values for each of 640 pixels in a horizontal line (projection) are summed over a period of one second adding 30 horizontal lines to each other. The maximum gray scale signal intensity from this acquisition for each pixel is 7650 and minimum is 0 (Kini, 1994).

Experiments

The x-ray data were collected in a stationary laboratory setting (fig. 5.2). A bin with a 100 kg grain capacity was used to obtain various flow rates from about 2 kg/s to 6 kg/s. Flow rates were
Figure 5.1. Configuration of the data acquisition system.
obtained at fixed openings of the grain bin taking approximately 10 seconds for each flow rate. A generic electronic scale was used to determine the accumulated weight of corn at each flow rate. The scale recorded the accumulated grain weight two times a second. The weight of corn added to the scale every half a second was used to derive the mass flow rate of free falling corn. This allowed the scale to be used as a reference flow rate measurement system for x-ray measurements. The accuracy of the scale was within ±0.1% of the applied force.

During the flow, gray scale values were recorded for one second yielding a projection of the flow. After the first projection was obtained, data collection paused for 0.5 second and then data were acquired for another projection. The projections that related to the flow in the beginning and the end of the experiments were discarded because of the unsteady flow. This process resulted in 3 to 8 projections for each flow rate. First, integrated gray scale values were added up over the pixels defining the grain flow projection. Then, the resulting numeric value was divided by the number of pixel values in the corresponding projection to obtain an adjusted gray scale value. Finally, adjusted gray scale values were plotted against mass flow rates and the correlation coefficient was found between the adjusted gray scale values and the estimated mass flow rate values. The experiments were repeated ten times.

2.2. Moisture measurements

The objective in this part of the tests was to determine whether the attenuation coefficient of corn depends on moisture content.

System setup

The effect of moisture content on attenuation coefficient was determined with a semiconductor based germanium detector (fig. 5.3). The germanium detector operates in photon counting mode and is capable of distinguishing the energy levels of the detected x-ray photons.
Figure 5.2. Setup for grain flow measurements.
Therefore, the resulting data is an energy spectrum of the recorded photon intensity. The germanium detector operates as a component of a multichannel analyzer where each channel of the analyzer records photons in a specific energy range. With a device specific calibration curve, these channels are correlated to the energy levels of the incoming photons.

2.3. Experiments

The photon counting is very sensitive to the thickness of the sample being measured. It is imperative that photon counting be made on the exact location on a sample corn kernel. Thus, the critical point is to acquire data at certain moisture values at the same spot on the sample. The change in weight, however, is needed to determine the moisture content of a sample being measured. Due to irregular shapes of corn kernels, the test sample should not be disturbed to determine the moisture content. To avoid removing the sample from the test setup, the moisture content of the test sample was determined by using three control kernels. To accomplish this, first, the moisture content of dry corn was determined (12%) using a portable moisture meter. Then three control samples and a test sample (one corn kernel) approximately equal in size were chosen, weighed (grams), and wetted. Dry and wet weights of kernels were measured to four-digit accuracy by using a laboratory electronic scale. Initial moisture content, dry weight, and wet weight were used to calculate the moisture content of each kernel after being wetted, which was about 25% before the experiments started. The initial thickness of the test sample and control samples were measured using an electronic caliper with two-digit accuracy.

The test specimen was placed between the x-ray generator and the germanium detector after being wetted. Each photon counting was done for three minutes at 40 kV and 0.5 mA. Control samples were kept in a room near the x-ray vault. The moisture values of the control samples and their averages were determined at the corresponding data collection times. Counting photons with the
Figure 5.3. Schematic of the point detector.
sample gives the transmitted beam intensity as a function of energy I(E). To obtain incident beam intensity I₀(E) the number of photons needs to be determined when there is no sample between the x-ray generator and the detector. The sample was placed on a sample holder that can be moved back and forth by using a step motor with an accuracy of one-thousandth of an inch. This provided a means of removing the sample from the test setup so that photons could be counted for three minutes without the sample. After collecting data for incident beam intensity the sample was moved back to its original position for data collection at another moisture content value. This procedure was repeated until the moisture content of the sample decreased to about 15%. The number of photons was correlated to energy values (keV) for each test. By using data acquired with and without sample, attenuation coefficients were calculated using Eq. 1. Thickness of the test sample was calculated for each photon counting using a curve obtained from the measured thickness values of the control samples whose thicknesses were determined during photon counting by using the electronic caliper.

