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MEASURING MASS-FLOW-RATE ON FORAGE CUTTING EQUIPMENT

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Summary: Parameters used to predict dry mass-flow-rate of crop through a self-propelled windrower included force on the conditioning roll springs, rise of the top conditioning roll, impact force of the crop on the swath shield, platform hydraulic drive pressure, conditioning roll speed and density of crop exiting the conditioning rolls. All systems were evaluated by averaging sensor output from one test run (about 80 s duration) and comparing the to the average dry mass-flow-rate from that run, as determined by subsequent harvesting with a forage harvester and collecting the material in a weighed container. The systems that showed promise of adequately predicting mass-flow-rate through the machine were impact force on the swath shield, platform drive pressure, and roll speed. The R^2 values for prediction models using the output from these sensors ranged from 83% – 90%. Neither the force on the conditioning roll springs, the rise of the top conditioning roll, nor density of crop exiting the conditioning rolls were deemed accurate enough to warrant further study.

Keywords: Forage, Mass-flow-rate, precision farming, mower-conditioners

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Introduction and Literature Review

Over the past decade, agricultural practices have been moving from managing fields as one large homogeneous body towards treating smaller areas or "cells" of the field independently (precision agriculture). The goal of this practice is to account for variability within a field so inputs into each cell can be selected to maximize economic output while remaining sensitive to environmental concerns. Colvin et al. (1991) concluded that resources could be used more efficiently if precision farming practices were used. He found considerable variation in yield within fields of hay, corn, and oats.

Precision agricultural practices have been established in many areas of agricultural crop production, but mainly in grain crops. Yield monitors are available on most grain combine harvesters. Yield monitoring systems have been developed for harvesters of other crops, mostly as after market kits.

For most crops, the difficult and challenging part of developing precision farming technology is the development of reliable, accurate systems to measure mass-flow-rate and moisture content of the crop as it is harvested. This information is incorporated with position data (usually from Differential Global Position Systems) to form yield maps. Development of systems to measure mass-flow on grain combine harvesters began in the early 1980's with the objective of controlling forward speed to regulate throughput and thus optimize machine performance (Schueller et al., 1982). The idea of recording crop yield on a site-specific basis began to develop in the mid 1980's. De Baerdemaeker et al. (1985) laboratory tested an impact plate type sensor to measure grain mass-flow-rate. Other systems were developed, most notably being a pivoted auger weighing mechanism (Wagner and Schrock, 1987; Wagner and Schrock, 1989), a system using piezo film strips to count seed impacts (Pang and Zoerb, 1990), and an optical volume flow-meter where the volume of grain on the paddles of the clean grain elevator was measured by the attenuation of a horizontal light beam (Pfeiffer et al., 1993). Presently, most systems used in North America use an impact plate principle or the optical volume flow meter (Morgan and Ess, 1997). Much of the recent research on grain yield monitors has focused on evaluating the performance of different systems as affected by ground slope, grain type, and moisture content (Auernhammer et al., 1993; Missotten et al., 1996; Perez-Munoz and Colvin, 1996; Sanaei and Yule, 1996; Strubbe et al., 1996; Kettle and Peterson, 1998; and Kormann et al., 1998).

Most yield measurement systems in grain harvesting also measure the moisture of the crop using a capacitance type moisture sensor (Morgan and Ess, 1997). These sensors provide acceptable accuracy, although they are somewhat sensitive to throughput (Hovinga, 1998; Helfrinch, 1998).

Cotton yield has been measured by optical methods, where the blockage of light between a light emitting diode and a photodiode is measured in the delivery ducts of the picker as bolls of cotton are transported to the basket (Durrence et al., 1998). Peanut yield has also been measured by weighing the basket on the peanut combine (Thomas et al., 1997; Perry et al., 1998). Both sugarbeet and potato mass-flow-rate have been monitored by installing load measuring idler wheels or supports under the crop conveyor on harvesters (Campbell et al., 1994; Schneider et al., 1996; Walter et al., 1996; Hall et al., 1997). Glancey et al. (1997) also has worked on measuring the mass-flow-rate in green pea and cucumber harvesters using impact plate principles similar to those found in grain harvesting equipment.

Precision farming research activities in the forage area have evolved slowly because: (1) so many different machines are used to harvest forages; (2) measuring the mass-flow-rate and moisture on forage equipment is more challenging than on grain combine harvesters; and (3) the evolution of hay into a commodity has been a relatively recent occurrence. Development of yield monitoring systems for forage harvesting equipment would be beneficial because better management of inputs can lead to greater economic efficiencies and forages are often grown in crop rotations and a continuous history of yields are needed to have complete knowledge of the production cycle.

Yield measurement on all forage harvesting equipment is challenging because the crop is generally not accumulated on the machine itself. Feedroll displacement has been used to measure mass-flow on a forage harvester (Mains et al., 1984; Ehlert and Schmidt, 1995, Barnett and Shinners, 1998). Vansichen and De Baerdemaeker (1993) measured the torque on the blower and the cutterhead and feedroll assembly to predict mass-flow through a forage harvester. van der Weft et al. (1994) predicted forage dry matter yield by measuring trailer volume and material density. Godwin and Wheeler (1997) developed yield maps for forage crops based on mass accumulation rates in a container. Auernhammer et al. (1995) measured the mass-flow in a forage harvester using a radiometric sensor. Martel et al. (1998) attempted to predict mass-flow-rate in a forage harvester using a measurement of feedroll rise, and impact force on a plate installed in the spout of the machine.

To date, yield measurements on round balers has been limited to determining the mass accumulation rate in the machine with load cells in the axles and tongue of the machine (Wild et al., 1994; Wild and Auernhammer, 1997; Behme et al., 1997).

No research as been found which deals with measuring forage crop yield at cutting. One advantage of measuring crop yield at cutting would be that yield would be measured where it was grown. With forage harvesters or balers, the crop windrow is often raked to combine multiple swaths from cutting or to increase the drying rate of the crop. During the process of manipulating the windrow, the crop is often displaced considerable distance from where it is cut, which would result in inaccuracies in the crop yield map. In addition at cutting, the width of the swath cut can be measured. When harvesting with a forage harvester or baler the exact width of crop accumulated in the windrow would be more difficult to determine, especially if multiple windrows are grouped together. Also, losses are incurred when manipulating and harvesting the crop, so one can only be certain of obtaining “true” crop yields from cutting equipment. Finally, if accurate systems are developed to measure yield on both cutting and harvesting equipment it may be possible to get an idea of losses incurred during the entire forage harvest.

In North America there are two general types of mower-conditioners used to harvest forage: sickle and disk cutterbar. Sickle cutterbar mower-conditioners generally consist of: (1) a pickup reel; (2) a sickle cutterbar; (3) a converging element to feed the conditioning rolls on wide machines; and (4) a roll-type conditioner. Disk cutterbar mower-conditioners generally consist of: (1) a disk cutterbar; (2) converging elements on wide machines; and (3) a conditioner. Disk cutterbar machines will have either a roll-type conditioner or an impeller-type conditioner. Ideally, a system to measure yield on a forage cutting machine should work with either mower-conditioner cutting or conditioning configuration. Of course any such system must not interfere with the primary operation of this machine: cutting forage.

The objectives of this research were to design, fabricate and field evaluate systems to measure mass-flow-rate of forages on a self-propelled forage windrower and to develop prediction models of mass-flow-rate as a function of sensor output.

Sensor Systems

Machine Description

The machine used in this research was a John Deere 4890* self-propelled sickle cutterbar mower-conditioner equipped with a model 890 4.9 m hydraulically driven cutting platform (fig. 1). The conditioner used two 2.54 m wide urethane-surfaced conditioning rolls.

FIGURE 1 -- JOHN DEERE 4890 WINDROWER WITH 890 CUTTING PLATFORM

Conditioning Roll Spring Force

On this machine, the bottom conditioning roll is fixed while the top roll floats to accommodate variations in thickness of the crop mat fed into the rolls. Pressure is maintained on the rolls and crop by two coil springs, which indirectly apply force to the top roll through a linkage. One of the links in this system also serves to adjust the clearance between the two conditioning rolls. As the top roll rises the two springs elongate, thus increasing the force on the crop mat entering the rolls.

It was hypothesized that the total force seen by the conditioning roll springs would be proportional to the amount of material flowing through the machine. To measure this force, two 4.45 kN "S" type load cells were installed in series with the conditioning roll springs (fig. 2). To accommodate these load cells, the top spring mounting on the machine were modified to accept the length of the load cells. The springs were preloaded to the manufacturer-specified length, which produced a force of 2550 N of force on each spring. Corresponding roll specific force was 2.9 N/mm, with a maximum allowable specific force of 3.7 N/mm. Overload stops were installed to insure that the load cell capacity would not be exceeded by excess roll movement. A junction box was used to sum the signal from the two load cells, so that one signal representing conditioning roll force was processed by the data acquisition system.