There were two factors in determining the length of experiments. The first factor was that a good signal-to-noise ratio be achieved. This was done by counting photons in each energy bin until the Poisson noise was reduced to approximately 1%. The second and more challenging factor was a limiting factor that related the changing moisture content with time. The moisture content of the test and control samples decreased at a fast rate especially at high moisture values in the first thirty minutes of the experiments. For instance, the moisture content of a wetted corn kernel can decrease from 25% to 20% in half an hour. Due to rapid evaporation of moisture from the corn kernels, the data could not be recorded for a long period. It was determined that three-minute data collection was enough to achieve a sufficient signal-to-noise ratio. Additionally, the use of control samples proved to be reliable since the moisture variation amongst the control samples was not larger than 0.5% at any time during the experiments.
3. RESULTS AND DISCUSSION

Flow rate measurements

Due to space limitations in the x-ray vault, grain flow rate was limited to a maximum of 6 kg/s (fig. 5.4). The curves in fig. 5.5 display spatial flow profiles of corn at various flow rates. The flow profile changes even when grain falls freely at a constant flow rate. Individual corn kernels do not maintain their initial placement during grain flow (fig. 5.6). This can be seen in fig. 5.5 as the shifts of the flow profiles to the right or left of a vertical line at about pixel 280.

The integrated gray scale values, corresponding to unabsorbed x-ray energy, were smallest in the center portion of fig. 5.5 because the thickness of grain was largest in the middle. Changes in the thickness of corn streams are apparent as the measurement position moves from the center to the edges for each flow. Since field slope variations and combine vibration cause grain flow profile to change, accurate measurement of the flow profiles as seen in fig. 5.5 should provide a means to account for such variations. Capture of a rapidly changing spatial flow profile also provides a measure of response characteristics of x-rays to dynamic changes in grain flow rates.

Pixel values from 100 to 450 provided the necessary information to relate integrated gray scale values to mass flow rate. Gray scale values outside this range were ignored. The increasing and decreasing gray scale values before the pixel value 100 and after 450, respectively, were caused by camera settings and were not relevant for the results. Gray scale values were summed up between pixel numbers 100 and 450 for each flow profile and were divided by the number of pixel values (450-100=350) yielding an adjusted gray scale value that represented the intensity of x-ray energy transmitted through flowing grain.

The linear fit in fig. 5.7 displays the relationship between the adjusted gray scale values and the measured mass flow rates. The flow rate and gray scale results were repeatable at fixed openings of the gravity box as shown in fig. 5.8. Table 5.1 shows the adjusted gray scale values, their averages, and associated standard deviations. The correlation coefficient ranged from 0.992 to 0.997
for ten replications. The electronic scale was used to determine the flow rates in five of these experiments; the scale was not used for the other five tests due to the excellent flow rate repeatability.

Contrast sensitivity of the measurements can be enhanced by increasing the gain and the number of sub-frames used for data acquisition (Kini, 1994). This would extend the dynamic range of the flow rates that can be measured accurately. The details regarding the effects of gain and so-called sub-framing are not discussed in this paper.

**Moisture effect**

No significant differences in attenuation coefficients were observed amongst three distinct moisture content values as shown in fig. 5.9, suggesting that changing moisture would not affect the mass flow measurements. Noise was present in these measurements since the curve for each moisture value is not smooth as shown in fig. 5.9. Greater number of photons would have reduced the noise further resulting in less fluctuation in attenuation coefficients. This might have revealed more differentiable attenuation coefficients at different moisture levels. The experiments conducted in this study did not suggest notable differences in attenuation coefficients at a Poisson noise of about 1%.