FIGURE 2 --CONDITIONING ROLL SPRING WITH LOAD CELL

Conditioning Roll Rise

It was hypothesized that the rise of the top roll with respect to the position of the bottom roll would be proportional to the conditioning roll

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* Mention of trade names does not imply endorsement by the University of Wisconsin.

spring force, and the rise should be correlated to the mass-flow of material passing through the rolls. Advantages of measuring roll rise as opposed to spring force include: (1) the rise of the top roll can be measured directly, and is unaffected by friction in the linkage joints; and (2) position sensors are less expensive than load sensors. Rotary potentiometers were used because of they are low cost, durable and require less complicated signal conditioning equipment.

To measure conditioning roll rise, rotary potentiometers with 45^{o} active measuring range were installed on either side of the crop conditioner. The input shaft of an individual potentiometer was connected to the link between the bottom spring mount and the conditioning roll via a two bar hinging linkage (fig. 3). The connection point of the two-bar linkage was chosen to maximize sensor output.

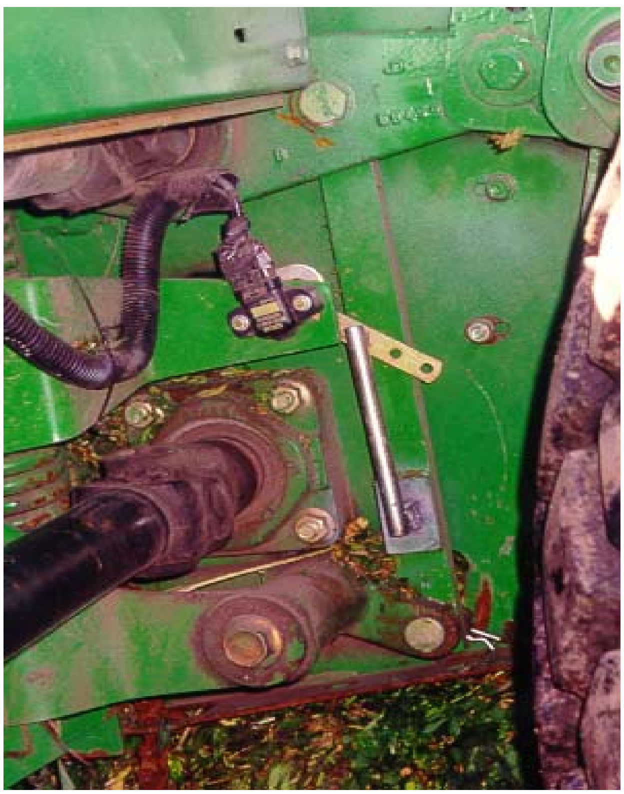

FIGURE 3 -- ROTARY POTENTIOMETER TO MEASUSURE ROLL RISE

The movement of the roll link had both linear and rotary components. To obtain a direct relationship between potentiometer output and displacement of the rolls, roll displacement on either side of the machine was calibrated as a function of the sensor output voltage. The total allowable displacement of the top conditioning roll was 80 mm.

Swath Shield Force

Most mower-conditioners use shields behind the conditioning mechanism to control the width of the swath formed. The John Deere model 4890 windrower and 890 cutting platform used two sets of shields to control width of swath formation. A shield behind the conditioning rolls directed crop to the ground directly (as a wide swath with shield angled downward), or to a set of windrow forming shields mounted on the traction unit with the shield angled upward .

It was hypothesized that the force of crop impacting this swath deflection shield would be proportional to the mass-flow of crop through the machine. The magnitude of the impact force would be reflected in the change of momentum in the crop (both speed and direction) before and after impacting the shield. The impact force on this shield would also be affected by the speed of the crop, angle of incidence on the crop shield, and the orientation of the cutting platform with respect to the horizontal (a combination of cutting angle and ground slope). In order to correlate the mass-flow with crop impact force on the shield, these parameters must also be determined. Velocity of crop was estimated from rotational speed of the conditioning rolls. The angle of incidence of the crop was determined by the angle of the swath shield with respect to the platform frame. Individual calibration equations for each swath shield position were made.