The same conclusion was drawn from the static tests using the image intensifier: the differences in gray scale values between dry and wet corn samples of the same thickness were not larger than the inherent drift in the x-ray flux provided by the x-ray generator (fig. 5.10). The gray

<table>
<thead>
<tr>
<th>Flow rate (kg/s)</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>average</th>
<th>std dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.10</td>
<td>7673</td>
<td>7670</td>
<td>7664</td>
<td>7676</td>
<td>7663</td>
<td>7669</td>
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<td>7339</td>
<td>7442</td>
<td>7439</td>
<td>7397</td>
<td>7414</td>
<td>47.7</td>
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<tr>
<td>3.44</td>
<td>6808</td>
<td>6777</td>
<td>6770</td>
<td>6872</td>
<td>6781</td>
<td>6802</td>
<td>41.7</td>
</tr>
<tr>
<td>4.23</td>
<td>6063</td>
<td>6073</td>
<td>6165</td>
<td>6238</td>
<td>6046</td>
<td>6117</td>
<td>81.7</td>
</tr>
<tr>
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<td>5482</td>
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<td>4958</td>
<td>4985</td>
<td>5007</td>
<td>5039</td>
<td>5006</td>
<td>35.8</td>
</tr>
</tbody>
</table>
scale values were summed up for each row of corn resulting in 4.9, 4.5, 5.0 and 0.2% differences between dry and wet samples for 35, 54, 69, and 94 mm thick corn samples, respectively. The experimental results agreed with Ruwe et al. (1966); that is, attenuation coefficients of corn are not significantly affected by grain moisture content.

4. CONCLUSIONS

Correlation coefficients were greater than 0.99 between constant grain flow rates and the corresponding x-ray intensity, pointing out excellent flow rate accuracy levels obtained using x-ray techniques. The results were repeatable at the same x-ray energy settings for mass flow rates from about 2 kg/s to 6 kg/s. The test set up seems promising for a continuous grain flow monitoring system on combines or for stationary applications such as elevators. The attenuation coefficient of corn kernels did not change notably when moisture content varied from 15% to 25%. Static thickness measurements on corn samples that had the same lengths but different moisture contents resulted in the same intensity, which suggested that the x-ray intensity measurements were not significantly dependent on the grain moisture content. Shielding of x-ray equipment would be very easy due to low voltage and current values (30 kV and 3.0 mA) used in experiments. Two to three millimeter thick lead foil would be enough to shield x-ray equipment. Furthermore, x-ray generators are not permanent radiation sources; the radiation terminates as soon as the power is turned off.

As a conclusion, this study demonstrated that x-ray techniques could be successfully used for grain flow measurements. Instantaneous mass flow rate can be measured with x-ray techniques without impeding the grain flow. This non-invasive grain flow measurement method also eliminates problems with the coating of sensors when wet grain, weeds, and other materials hit the impact based flow sensors. As has been demonstrated, the moisture content variation is not an issue for x-ray techniques and flow profile variations resulting from slope variations can easily be handled by this technique. The aspect of a large dynamic measurement range was not investigated extensively in this
study; however, with proper arrangements and data analysis algorithms, a wider range of flow rates can be measured using a similar setup to that used in these experiments. This could eventually eliminate the need for frequent calibrations as crop and field conditions change.

ACKNOWLEDGMENTS

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References


Figure 5.4. Flow rate steadiness of the gravity box as determined from electronic scale data.
Figure 5.5. Corn flow at different flow rates.
Figure 5.6. The variation of the arrangement of corn kernels at a constant flow rate.
Figure 5.7. Average of the adjusted gray scale values.

\[ y = -744.29x + 9339.1 \]

\[ R^2 = 0.993 \]
Figure 5.8. Repeatability of gray scale measurements.
Figure S.9. Absorption coefficients at three moisture content values.
Figure 5.10. Gray scale values for wet and dry samples having approximately the same thickness.
CHAPTER 6. GENERAL CONCLUSIONS

Conclusions

The accuracy of an impact-based yield monitor was investigated through field and laboratory experiments. It was found that the accuracy of a yield monitor was affected by calibration procedure, combine ground speed, grain flow rate variations, and the number data points used to determine the yield for small areas. Furthermore, the combine mixes the grain as the grain is processed through the combine, which would potentially make the yield estimated at the yield sensor differ from the yield at the combine head. X-ray techniques were used to determine flow rate of corn in a laboratory test setting in an attempt to devise a grain yield sensor that is not affected by error sources considered to be significant problems for yield monitors used in commercial practices. The following were found based upon the research projects conducted:

Calibration

The most important factor in achieving good accuracy was the range of flow rates used in the calibration of the yield sensor. Despite the small loads used in the calibration it was possible to calibrate the yield sensor with an estimated average error less than 2% using constant flow rates in laboratory experiments. Large errors reported in the literature could be due to poor calibration of the yield monitors. Recent developments in the yield monitoring devices might have improved the accuracy.

Combine ground speed

The grain yield changes indicated by the yield sensor were better when the combine ground speed was kept constant. The average error was 3.4% at constant ground speed whereas the average error was 5.2% at varying combine speed when a wide range of grain flow rates were introduced to
the combine. Combine operators should avoid sudden ground speed changes and stoppages to attain the best accuracy possible.

**Combine dynamics**

In field experiments the yield monitor reflected abrupt yield changes as gradual increases and decreases because of the grain mixing in the combine. Evidence was clear that grain yield variations were smoothed inside the combine. When grain flow through a combine is considered a lumped parameter system, the measured yield at the yield sensor is indicated as the true yield value at the combine head. Some yield monitors assume linear grain flow, which would eventually lead decision makers to misinterpret the yield variability. Because of the nonlinear grain flow through combines, an individual dot on a yield map does not necessarily accurately indicate yield, however, yield maps can display the yield trends successfully. Since there are no excellent combine flow models to reconstruct the yield measured at the yield sensor, the decision making should be made based on the knowledge that yield measurement is about grain yield averaging with current yield monitoring equipment and combines.

**Yield variations**

Laboratory tests resulted in an average error of 2.1% for constant flow values. Varying the flow rate by applying step and transient changes reduced the average accuracy of the yield sensor to 3.2% and 4.3%, respectively. This information may be translated into field applications. Less accuracy can be expected when measuring rapidly changing yields whereas relatively higher accuracy is more likely to be accomplished in fields displaying gradual yield changes.
Averaging

Averaging 4 to 6 data points was needed to maintain accuracy below 4% in laboratory tests. Ten-second data averaging eliminated almost all possibilities for reduction of accuracy. For site-specific decision making, changes in crop conditions (moisture and density variations), field conditions (slope, surface roughness), operating conditions (ground speed changes, ability to keep the swath width constant), changing grain flow profiles due to vibration and field slope variations should be considered. It does not seem reasonable to use individual yield measurements to form small management areas within fields. Rather, averaging data over 4 to 10 s could display yield trends sufficiently for preparing prescriptions for each site. If the minimum and maximum number of data points found for averaging in the laboratory were to be considered valid for field applications, the cell lengths would approximately be 9 m (30 ft) and 22.5 m (75 ft) for a combine speed of 8 km/h.

The laboratory test stand did not exactly simulate field conditions. It would be more reasonable to be conservative regarding the number of data points for averaging considering the sources for potential errors in field operations.

Sensor response

The yield sensor responded to flow rate changes immediately. Yield signals that have increasing and decreasing segments in the entry and exit of harvest strips result from the complex combine threshing and separating behavior. Improvement is necessary in combine grain flow models to reconstruct the yield signals more accurately.

X-ray flow rate measurements

X-ray techniques can be used as to measure grain flow rate accurately. Correlation coefficients were larger than 0.99 between constant corn flow rates and the corresponding x-ray intensity pointing out excellent accuracy levels obtained using x-ray techniques. The results were
repeatable at the same x-ray energy settings for mass flow rates from about 2.0 kg/s to 6 kg/s. The test set up can be used as a continuous grain flow monitoring system on combines or for stationary applications such as elevators. The mass attenuation coefficient of corn kernels did not change significantly when the moisture content varied from 15% to 25%. Shielding of x-ray equipment would be very easy due to low voltage and current values (30 kV and 3.0 mA) used in the experiments. Two to three millimeter thick lead foil would be enough to shield x-ray equipment. Furthermore, x-ray generators are not permanent radiation sources; the radiation terminates as soon as the power is turned off.