The mechanism used to set swath shield position was removed, and replaced by a link with an 890 N capacity "S" type load cell in series between the cutting platform and the swath shield (fig. 4). The link could to be pined in three positions, one for forming wide swaths (down) one for forming narrow windrows (up) and one intermediate position. To reduce friction, flange mount ball bearings replaced bushings at the joints where the pivot shaft of the swath shield mounted to the frame. Also, high quality bushing type eyebolts were used to reduce friction at the pined ends of the load-measuring link. The length and point of attachment of the load-measuring link were selected to maximize the link force, without exceeding the load cell capacity. The load measuring link experienced a maximum force when no crop is flowing through the machine, and crop impact on the shield reduced the force on the link. To insure that the load cell would always be measuring a tension force in all swath board positions, some ballast weight was added to the swath shield.

FIGURE 4 -- SWATH SHIELD FORCE MEASURING SYSTEM

Instrumentation

For the mower-conditioner mass-flow measuring system, the requirements for the individual sensors were determined (table 1). To perform the data acquisition, a portable computer with two PCMCIA slots was used. LabVIEW® (Version 4.1) software was used to collect and manipulate the data.

TABLE 1 -- SENSOR REQUIREMENTS

Sensor	Magnitude of Measurement	Sensor Excitation	Output Signal
Conditioning roll force (load cell)	5-10 kN	10 V	3 mV/V
Swath shield impact force (load cell)	0-800 N	10 V	3 mV/V
Roll rise (potentiometer)	0-80 mm	5 V	0-20 V
Magnetic pickup	0-525 RPM	None	Pulse

A National Instruments DAQ700 PCMCIA card was used to perform the analog to digital (A/D) conversions. NIDAQ driver software (version 6.0) controlled data acquisition. Three National Instruments strain gauge input modules (5B38) were used for signal excitation and fixed ratio signal amplification gain (167) for the strain gage load cells. A National Instruments 5B45 frequency input module was used to convert speed pick-up frequency to a voltage.

Signals from the sensors were sampled at a rate of 100 Hz and every 50 points averaged producing 2 recorded data points per second to an ASCII spreadsheet file. Averaging every 50 data points allowed data files to be reduced in size from about 500 KB to 10KB, without concern of signal alias which would have been the case at a 2 Hz sampling rate. To further insure no signal aliasing, all data were passed through a first order low pass Butterworth filter with a cutoff frequency of 1 Hz.

Experimental Conditions and Tests Conducted

The sensor systems were evaluated at the University of Wisconsin’s Arlington Agricultural Research Station during the summer of 1998. The crop used for the study was either alfalfa or an alfalfa/grass mixture. Five days of testing were conducted and dry matter yields on the crop used for the experiment ranged from 4-6 tonnes/ha (table 2).

TABLE 2 -- SUMMARY OF TESTS

Cutting date	Crop	Average moisture content, % wet basis
June 3	Early first cutting alfalfa	79.0%
June 15	Late first cutting alfalfa	76.8%
July 8	First cutting – new seeding	84.0%
August 12	Third cutting alfalfa/grass	77.7%

Forage was cut in discrete data runs about 80 s in length. The data acquisition system was started before cutting began, and stopped after cutting finished, capturing the steady-state, no mass-flow conditions at both ends of a test run. The systems were evaluated over a wide range of mass-flow-rates by changing forward speed. For each test date, crop was cut at three different forward speeds of about 3.3, 6.5 and 9.8 km/hr (except for June 15, 1998 when heavy, tangled crop required a reduction in forward speed to about 2.4, 4.1, and 5.7 km/hr.)

Consequently, test runs varied in length from 50 to 200 m. Additionally, different positions of the swath shield were evaluated. Initially all three swath shield positions were tested, producing swaths about 1.6, 1.9 and 2.2 m wide. The system was evaluated only with the two extreme positions during the final two cuttings, in order to create larger data sets at those positions. Nine experimental conditions were used during the first 2 test dates (3 speeds, 3 swath shield positions) and six conditions were used during the remaining test dates (3 speeds, 2 swath shield positions). For the first 2 test dates, the crop was cut replicating each experimental condition 3 times (27 test runs) while each condition was replicated 5 times (30 test runs) over the remaining test dates. All runs were cut in the same direction in the field, against the crop lodge. So that the overlap was not always on the same side of the platform, replicates for each experimental condition were cut from opposite sides of the field. Following the cutting of each row, it was marked with a wooden stake, with the data run and experimental condition labeled on each stake. Tests were run with the guard angle at the most aggressive level, and were carried out on reasonably level ground to reduce the effect of header horizontal orientation.