X-ray techniques could be successfully used for grain flow measurements. Instantaneous mass flow rate can be measured with x-ray techniques without impeding the grain flow. This non-invasive grain flow measurement method also eliminates problems with the coating of sensors when wet grain, weeds, and other materials hit the impact based flow sensors. With proper arrangements and data analysis algorithms, a wider range of flow rates can be measured using a similar setup to what was used in experiments. X-rays can also capture the variations in grain flow profile easily. These advantages eventually make an x-ray yield sensor less prone to errors that are significant issues in other types of measurement devices.

**Recommendations for Future Studies**

Field experiments provided clear evidence of grain smoothing inside the combine. Therefore grain yield reconstruction is important to accurately estimate grain flow entering the combine head. Grain distribution within the combine should be investigated thoroughly to determine how accurately the yield can be reconstructed for yield mapping. Though some investigations have been made by a few researchers to determine the grain distribution inside the combine harvesters, more work seems to be necessary for modeling of the grain flow though the combines. Some of the future studies should be directed towards improving combine grain flow models.
A yield monitor's performance was investigated in laboratory experiments, which was a strain-gage based sensor. There are other types of commercially available yield sensors such as a wheel paddle sensor and an infrared sensor both making volumetric flow rate measurements. The performance of each type of yield monitor would be of interest for end users of these products. Experiments on the accuracy of these products under controlled conditions are encouraged.

Finally, the x-ray test setup should be tested in the field where crop and field conditions would differ from controlled laboratory conditions.
APPENDIX A. SPECIFICATIONS FOR AGLEADER 2000 YIELD MONITOR AND WEIGH-TRONIX 1015 INDICATOR

Yield Monitor 2000

Sampling rate: 500 Hz
Display rate: 1 Hz (1/2 Hz and 1/3 Hz optional)
Accuracy: ± 2% in general, ± 4% most cases

Weigh-Tronix 1015 Indicator

Sampling rate: 30 Hz
Display rate: 2 Hz (default value at Broadcast Mode)
Accuracy: ± .1% of applied load ± 1 division, whichever is greater
APPENDIX B. SAMPLE CALCULATIONS FOR STANDARD GRAIN WEIGHT AND ERROR

Grain weight at standard moisture content

Known: \( W_1 = \) grain weight at initial moisture content, N

\( MC_1 = \) initial moisture content, %

\( W_1 = 600 \text{ N} \)

\( MC_1 = 17.5\% \)

Unknown: grain weight \( (W_2) \) at standard moisture content \( (15.5\%) \)

Formula: \( W_2 = \frac{W_1 \cdot (1 - MC_1/100)}{1 - MC_{st}/100} \)

\( W_2 = 586 \text{ N} \)

Percent difference or error (%)

Known: \( FR_{ym}: \) measured flow rate by yield monitor, kg/s

\( FR_{sc}: \) flow rate derived from electronic scale data, kg/s

\( FR_{ym} = 3.5 \text{ kg/s} \)

\( FR_{sc} = 3.3 \text{ kg/s} \)

Unknown: percent error in flow rate measurements

Formula: \( \text{Error} = \frac{100 \cdot (FR_{ym} - FR_{sc})}{FR_{ym}} \)

\( \text{Error} = 5.7\% \)
### Table 1. Yields (kg/ha) in 15 m segments in East-West direction - field 1.

<table>
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<tr>
<th>Strip no.</th>
<th>1</th>
<th>2N</th>
<th>2S</th>
<th>3</th>
<th>4N</th>
<th>4S</th>
<th>5</th>
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<tr>
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</table>

1. CaseIH: Case-IH 2188 combine with AgLeader 2000 Yield Monitor, continuous harvest; AL: John Deere 4420 combine with AL 2000, continuous harvest; Scale: John Deere 4420 combine with scale, stop-and-go method.

2. Yield are standardized at 15.5% moisture content.
Table 2. Average yields in individual strips - field 1.

<table>
<thead>
<tr>
<th>Strip no</th>
<th>Kg/ha</th>
<th>Strip no</th>
<th>bu/Ac</th>
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<tbody>
<tr>
<td>1</td>
<td>10005</td>
<td>1</td>
<td>159</td>
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<td>7</td>
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<td>151</td>
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</table>

1. Strips 1, 3, 5, and 7 were harvested with Case-IH 2188 combine with AgLeader 2000 Yield Monitor continuously.
2. Strips 2N, 4N, and 6N were harvested with JD 4420 combine with a scale in 15 m segments - stop-and-go method.
3. Strips 2S, 4S, and 6S were harvested with JD 4420 combine with AgLeader 2000 yield monitor continuously.
Stepped yield increases and decreases in six-row harvest strips to determine the response of the yield monitor and the combine to varying yields

Table 3. Individual grain loads at a constant combine ground speed (8 km/h) - field 2.

<table>
<thead>
<tr>
<th>Direction</th>
<th>No. of rows</th>
<th>Scale (kg)</th>
<th>Yield Monitor (kg)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN</td>
<td>6 to 1</td>
<td>389</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>NS</td>
<td>6 to 1</td>
<td>355</td>
<td>366</td>
<td>3.1</td>
</tr>
<tr>
<td>NS</td>
<td>6 to 1</td>
<td>384</td>
<td>401</td>
<td>4.3</td>
</tr>
<tr>
<td>SN</td>
<td>1 to 6</td>
<td>349</td>
<td>359</td>
<td>2.7</td>
</tr>
<tr>
<td>SN</td>
<td>1 to 6</td>
<td>408</td>
<td>422</td>
<td>3.3</td>
</tr>
<tr>
<td>NS</td>
<td>1 to 6</td>
<td>345</td>
<td>357</td>
<td>3.4</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>371</td>
<td>381</td>
<td>3</td>
</tr>
</tbody>
</table>

1. SN: harvest from South to North.
2. 6 to 1: harvest starts with six-rows, decreases 1 row every 23 m till 1 row of crop is harvested with a six-row head.
3. n.a.: not available.
Table 4. Individual grain loads at a varying combine ground speed (8 to 11 km/h) - field 2.

<table>
<thead>
<tr>
<th>Direction</th>
<th>No. of rows</th>
<th>Scale (kg)</th>
<th>Yield Monitor (kg)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
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<td>382</td>
<td>5.7</td>
</tr>
<tr>
<td>SN</td>
<td>1 to 6</td>
<td>358</td>
<td>379</td>
<td>5.6</td>
</tr>
<tr>
<td>NS</td>
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<td>SN</td>
<td>6 to 1</td>
<td>299</td>
<td>319</td>
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</tr>
<tr>
<td>Average</td>
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<td>343</td>
<td>364</td>
<td>5.9</td>
</tr>
</tbody>
</table>

1. SN: harvest from South to North.
2. 6 to 1: harvest starts with six-rows, decreases 1 row every 23 m till 1 row of crop is harvested with a six-row head.
Individual loads obtained from harvest strips having borders of 4.5, 9, 13.5, and 18 m to determine the response of combine to abrupt yield changes

Table 5. Individual grain loads at a constant combine ground speed (8 km/h) obtained from step yield changes - field 3.

<table>
<thead>
<tr>
<th>Load no.</th>
<th>Direction</th>
<th>Border lengths (m)</th>
<th>Scale (kg)</th>
<th>Yield Monitor (kg)</th>
<th>Error (%)</th>
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<tr>
<td>2</td>
<td>SN</td>
<td>9 - 4.5</td>
<td>345</td>
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</tr>
<tr>
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<td>SN</td>
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<tr>
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<td>305</td>
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<td>9 - 4.5</td>
<td>319</td>
<td>337</td>
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<td>6</td>
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<td>Average</td>
<td></td>
<td></td>
<td>342</td>
<td>361</td>
<td>5</td>
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</table>

1. SN: harvest from South to North.
2. Two segments were removed from each harvest strip to introduce sudden yield variations.
APPENDIX D. YIELDS IN 15 M SEGMENTS FOR SIDE-BY-SIDE YIELD COMPARISONS BETWEEN SCALES AND YIELD MONITORS

Included strip pairs are 1-2N, 2N-2S, 3-4N, 4N-4S, 5-6N, 6N-6S.