To measure the weight of crop cut during each test run, crop was harvested with a John Deere 3950 forage harvester and collected in a weighed container (Kraus et al., 1993). The weighed container forage box allowed for the determination of the net mass of forage harvested in each test cell. The harvester's windrow pickup was only 2.1 m wide, and could not pickup the wide swaths so all data runs were raked before harvest with a New Holland model 258 parallel-bar rake into a windrow about 1 m wide.

Three random sub-samples were taken from each data run at harvesting. These sub-samples were dried for 24 h at 103^{o}C as per ASAE Standard S328.1 to determine moisture content. This allowed for a calculation of dry matter harvested in each run. Two samples were taken each day during cutting to determine moisture content of the fresh crop. Each sample consisted of handfuls of crop from various windrows. Three sub-samples (6 per day) were dried using the same procedure as the samples taken at forage harvesting.

Data Analysis

Individual sensor data for each run were plotted versus time and the steady state periods before and after data collection for each run were deleted. The remaining data were averaged resulting in a run average value for each sensor output (conditioning roll rise was an average of sensors from both sides). The time elapsed during data collection was also determined by the data acquisition system. The wide black line in figs. 5 through 8 represent the "run average" value for that sensor. The extremities of the heavy black line represent the limits of data used to determine the run average. Average dry-mass-flow-rate (DMFR) during the data run was calculated by dividing the total dry mass of material collected in the forage box by the elapsed time during cutting. Run average data sets were constructed to perform regression analysis with DMFR as the dependent variable and sensor output as independent variables. In the regression analysis, only parameters with $P < 0.05$ were kept in the final prediction models.

RESULTS

Conditioning Roll Force as a Predictor of Mass-Flow-Rate

Dynamic plots of conditioning roll force versus time illustrate large deviations of individual points from the run average (fig. 5). The alfalfa stands appeared to be quite uniform before cutting. However, machine dynamics evidentially caused some non-uniformity in flow through the rolls. A plot of run average conditioning roll force versus run average dry mass-flow-rate is presented in figure 9 and the single parameter regression analysis produced a 47% correlation coefficient.

Multiple regression analysis was performed using run average conditioning roll force and conditioning roll speed as independent variables and dry-mass-flow rate as the dependent variable produced the following relationship (fig. 10, table 3). The correlation was improved by including the roll speed as an independent variable.

TABLE 3 -- CONDITIONING ROLL FORCE AS A PREDICTIOR OF MASS-FLOW-RATE

DMFR = 4.29E-3 * CRF – 4.17 * CRS		
R^2	**SEC**	**N**
62%	0.68	117

Conditioning Roll Rise as a Predictor of Mass-Flow-Rate

It was evident that conditioning roll rise also varied considerably with time (fig. 6). Conditioning roll rise versus dry mass-flow-rate is presented in figure 11 and the single parameter regression analysis produced a 39% correlation coefficient. Multiple regression of the data using conditioning roll rise and conditioning roll speed as independent variables and dry mass-flow-rate as the dependent variable produced the following relationship (fig. 12, table 4).

TABLE 4 -- CONDITIONING ROLL RISE AS A PREDICTIOR OF MASS-FLOW-RATE

DMFR = 23.4 + 0.61*CRR – 4.36E-2*CRS		
R^2	**SEC**	**N**
59%	0.71	117

Again, the addition of conditioning roll speed significantly improved the model. In fact, conditioning roll speed was better correlated with dry-mass-flow rate (56%, fig. 15) than conditioning roll rise (39%, fig. 9) or conditioning roll force (47%, fig. 11).

Swath Shield Impact Force as a Predictor of Dry Mass-Flow-Rate

A dynamic plot of swath shield force (fig. 7) versus dry mass-flow-rate shows that the deviations of the individual data points from the mean (SD = 33 N) were much smaller than the difference between the mean (405 N) and the null (595 N). This was true when the swath shield was in all positions, with the most consistent data coming when the shield was angled down for wide swath formation, and hence producing the largest impact forces. A plot of swath shield force versus dry mass-flow-rate is shown in figure 13 and the single parameter regression analysis produced correlation coefficients between 76 and 90% depending upon swath shield position. Multiple regression of the data using swath shield force and conditioning roll speed as independent variables and the dry mass-mass-flow rate as the dependent variable produced the following relationship (fig. 14, table 5).

TABLE 5 -- SWATH SHIELD FORCE AS A PREDICTIOR OF MASS-FLOW-RATE

DMFR = 26.85 - 2.38E-2*SSF – 1.82E-2*CRS (Forming 1.6 m swath)		
R^2	**SEC**	**N**
83%	0.44	50

DMFR = 21.26 - 1.14E-2*SSF – 2.46E-2*CRS (Forming 1.9 m swath)		
R^2	**SEC**	**N**
86%	0.41	19

DMFR = 7.30 - 1.22E-2*SSF (Forming 2.2 m swath)		
R^2	**SEC**	**N**
90%	0.38	48

The effect of adding conditioning roll speed to the regression analysis with impact force was less effective in improving the model correlation than with the sensors because impact force on the swath shield alone was well correlated with mass-flow-rate.

Discussion of Results

It appears that only the measurement of swath shield force has potential to predict dry mass-flow-rate. From observations, it appeared that the conditioning rolls did not displace smoothly with changes in mass-flow-rate, but rather displaced abruptly at frequencies corresponding to feeding caused by the reel bats or auger paddles. Also, roll specific force was large enough that at low mass-flow-rates the rolls would not displace off their stops. Roll displacement values were very low, often less than 1 mm on average. Accurate measurement of this range of displacement would be difficult in practice due to tolerance limits in linkage joints. The tolerance limits in the measuring linkage was probably one of the reasons that conditioning roll force was better correlated with mass-flow-rate than was conditioning roll rise. Large capacity load cells used to measure conditioning spring force are relatively expensive. Maintaining these sensors with such a high preload level (60 % of full scale rating in this research), also makes them prone to null drift. Finally, spring hysteresis could introduce further errors.

The addition of conditioning roll speed improved prediction models considerably, and, in fact conditioning roll speed was better correlated to dry mass-flow-rate than was either conditioning roll force or conditioning roll rise (fig. 15).

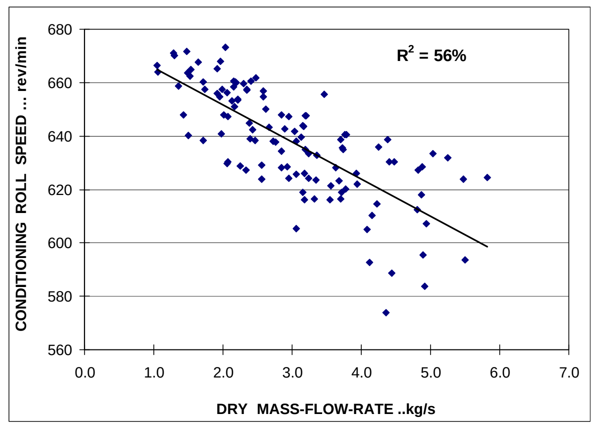

FIGURE 15 -- CONDITIONING ROLL SPEED VERSUS ALFALA DRY MASS-FLOW-RATE

Most cutting machines employ a swath shield to control crop flow, so predicting mass-flow with impact force on this shield could be adapted to many types of cutting machines. This system has no adverse effect on material flow through the machine. However, the load cell system used to measure impact force was prone to null shift. Another disadvantage of this system is that a calibration curve is required for every swath board position. Ideally, a real-time measurement of swath board position should be made along with the measurement of swath shield force. Ground slope and guard angle are factors that are likely to effect the accuracy of using swath shield force as a predictor of mass-flow-rate, so measurement of these parameters is also required.

Summary

- Parameters used to predict dry mass-flow-rate of crop through a self-propelled windrower were the force on the conditioning roll springs, rise of the top conditioning roll, and impact force of the crop on the swath shield.

- All systems were evaluated by averaging sensor output from one test run (about 80 s duration) and comparing to the average dry mass-flow-rate from that run, as determined by subsequent harvesting with a forage harvester and collecting the material in a weighed container.

- The only system evaluated to show promise of adequately predicting mass-flow-rate through the machine was impact force on the swath shield. R^2 values for prediction models using this sensors output ranged from 83-90 %. Neither the force on the conditioning rolls nor the rise of the conditioner rolls was deemed accurate enough to warrant further study.

- Further study is required for the swath shield impact force measuring system to investigate alternatives to using load cells for obtaining a measurement of swath shield force, and to evaluate the effect of the parameters of ground slope, guard angle, and shield position on the accuracy of the system.

Nomenclature

DMFR = Dry mass-flow-rate, kg/s
CRF = Conditioning roll force, N
CRR = Conditioning roll rise, mm
SSF = Impact force of crop on swath shield, N
CRS = Conditioning roll speed, rev/min

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