Figure 1. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments, Strip 1-2N.
Figure 2. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments, Strip 2N-2S.
Figure 3. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments, Strip 3-4N.
Figure 4. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments, Strip 4N-4S.
Figure 5. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments, Strip 5-6N.
Figure 6. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments, Strip 6N-6S.
Side-by-side yield comparisons between scales and the yield monitors – moving average

Figure 7. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments, Strip 1-2N - 3rd order moving average.
Figure 8. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments, Strip 2N-2S - 3rd order moving average.
Figure 9. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments, Strip 3-4N - 3rd order moving average.
Figure 10. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments, Strip 4N-4S - 3rd order moving average.
Figure 11. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments, Strip 5-6N - 3rd order moving average.
Figure 12. Yield comparisons in adjacent strips based on average yield (15.5% MC) in 15 m segments. Strip 6N-6S - 3rd order moving average.
Yield correlation between neighboring 15 m segments

Included strip pairs are 1-2N, 2N-2S, 3-4N, 4N-4S, 5-6N, 6N-6S.

Figure 13. Correlation between scale and yield monitor strips based on 15 m segments, Strip 1-2N.
Figure 14. Correlation between scale and yield monitor strips based on 15 m segments, Strip 2N-2S.
Figure 15. Correlation between scale and yield monitor strips based on 15 m segments, Strip 3-4N.
Figure 16. Correlation between scale and yield monitor strips based on 15 m segments, Strip 4N-4S.
Figure 17. Correlation between scale and yield monitor strips based on 15 m segments, Strip 5-6N.
Figure 18. Correlation between scale and yield monitor strips based on 15 m segments, Strip 6N-6S.
Yield correlation between neighboring 15 m segments - moving averages

Figure 19. Correlation between scale and yield monitor strips based on 15 m segments, Strip 1-2N, 3rd order moving average
Figure 20. Correlation between scale and yield monitor strips based on 15 m segments, Strip 2N-2S, 3\textsuperscript{rd} order moving average.
Figure 21. Correlation between scale and yield monitor strips based on 15 m segments, Strip 3-4N, 3rd moving average.
Figure 22. Correlation between scale and yield monitor strips based on 15 m segments, Strip 4N-4S, 3rd order moving average.
Figure 23. Correlation between scale and yield monitor strips based on 15 m segments, Strip 5-6N, 3rd order moving average.
Figure 24. Correlation between scale and yield monitor strips based on 15 m segments, Strip 6N-6S, 3\textsuperscript{rd} order moving average.
APPENDIX E. SAMPLE CALCULATIONS FOR THE X-RAY MEASUREMENTS

**Attenuation coefficient**

**Knowns:**
- $I_o(E)$: incident beam intensity – photon counts = 13,563
- $I(E)$: transmitted beam intensity – photon counts = 7141
- $x$: distance X-rays traverse in the material = 0.39 cm
- $E$: x-ray energy (KeV) = 13.06 KeV

**Unknown:** linear attenuation coefficient ($\mu(E)$) of the material, cm$^{-1}$

**Formula:**
$$I(E) = I_o(E) e^{-\mu(E)x}$$

$$\mu = \log \left( \frac{I_o}{I} \right) / x$$

$$\mu = 1.644 \text{ cm}^{-1}$$

---

**Moisture content**

**Knowns:**
- $W_1$: initial weight of wet sample = 0.4 grams
- $MC_1$: initial moisture content of wet sample = 25%
- $W_2$: sample weight after drying = 0.38 grams

**Unknown:** $MC_2$: sample moisture after drying, %

**Formula:**
$$MC_2 = 100 \times \frac{W_2 \times (1 - MC_1/100) - W_1}{W_1}$$

$$MC_2 = 21\%$$
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